Integrated modelling of control and adaptive building envelope: development of a modelling solution using a co-simulation approach

by

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A thesis submitted for the degree of Doctor of Philosophy

2021

Student declaration

I, Esther Borkowski confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Adaptive building envelopes can dynamically adapt to environmental changes, often supported by a control system. Although adaptive building envelopes can play a significant role in improving thermal building performance, uncertainties and risks have led to a slow uptake in the built environment. A reason for this is the reluctance of practitioners to consider integrating adaptive building envelopes in building design. This may be due to Building Performance Simulation (BPS) tools that can be employed for performance prediction of design proposals with adaptive building envelopes. However, a shortcoming of existing tools is their limited adaptation that hinders proper modelling of the influence of control decisions on the dynamic behaviour of these building envelopes.

This thesis investigates an approach for the integrated modelling of control and adaptive building envelope. To this aim, an interview-based industry study with experts in adaptive building envelope simulation was conducted. The interview study aimed to advance the understanding of the limitations of adaptive building envelope simulation in current design practice and to identify implications for future tool developments. The feedback from the interviewees was then used to inform the development of an integrated modelling approach using co-simulation, the accuracy and functionality of which were subsequently tested through a validation study and a multiple-case study.

The findings of the interview study outline the need for more flexible modelling approaches that enable designers to fully exploit adaptive building envelopes in building design. The proposed modelling approach for predicting the thermal performance of adaptive building envelopes has shown that its co-simulation setup seems to offer more flexibility in integrating the dynamic behaviour of adaptive building envelopes. What is now needed is to observe the execution of the modelling approach in design practice to obtain realistic feedback from its users and to verify that it works as intended.

Impact statement

Adaptive building envelopes can dynamically adapt to environmental changes to improve the thermal performance of buildings. To integrate adaptive building envelopes into building design, Building Performance Simulation (BPS) tools can be used for performance prediction. However, a shortcoming of existing tools is their varying levels of control system development and integration into the simulation code. This implies that the flexibility to accurately represent adaptive building envelopes remains challenging. This challenge has made practitioners reluctant to consider the use of adaptive building envelopes in the design decision-making process, which in turn has led to a slow uptake of these building envelopes in the built environment.

This study first sought to advance the understanding of adaptive building envelope simulation in design practice and to identify implications for future tool developments. To this aim, the study took into account the end user perspective through interviews with experts in the field. The findings of the interviews suggest that more flexible modelling approaches that can adapt to changing requirements are needed to enable designers to take full advantage of adaptive building envelopes. Following this, the interview findings were used to develop a potential approach to modelling adaptive building envelopes tailored to the needs of practitioners (i.e. flexibility). It is based on a method that combines models of the interactions of multiple adaptive building envelope components in an integrated modelling system using co-simulation, where models developed in heterogeneous modelling environments are flexibly combined. However, it was unclear whether co-simulation can accurately predict adaptive building envelope performance. While each individual tool may be validated, less work has been done to understand the process of validating adaptive building envelope models created in a co-simulation setup. This study therefore empirically validated a co-simulation model for an adaptive building envelope. It was shown that the model can accurately predict the performance of adaptive building envelopes. While the proposed modelling approach may enable practitioners to consider adaptive building envelopes in the design process, it needs to be tested under real-world conditions to ensure that the research result may be transformed into a practical application that creates lasting benefits for practitioners. Consequently, the functionality of the modelling approach was tested to determine whether it can be used to test design alternatives of adaptive building envelopes under conditions likely to be encountered in real design projects.

The main findings of this research have been discussed through the publication of peer-reviewed articles in journals and proceedings, and further publications are in preparation. As the modelling approach seeks to turn into a practical application that creates a lasting benefit for practitioners, dissemination of findings beyond academic publications is an important issue that was considered from the very beginning of the research. Consequently, the findings were presented on a number of opportunities:

- Reflecting the collaborative nature of the research, key findings were presented at invited talks and meetings with the industry.
- Recognising the significant role of industry professionals in the interview phase of the research, key findings were shared with the industry professionals who participated in the interviews.

Furthermore, the code of the proposed modelling approach has been published on Github.

The research has been funded by Stiftung der Deutschen Wirtschaft (Foundation of German Business).

Acknowledgements

First of all, I would like to express my sincere gratitude to my supervisors Dr Rokia Raslan and Dr Dimitrios Rovas for their invaluable guidance and feedback at every stage of this work. Without them, this thesis would not have been possible.

I am deeply grateful to Alessandra Luna-Navarro (University of Cambridge), Michalis Michael (University of Cambridge) and Mauro Overend (Delft University of Technology) for their help in providing valuable data for this work and their advice.

This research was made possible through funding provided by the Stiftung der Deutschen Wirtschaft (Foundation of German Business), whose generous support I would like to acknowledge.

Much of this research was conducted in collaboration with the industry. I would therefore like to thank the companies that kindly offered support, feedback and case studies, especially Mattia Donato (Arup), Giovanni Zemella (Arup) and Charis Cosmas (BuroHappold). In particular, I would also like to acknowledge the valuable contribution of the study participants from the industry, whose generosity in giving their time and effort despite busy work schedules was crucial to the completion of the work.

The author acknowledges the use of the UCL Myriad High Throughput Computing Facility (Myriad@UCL), and associated support services, in the completion of this work.

My very special thanks goes to my family, especially my parents, and my friends for their encouragement and patience throughout my studies. Finally, I could not have completed this work without the support and love of my husband. Thanks also to our daughter, who was such a supportive little baby over the last few months.

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Glossary

This glossary clarifies some of the terms used in this thesis, and it shows how certain terms are understood within it.

Actuator Device to translate a control signal from a sensor into an action.

Adaptive building envelope Building envelope with the ability to dynamically adapt its behaviour over time to changing environmental conditions.

Building envelope Above-ground wall that physically separates an interior from an exterior environment.

Building Performance Simulation (BPS) tool A tool to predict the performance of buildings by dynamically solving a set of mathematical equations.

Co-simulation Representation of a system by multiple models executed or solved in individual runtime environments.

Control algorithm Planned set of algorithms derived process understanding to achieve objectives of a control system.

Control strategy Link between sensed variables and actuator actions in a BPS tool.

Control system Set of devices to manage, command, direct or regulate the behaviour of other devices.

Input parameter Data that describe and define a building model, e.g. weather condition, building equipment and building structure.

Model Representation of physical processes in a real building.

Modelling Process of reducing a model to an idealised form on some desired level of abstraction.

Mono-simulation Representation of a system by one model executed within a dedicated runtime environment or solver.

Performance prediction Estimation of interactions and processes within a building.

Research & Development (R&D) Work directed towards innovation, introduction and improvement of products and processes.

Sensor Device to measure physical quantities and to convert them into readable outputs.

Simulation A computer-aided, physics-based method to quantify aspects of building performance.

Testing Process of determining if model or tool is inaccurate or erroneous through test data or test cases.

Tool A computer software that requires a tool user or another software programme to perform a set of functions.

Truth standard Standard of accuracy to predict real system behavior.

Validation Process of determining that a model implementation accurately represents the model description and solution.

Verification Process of determining the degree to which a model accurately represents the real world.

Abbreviations, symbols and subscripts

Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
ASHRAE	American Society Of Heating, Refrigerating And Air Conditioning Engineers
BCVTB	Building Controls Virtual Test Bed
BIM	Building Information Modelling
BMS	Building Management System
BPS	Building Performance Simulation
BSA	British Sociological Association
BSI	British Standards Institution
CAQDAS	Computer Assisted Qualitative Data Analysis Software
CCF	Closed Cavity Façade
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution Of Building Services Engineers
DOE	U.S. Department Of Energy
DSF	Double Skin Façade
DTG	Digital Technology Group
EC	Electrochromic
EMS	Energy Management System
ERL	EnergyPlus Runtime Language
ETH	Eidgenössische Technische Hochschule
EU	European Union
FMI	Functional Mock-Up Interface
FMU	Functional Mock-Up Unit
FR	Functional Requirement
GHG	Greenhouse Gas
GUI	Graphical User Interface
HHS	U.S. Department Of Health And Human Services
HVAC	Heating, Ventilation And Air-Conditioning
IBPSA	International Building Performance Simulation Association
ICD	Institute For Computational Design
IDA ICE	IDA Indoor Climate And Energy
IDD	Input Data Dictionary
IDF	Input Data File
IEA	International Energy Agency
IES VE	IES Virtual Environment
IPC	Interprocess Communication
IPCC	Intergovernmental Panel On Climate Change
ISO	International Organization For Standardization
LBNL	Lawrence Berkeley National Laboratory
LHS	Latin Hypercube Sampling
MATELAB	Mobile Adaptive Test Experimental Lab
MCSA	Monte Carlo Sensititvity Analysis
NFR	Non-Functional Requirement
NMF	Neutral Model Format
NREL	National Renewable Energy Laboratory
OSMC	Open Source Modelica Consortium
PCM	Phase Change Material

R&D	Research & Development
RBC	Rule-Based Control
SA	Sensititvity Analysis
SPAWN	Spawn-Of-EnergyPlus
SRS	Software Requirements Specification
TRL	Technology Readiness Level
TRNSYS	Transient System Simulation Tool
UA	Uncertainty Analysis
UCL	University College London
UK	United Kingdom
UNEP	United Nations Environment Programme
USA	United States Of America
UV	Ultraviolet

Symbols

I_{sol}	Global Solar Irradiance	W/m^2
M	Mean	–
Max	Max	–
Min	Min	–
N	Population Size	–
Q_{inf}	Infiltration Design Flow Rate	m^3/sm^2
Q_{int}	Internal Heat Gains	W/m^2
SD	Standard Deviation	–
T	Temperature	°C
γ_{sol}	Solar Altitude	°
ρ	Solar Reflectance	–
CV-RMSE	Coefficient Of Variation Of Root Mean Square Error	–
MBE	Mean Bias Error	–
NMBE	Normalised Mean Bias Error	–
$\mathrm{S}_{\mathrm{Pear}}$	Pearson Correlation Coefficient	–
$\mathrm{S}_{\mathrm{Spear}}$	Spearman Rank-Order Correlation Coefficient	–
c	Specific Heat Capacity	J/kgK
h	Slat Separation	m
k_{T}	Clearness Index	–
p	Density	kg/m^3
t	Time	s, min
u_{blind}	Position Of Blind	–
u_{slat}	Slat Angle Of Blind	°

Subscripts

C	Cooling
H	Heating
L	Lighting
avg	Average
a	Air
diff	Diffuse
dir	Direct
gn	Gain

i	Inside
ls	Loss
o	Outside
r	Radiant
t	Total

Publications and key presentations arising from thesis

Articles in refereed journals

Published

Borkowski, E., Rovas, D. and Raslan, R., 2021. 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. *Intelligent Buildings International*. Available from: https://doi.org/10.1080/17508975.2021.1902257.

Under review

Luna-Navarro, A., Borkowski, E. et al., 2021. Thermal Building Performance Simulation of Full-Scale Outdoor Test Cells – Part 1: Workflow for the Empirical Calibration. *Journal of Building Performance Simulation*. Manuscript submitted for publication.

Borkowski, E., Luna-Navarro, A. et al., 2021. Thermal building performance simulation of full-scale outdoor test cells – Part 2: calibration and validation of a co-simulation model for adaptive building envelopes. *Journal of Building Performance Simulation*. Manuscript submitted for publication.

Articles in refereed proceedings

Borkowski, E., Donato, M. et al., 2019. Optimisation Of Controller Parameters For Adaptive Building Envelopes Through A Co- Simulation Interface: A Case Study. In: Corrado, V. and Gasparella, A. eds. *Proceedings of Building Simulation 2019: 16th Conference of IBPSA*. vol. 16. Rome (Italy): International Building Performance Simulation Association (IBPSA).

Borkowski, E., Donato, M. et al., 2018. Optimisation Of The Simulation Of Advanced Control Strategies For Adaptive Building Skins. *Proceedings of BSO 2018: 4th Building Simulation and Optimization Conference*. Cambridge (UK), pp.482–487.

Key presentations

Because of its collaborative nature, this research has been presented at invited talks and meetings with the industry.

Arup, Façade engineering team, London (UK)

Adaptive building envelopes: what can we simulate?, 20 October 2016
Barriers and challenges in adaptive building envelope simulation, 17 February 2017
Requirements for adaptive building envelope simulation, 26 April 2017
How can the behaviour of adaptive building envelopes be predicted?, 13 October 2017
Prediction of control strategies for adaptive building envelopes, 23 May 2018

BuroHappold, Sustainability & Building physics team, London (UK)

Requirements for adaptive building envelope simulation, 26 April 2017
How can the behaviour of adaptive building envelopes be predicted?, 16 October 2017

Ramboll, Façade engineering team, Copenhagen (Denmark)

Prediction of control strategies for adaptive building envelopes, 9 January 2019

1 Introduction

Adaptive building envelopes can dynamically adapt to environmental changes, often supported by a control system. While Building Performance Simulation (BPS) tools can be employed to test different design alternatives, representing control strategies within current BPS tools can be challenging, especially for systems with a fast, dynamic response. The following is an introduction to a research study undertaken with the aim to investigate an integrated modelling approach for the accurate and reliable prediction of adaptive building envelopes and their operation strategies.

1.1 Rationale for the study: research background

The Intergovernmental Panel on Climate Change (IPCC) estimates that human activities have contributed to about 1.0 °C of global warming caused by Greenhouse Gas (GHG) emissions since the pre-industrial era (IPCC, 2018). A major contributor to global GHG emissions is the building sector, which accounted for 28 % of energy-related carbon dioxide emissions. The building sector is improving the energy intensity, i.e. the energy use per m^2, at an annual average rate of approximately 1.5 %. Nevertheless, it must be further improved by an average of 30 % by 2030 compared to 2015 in order to meet Paris Agreement climate goals (International Energy Agency (IEA) and United Nations Environment Programme (UNEP), 2018). A key mitigation strategy to cut GHG emissions from the global building sector is the development of low-carbon, technological innovations, as set out in the Global Status Report 2017 by UNEP and IEA (2017).

At the heart of the technological innovations are adaptive materials, components and systems for building envelopes (European Commission, 2013), 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, Favoino 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 a user input to trigger a response from the building envelope. Rather, intelligent control strategies are used in operation to negotiate individual building envelope behaviours (Boeke, Knaack and Hemmerling, 2019). Due to their adaptivity, these types of building envelopes can lead to a reduced energy demand compared to static building envelopes (Matin and Eydgahi, 2019b).

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 them:

- 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 (BMSs) to manage plants and building envelope elements.

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 BPS tools that ‘act as a virtual laboratory’ (Loonen, Klijn-Chevalerias and Hensen, 2019, p. 272). A significant part of building energy regulations concerns the thermal performance of buildings (Chartered Institution of Building Services Engineers (CIBSE), 2015b), such as air temperature, occupant factors and controls (Wilde, 2018). This is why this research focuses on whole-building 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 capability to provide insights into building-integration issues of adaptive building envelopes and their operation strategies (Taveres-Cachat, Grynning et al., 2017; COST Action TU 1403 adaptive facade network, 2018a). A 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 Treeck, 2017). The tight coupling makes it particularly difficult for the user to combine component models with e.g. control sequences; it also introduces barriers to the software developer in flexibly developing and deploying new tool functionalities without accidentally creating an error in other parts of the tools.

BPS tools consequently lack flexibility in modelling and testing adaptive building envelope concepts (e.g. control) beyond what is possible by simple scripting approaches, such as the Energy Management System (EMS) scripting feature of EnergyPlus, a simple scripting language (Ellis, Torcellini and Crawley, 2007). The lack of flexibility poses a challenge for the use of BPS tools to provide information about the integration of adaptive building envelopes in the built environment, although they would benefit the explorative nature of Research & Development (R&D) projects. On the one hand, this has the potential to complicate informed decision-making from early R&D phases to marketing and sales support of adaptive building envelopes. On the other hand, this may lengthen the time until market introduction of adaptive building envelopes (Hensen, Loonen et al., 2015). Modelling issues and process integration challenges of BPS tools are therefore a primary concern, especially as scientific literature on this emergent topic is limited, as suggested by Loonen, Klijn-Chevalerias and Hensen (2019).

1.2 Research questions, aims and objectives

The exploratory nature of the research seeks to achieve familiarity with a novel subject area and provide insights and understanding of it. As such, this research aims at answering the following research question:

> What requirements should future tool developments meet to represent the behaviour of adaptive building envelopes, and how can future tool developments contribute to an accurate prediction of the thermal performance of adaptive building envelopes?

Particularly, this research addresses the following objectives through a mixed-methods research design:

1. Identify requirements for future tool developments for predicting adaptive building envelope behaviour.
2. Use the previously identified requirements to develop an approach for the integrated modelling of control and adaptive building envelope.
3. Test the accuracy and the representativeness of the proposed approach for predicting the thermal performance of adaptive building envelopes.
4. Analyse the applicability of the proposed approach to evaluate the thermal performance of design alternatives for adaptive building envelopes under conditions likely to be encountered in real design projects.

1.3 Methodological overview: a mixed-methods approach

In accordance with the exploratory nature of the research, the selection of the research design was undertaken as an iterative process. In light of the aim of this study, aspects such as the domain, objectives and nature of the research subject were taken into account in this process when selecting the appropriate methodology.

A mixed-methods design was accordingly considered most appropriate for the purpose of this study due to its effectiveness in combining quantitative and qualitative approaches and its flexibility in integrating the different research instruments for data collection involved in each. It also has the potential to improve cross-data validity of meta-inferences and strengthen theoretical assumptions by providing the opportunity to improve the scope, depth and consistency of the interpretations and increase possibilities for causal inferences (Kelle, 2005; Venkatesh, S. Brown and Sullivan, 2016).

The general structure of the research design and the application of the mixed-methods approach are outlined in Chapter 4, where a brief description of each of the research instruments used (i.e. interview, validation and case study) is given. The process of applying each of the instruments is discussed in more detail in the relevant chapters of the thesis.

The COVID-19 pandemic affected the research study design and execution in two ways. Firstly, the validation study was affected by the fact that the researcher responsible for the test cell had to travel home for family reasons. It was possible to take measurements remotely, but only sensor data connected to the BMS system could be accessed. This resulted in a limited number of variables available for the validation. Secondly, the case study was affected by longer waiting times for support from the Research Computing Clusters support team at University College London (UCL) to install Dymola on the UCL Research Computing Clusters. The installation of Dymola on the clusters was needed for the originally planned optimisation as another unit of analysis in the case study. This led to Dymola not being installed in time to be used in the case study before the end of the research project.

1.4 Thesis structure and chapter layout

The research is structured into three parts: literature review, analysis and synthesis, as outlined in Figure 1.1. The chapters are therein organised as follows:

Part I: Literature review

Chapter 2: Operation and design of adaptive building envelopes

The purpose of this chapter is to review the literature on the operation and design of adaptive building envelopes. It begins by describing the technologies used in adaptive building envelopes and reviewing examples of already realised adaptive building envelopes. The chapter then discusses the importance of predicting the performance of adaptive building envelopes in the design process and implications for this study.

Chapter 3: Integrated modelling of control and adaptive building envelope

Following a detailed discussion of integrated modelling and its relevance for the development of all-inclusive adaptive building envelope models, this chapter explores the capabilities of different simulation approaches for the simulation of adaptive building envelopes together with their control. It concludes with a summary of the evidence from the literature and a discussion of the gaps in knowledge.

Part II: Analysis

Chapter 4: Study methodology

This chapter defines the main areas of investigation of this study and outlines methodological considerations arising from the research subject. Various possible research designs are explored, and a rationale for the selected research methodology based on a mixed-methods design is presented. The different research instruments used in the study are discussed, followed by details on data collection and analysis methodology.

Chapter 5: Industry interviews

In this chapter, an interview-based industry study with experts in the field undertaken to advance the understanding of the limitations of adaptive building envelope simulation in current design practice is presented. After outlining the methodology of this part of the study, this chapter discusses key findings from the interviews to identify resultant key needs and gaps and implications for future tool developments.

Chapter 6: An integrated modelling approach for control and adaptive building envelope

The use of the findings of the literature review and the interviews for the development of a potential approach for the integrated modelling of control and adaptive building envelope for thermal performance prediction is described in this chapter. It provides a thorough overview of the development of the modelling approach, including the structure of the modelling approach with their functions, relationships, input and output parameters and software adopted.

Chapter 7: Validation of adaptive building envelope performance in modelling approach

The purpose of this chapter is to assess the accuracy of the proposed modelling approach, a key issue identified in the interview study, through the use of validation techniques. It begins by laying out the validation strategy and methodology and looks at how the data predicted by (i) the modelling approach compare against data measured in a full-scale laboratory with realistic building envelope conditions and (ii) another tool commonly accepted to represent the state-of-the-art.

Chapter 8: Test of functionality of modelling approach through a case study

This chapter presents the findings of a functional test of the modelling approach, which was carried out using an embedded multiple-case study design to analyse its applicability for the evaluation of the thermal performance of adaptive building envelopes. In addition to describing the case study methodology, this chapter discusses the key findings of the thermal performance of each case predicted by the modelling approach. An important issue for future research is to get feedback from practitioners regarding the applicability of the modelling approach in design practice.

Part III: Synthesis

Chapter 9: Analysis of data and discussion

The findings reported in the core chapters of the analysis part of the thesis are jointly analysed and interpreted. To justify the interpretation, the findings are related back to the contextual issues highlighted in the relevant literature discussed in the review part of the thesis. The chapter also discusses future implications arising from this study and presents recommendations that address the major issues.

Chapter 10: Conclusion

The final chapter highlights the main conclusions of the research and discusses its original contribution to knowledge. It also identifies gaps in current knowledge and proposes directions for future work, both in academia and in practice. Finally, it emphasises the practical application of the research findings through dissemination activities.

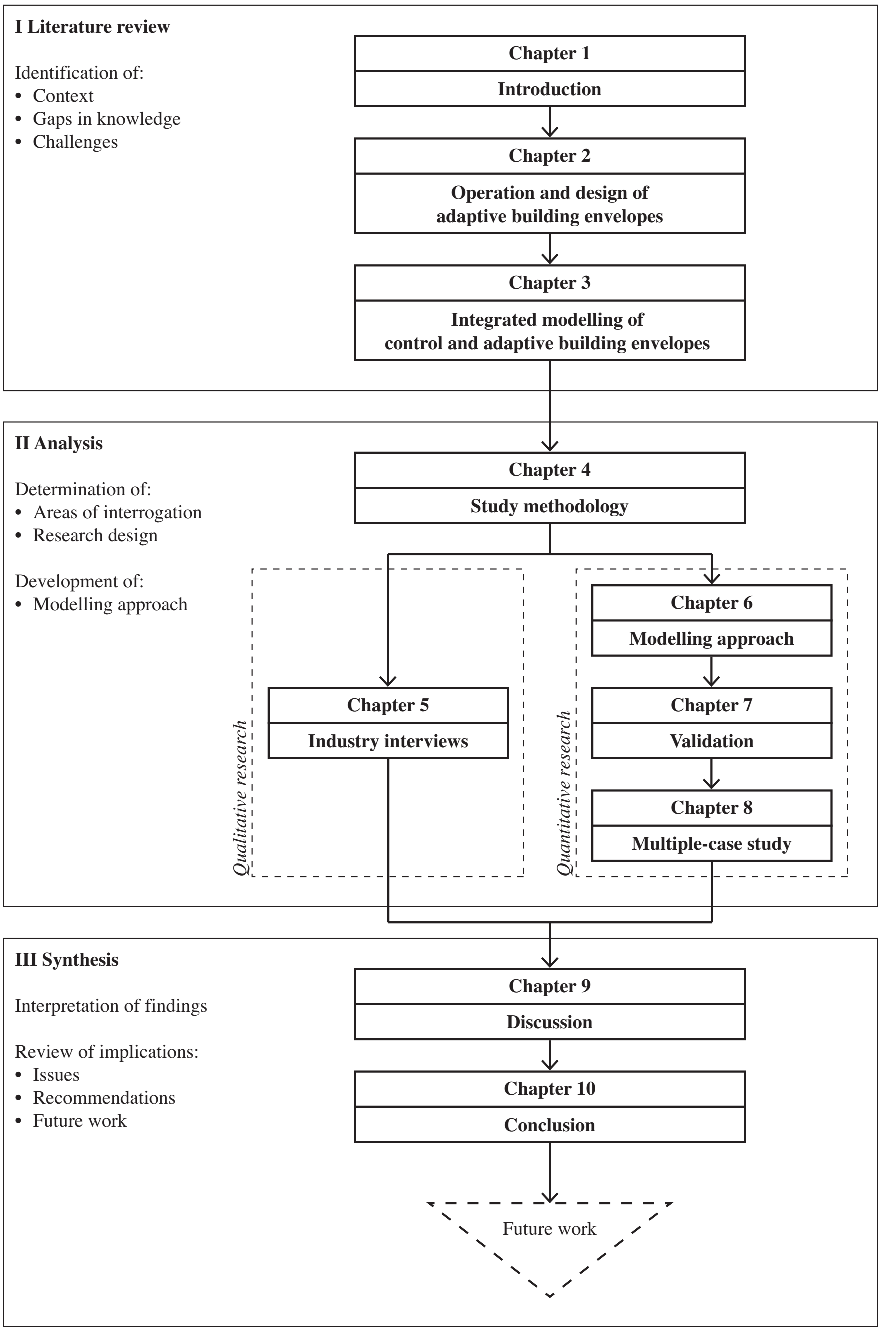


Figure 1.1: Thesis structure.

Part I

Literature review

2 Operation and design of adaptive building envelopes

Building envelopes are exposed to a highly diverse interior and exterior environment. When building envelopes can dynamically adapt to environmental changes, often supported by a control system, they are commonly referred to adaptive building envelopes (Figure 2.1). The purpose of this chapter is to review the literature on the operation and design of adaptive building envelopes. It begins with an overview of the technologies used in adaptive building envelopes and a classification of the technologies. The chapter then describes and discusses the application of adaptive building envelopes in real-world buildings and the performance prediction of adaptive building envelopes in the design decision-making process. It concludes with a chapter summary and a discussion of the implications of the findings on the study.

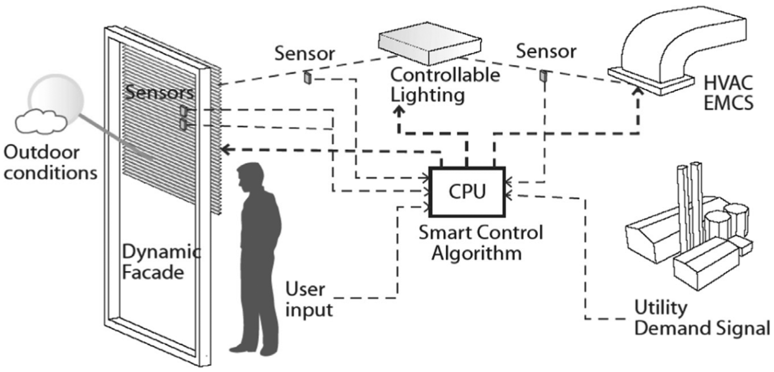


Figure 2.1: Example of adaptive building envelope (Konstantoglou and Tsangrassoulis, 2016).

2.1 Overview of technologies used in adaptive building envelopes

Adaptive building envelopes pursue their objectives through three particularly relevant abilities listed in Table 2.1. The adaptability, multi-functionality and evolvability of adaptive building envelopes ensure that variations, conflicts and occupant behaviour can be addressed (European Commission, 2013).

Due to their adaptability, multi-functionality and evolvability, adaptive building envelopes can actively exploit and efficiently use the resources surrounding them. However, adaptive building envelopes can only use the surrounding resources if the individual building envelope behaviours are negotiated by inter-connected and intelligent decision-making strategies in the control mechanism during operation (Böke, Knaack and Hemmerling, 2019). Figure 2.2 shows a conceptual scheme of an adaptive building envelope. It consists of sensor, control and actuator technologies to measure environmental variables, translate them into actuation commands in response to the variables and actuate the target component of the adaptive building envelope. Part of the target building envelope component is usually a material (Figure 2.3) supported by a structural system, such as a cable net or a space frame (Matin

Table 2.1: Key abilities of adaptive building envelopes (adapted from Wyckmans, 2005).

Ability	Description
Adaptability	• Deliberate response to changes in the environment by manipulating adaptive building envelope properties • Balance of occupants' preferences and ambient conditions → Active exploitation of surrounding resources
Multi-functionality	• Anticipation of actions' effects on tasks and their translation into the optimisation of performance criteria • Management of complex priorities and performance criteria due to flexibility in strategies → More efficient use of resources compared to static building envelopes
Evolvability	• Coping with regular variations, unanticipated events and changes in priorities and performance criteria • Consideration of long-term performance changes due to e.g. ageing, dust or component failure over time → Continuation of intended building operation without being affected by unforeseen future conditions

and Eydgahi, 2019b). The following sections describe the technologies used in adaptive building envelopes in greater detail.

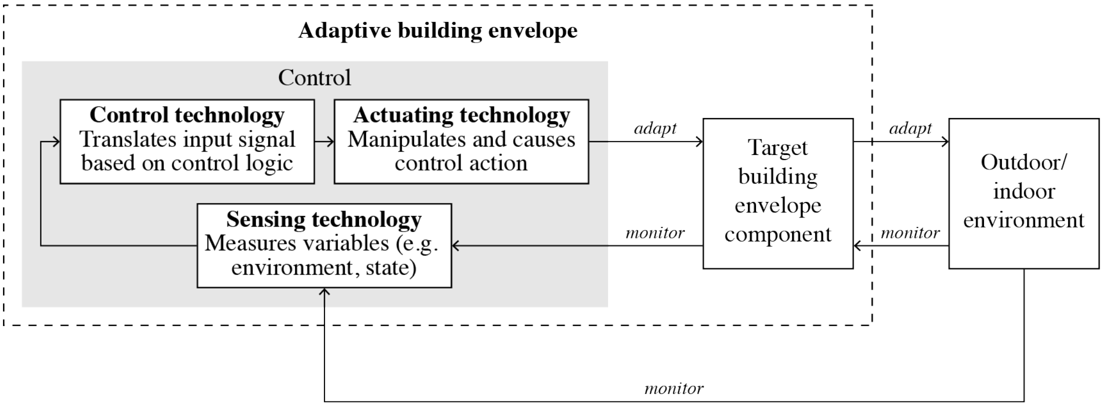


Figure 2.2: Conceptual scheme of a control mechanism of an adaptive building envelope.

2.1.1 Sensor technologies: measuring environmental variables

Adaptive building envelopes receive information through sensors from environmental conditions and their own interactions with the environment, internal backup and restored information as well as manually entered information by being connected online and by occupants. Sensor technology in adaptive building envelopes (i) detects and measures the information, (ii) translates it into digital or analogue signals or new changes in physical properties and (iii) documents the state of the environment and the building envelope in real-time (Aste, Manfren and Marenzi, 2017). The data obtained from sensor technologies are used to:

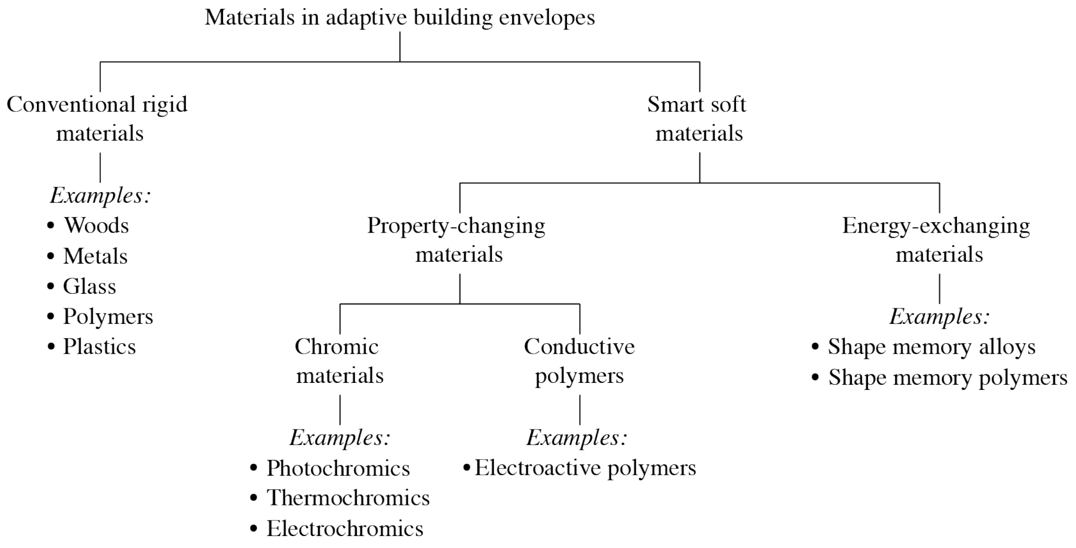


Figure 2.3: Classification of materials in adaptive building envelopes (adapted from Matin and Eydgahi, 2019b).

- enable the building envelope to fine-tune its operation when environmental changes occur;
- ensure optimal operation of the building envelope; and
- identify the occurrence of faults and other unfavourable events.

2.1.2 Control technologies: translating environmental variables into actuation commands

Control technology used in adaptive building envelopes translates input signals received from the sensor technology into actuation commands based on a determined control logic (Matin and Eydgahi, 2019b, p. 2). The control logic has a significant influence on the characteristics of the building envelope, such as movement patterns and thermo-physical properties, and thus on the building performance (Aste, Manfren and Marenzi, 2017). Loonen, Favoino et al. (2016) and Matin and Eydgahi (2019b) classified control technology in adaptive building envelopes into two broad types:

- **Intrinsic:** In intrinsic control, a stimulus automatically triggers an adaptive mechanism of a self-adjusting envelope. It uses a passive open-loop system, which responds to changes in input variables in a predefined way.
- **Extrinsic:** In extrinsic control, an external decision-making unit triggers an adaptive mechanism according to a feedback rule. It uses an active closed-loop system, which measures output actions and sends the collected information as feedback to the processor of the controller.

As shown in Figure 2.4, intrinsic control may be further divided into two sub-classes: (i) inner control is a configuration that is embedded in the material itself and (ii) direct control contains sensors, microprocessors and actuators within the actual building envelope

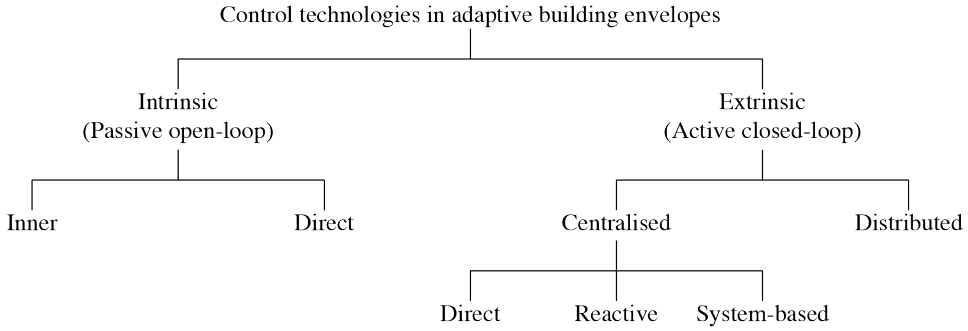


Figure 2.4: Classification of controllers for adaptive building envelopes.

component and with no relation to other components or systems (Velasco, Brakke and Chavarro, 2015). Meanwhile, extrinsic control may be further grouped into centralised and distributed control systems, which provide either independent or dependent interactions between building envelope components depending on whether the building envelope behaves as a whole component or as a number of separate components (Yekutiel and Grobman, 2014; Matin and Eydgahi, 2019b):

- **Centralised:** Sensors, actuators and other systems are connected to a single control system or group of control systems in a common location. Their control is provided by a supervisory control unit that is able to make decisions by taking into account multiple parameters, thus ensuring a smooth operation of the building envelope system.
- **Distributed:** A control system is made available locally to systems or groups of systems but are networked to one or more operator stations in a central location. While the control action in each system happens in the local control system, the operator has complete overview of the status of all systems and can intervene in the control logic of the local control system if necessary.

Depending on the complexity and the user integration of the responses of the control technology, Velasco, Brakke and Chavarro (2015) further divide centralised control systems into the three sub-classes shown in Figure 2.5. While direct control has the lowest degree of complexity as its responses are preprogrammed directly in the control logic, system-based control has the highest degree of complexity as its responses are generated by solving complex problems by applying exploration strategies with multi-deterministic or stochastic processes of heuristic methods, such as Evolutionary Algorithms and Artificial Neural Networks. However, the real-time implementation of system-based control can be challenging with the hardware currently available (Matin and Eydgahi, 2019b).

2.1.3 Actuator technologies: actuating target components

Adaptive building envelopes use actuator technology to translate incoming control signals from a control system into actuation commands. As soon as an adaptive building envelope

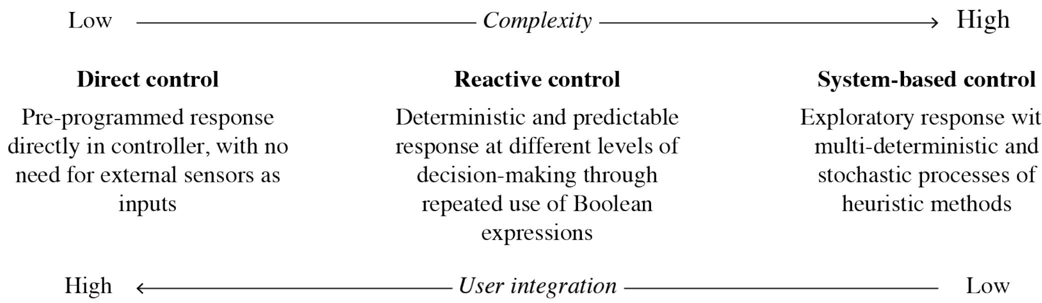


Figure 2.5: Various responses to environmental stimuli from centralised control.

has identified and executed an appropriate response to an environmental change, the result of the action is fed back into the envelope to influence subsequent control processes. Actuator technology may be either active or passive (Neugebauer and Wallner-Novak, 2018). While active actuator technology needs electricity to operate (e.g. motor-based, electrical or pneumatic actuators), passive actuator technology works autonomously (e.g. chemical, magnetic or material-based actuators). In addition to the type, the timing and the extent of adaptation play a key role in actuator technology used in adaptive building envelopes:

- **Response time:** The time to respond to an activating event can be in seconds, minutes, hours, days, seasons or years, and adequate timing to execute a building envelope's response depends on the type of event that triggered the response (D. Aelenei, L. Aelenei and Vieira, 2016). For example, the response time should be as short as possible if occupants request an action from the building envelope to prevent an erroneous impression that the system may have failed (Wyckmans, 2005).
- **Degree of adaptation:** Adaptive change can occur between two specified envelope states either gradually, directly or as a mixture of both, i.e. hybrid (Basarir and Altun, 2017). A too frequent, too fast or too extensive response to environmental changes can increase the risk of disturbances and discomfort for occupants (Bakker et al., 2014). To avoid this, adaptive building envelopes may, for example, require preventive actions to stop or attenuate the occurrence of an event.

2.2 Classification of technologies used in adaptive building envelopes

A recent study by Matin and Eydgahi (2019b) classifies technologies used in adaptive building envelopes based on the types of sensors, controllers and actuators they use. The authors identified two main groups of technologies, namely active and passive technologies, as shown in Figure 2.6. The main difference between the technologies is that passive technologies are independent of energy sources compared to active technologies.

Since the technologies' development, some of the active and passive technologies have been integrated into real-world building envelopes. This section subsequently discusses

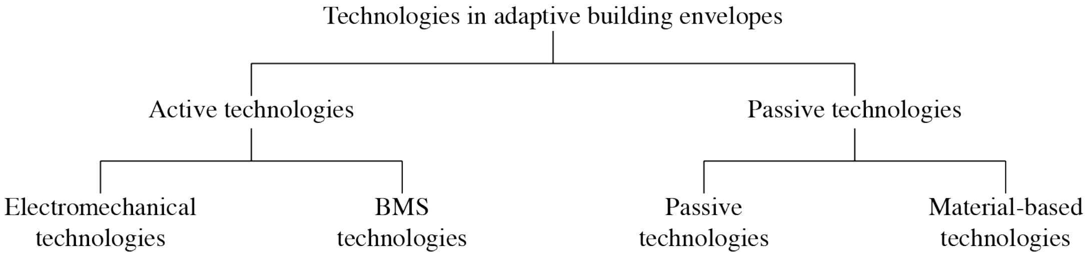


Figure 2.6: Classification of technologies in adaptive building envelopes.

examples of already realised adaptive building envelopes to give an overview of the application of the technologies in the built environment and to provide practical and context-dependent knowledge (Flyvbjerg, 2006). For a detailed discussion of the advantages and disadvantages of the technologies implemented in adaptive building envelopes, see Matin and Eydgahi (2019b).

2.2.1 Electromechanical technologies

Electromechanical technologies combine electrical and mechanical processes in a centralised control system that often involves electromagnetic principles and consists of relays, timers and/or counters. By using a centralised control system, they are easy to install, monitor, control and troubleshoot, but larger façade areas can only be controlled with a single actuator, resulting in invariable control.

An example of an electromechanical technology is the adaptive building envelope of the showroom of the company Kiefer Technic in Graz, Austria (Figure 2.7a). It uses a centralised control system to lift, lower and fold perforated aluminium panels through light sensors and electrically-operated motors integrated into the guide rails to optimise indoor environmental conditions (M. Schumacher, Schaeffer and Vogt, 2012). Similarly, the Campus of the University of Southern Denmark in Kolding, Denmark, is equipped with dynamic solar shading, which consists of triangular shutters made of perforated steel and adjusts to changing daylight and desired light incidence to create optimal daylight and comfortable indoor conditions (Figure 2.7b).

2.2.2 BMS technologies

BMS technologies in adaptive building envelopes use information systems in a distributed control system, commonly referred to as digital and communicating control system. They consist of interconnected panels with different units, and each unit knows the control panels surrounding it and freely exchanges data with them. BMS technologies have a short response time due to an efficient time calculation of the control data in each panel. However, their

(a) Kiefer Technic Showroom designed by Ernst Giselbrecht + Partner in 2007 (paul ott photografiert, used with permission).

(b) University of Southern Denmark Campus Kolding designed by Henning Larsen Architects in 2014 (ImageQuest).

Figure 2.7: Examples of electromechanical systems in adaptive building envelopes.

dependence on computers heightens their vulnerability to computer failures and cyber security risks.

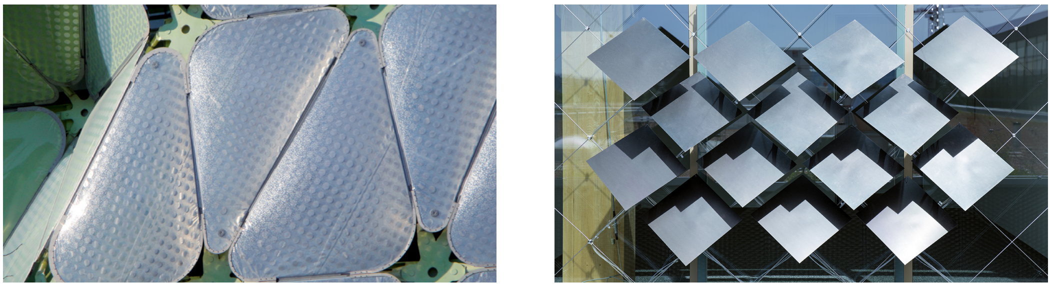
According to Matin and Eydgahi (2019b), BMS technologies in adaptive building envelopes are constantly evolving, and further advancements may be driven by:

- more powerful hard- and software to design and control even more complex systems;
- new internet technologies like wireless communication, cloud-based data storage and sensor networks to integrate adaptive building envelopes with other building systems; and
- the possibilities for occupants to control adaptive building envelopes with their smartphones.

An example of an adaptive building envelopes using BMS technology is the adaptive building envelope of the Media-ICT building in Barcelona, Spain (Figure 2.8a). It utilises a decentralised control system that integrates a network of sensors to measure heat and sunlight to inflate or deflate Ethylene Tetrafluoroethylene air cushions that affect the appearance of the building envelope (Matin and Eydgahi, 2019b). In contrast to the Media-ICT building, the Eidgenössische Technische Hochschule (ETH) House of Natural Resources in Zurich, Switzerland, uses soft robotic pneumatic actuators with three inflatable chambers to operate the building envelope (Figure 2.8b). It aims at generating power through the Photovoltaic panels attached to the actuators and at creating a comfortable indoor environment by sensing the humidity and tracking the sun path (Nagy et al., 2016).

2.2.3 Passive technologies

In contrast to active technologies, passive technologies for adaptive building envelopes use natural resources, such as wind or light, which eliminates dependencies on a power source and enables autonomous working. They consequently have no energy consumption. On the other hand, their reaction to unpredictable conditions is limited due to the system's uncontrollability.

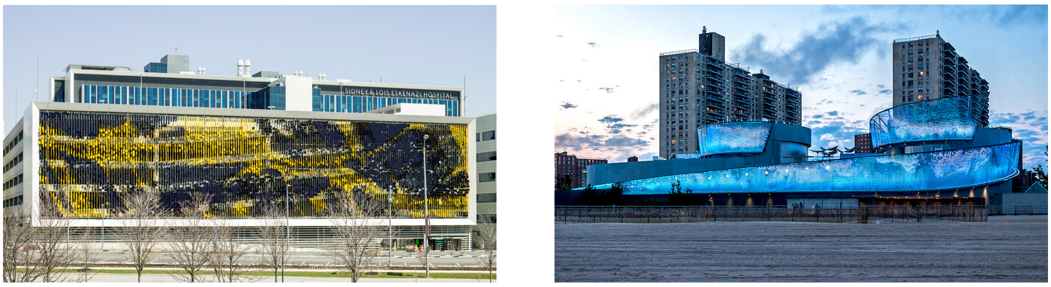


(a) Media-ICT building designed by Enric Ruiz-Geli and cloud 9 in 2011 (Albiñana et al., 2010, p. 48).

(b) ETH House of Natural Resources designed by the Laboratory of Sustainable Construction in 2015 (ETH Zurich and Carocari, used with permission).

Figure 2.8: Examples of information systems in adaptive building envelopes.

An example of a passive technology is the adaptive building envelope of the Eskenazi Hospital car park in Indianapolis, United States of America (USA) (Figure 2.9a). It functions as a mask for the multi-storey car park by hiding e.g. cars and concrete beams and consists of angled metal panels with an east/west colour strategy that offers passers-by a visual experience depending on their angle of view and pace (Rob Ley Studio, 2014). Compared to the Eskenazi Hospital car park, the light- and wind-responsive building envelope of the New York Aquarium in New York, USA, consists of hinged aluminium and stainless steel plates that reflect the light and colour of the sky and the immediate surroundings and move in the wind (Figure 2.9b). The building envelope consequently changes from moment to moment and blurs the boundary between building and atmosphere (Kahn, 2018).



(a) Eskenazi Hospital designed by Rob Ley Studio in 2014 (Ley, used with permission).

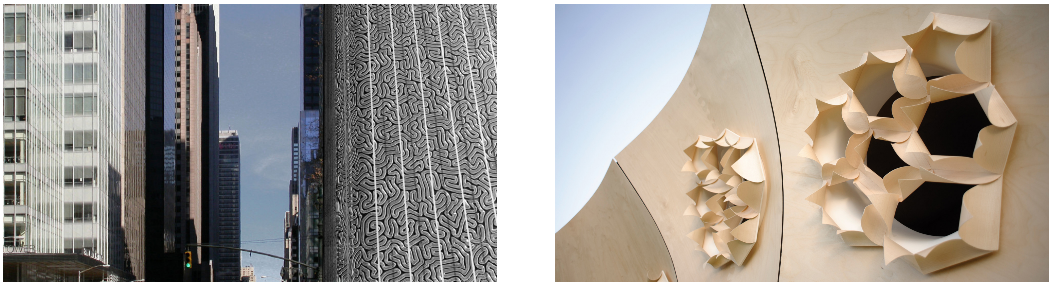
(b) New York Aquarium designed by Ned Kahn in 2018 (Kahn, used with permission).

Figure 2.9: Examples of passive systems in adaptive building envelopes.

2.2.4 Material-based technologies

Material-based technologies replace active technologies by integrating self-adjusting materials. When the material structure is stimulated by an external signal, changes occur either in the molecules of the material structure or in the material movements. Due to the use of a simple control system without sensors, actuators and external energy resources, their responses to environmental stimuli are fixed, limited and not programmable. The controllability of the building envelope is therefore restricted, especially when applied in large scale (Matin and Eydgahi, 2019b).

An example of a material-based system is the homeostatic façade system developed by Decker (2013) (Figure 2.10a). It is based on electroactive polymer, an ultra-lightweight material that consists of a polymeric membrane sandwiched between two electrodes and bends as the material expands or contracts according to the solar heat gains. When a high voltage is applied to the electroactive polymers, the polymer is deformed due to the electrostatic forces that exist between the two electrodes. In contrast to the homeostatic façade system, the HygroSkin developed by the Institute for Computational Design (ICD), University of Stuttgart (2013) is a responsive wood-composite envelope that opens and closes autonomously depending on the relative humidity of the environment (Figure 2.10b). It makes use of the self-forming capacities of the plywood sheets, which move due to the instability of the wood in relation to the moisture content.



(a) Homeostatic façade system designed by Decker and Yeadon in 2011 (Decker and Yeadon, used with permission).

(b) HygroSkin-Meteorosensitive Pavilion designed by the ICD in 2013 (ICD, University of Stuttgart, used with permission).

Figure 2.10: Examples of material-based systems in adaptive building envelopes.

2.2.5 Comparison of control systems of active and passive technologies

The technologies used in adaptive building envelopes may be divided into active and passive technologies, the main difference being that passive technologies are independent of energy sources compared to active technologies. However, another difference is the type of sensors, controllers and actuators used. As can be seen from Table 2.2, active technologies use a wider range of sensors, controllers and actuators than passive technologies. It is also worth noting that passive technologies use either material-based sensors, controllers and actuators or no sensors and controllers in combination with natural phenomena, such as moisture, wind or sunlight, as actuators.

2.3 Application of adaptive building envelopes in real-world buildings

The past decades have seen a rapid development of adaptive building envelope technologies. Their development has largely been influenced by technological and environmental factors,

Table 2.2: Comparison of control systems of active and passive technologies.

Technology	Active technologies	Passive technologies
Sensors	• Temperature sensors • Moisture sensors • Light sensors • Photovoltaic/UV sensors • Network of sensors • Etc.	• Material-based sensors • No sensors
Controllers	• Centralised controllers • BMS • Distributed controllers	• Material-based controllers • No controllers
Actuators	• Motor-based actuators • Electrical-based actuators • Pneumatic actuators • Hydraulic actuators • Material-based actuators • Etc.	• Material-based actuators • Natural phenomena

which have their origin in advancements in technology and construction since the end of the nineteenth century (Matin and Eydgahi, 2019a). A recent report by the COST Action TU 1403 adaptive facade network (2018b) — an European Union (EU) initiative to harmonise and disseminate knowledge on adaptive building envelopes -– presented 165 concepts of adaptive building envelopes. They have been developed and tested in research laboratories but only a few found application in real-world buildings (see Section 2.2).

Hensen, Loonen 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. Exceptions to the bespoke solutions are technologies that are widely commercially available, such as Phase Change Materials (PCMs), Electrochromic (EC) glazing and multi-functional shading systems (Loonen, Trčka et al., 2013; Attia, Bilir et al., 2018). 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, Favoino et al., 2016).

The fact that only few adaptive building envelopes have been applied to real-world buildings highlights the challenges of their transition from research to practice (Attia, Bilir et al., 2018). A potential reason for this is that new technologies like adaptive building envelopes pass through several Technology Readiness Levels (TRLs) in their development, as introduced by Sadin, Povinelli and Rosen (1989), and have not made the transition from lab to market yet. Figure 2.11 reveals that academia tends to focus on TRLs 1-4 and industry on TRLs 6-9, leaving a challenging gap, commonly referred to as *valley of death* (TRLs 4-6), between research and successful commercialisation.

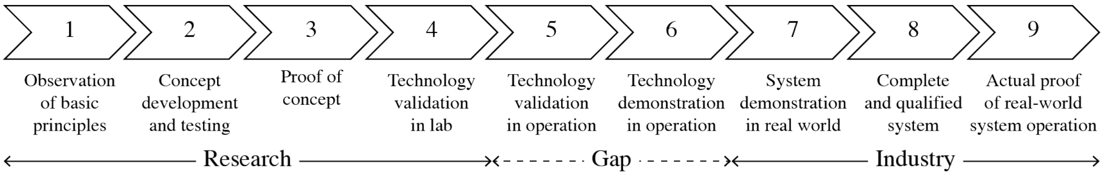


Figure 2.11: New product development at various TRLs.

The slow rate of technology transfer from research to practice 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, Loonen et al., 2015). This lack of evidence of technology benefits, combined with risks associated with disproportionately long payback times caused by higher capital, operating and/or failure costs, may negatively influence the decision-making of designers and clients regarding adaptive building envelopes. In turn, this may result in limited use of adaptive building envelopes in buildings at the design, construction and operation phase. Further reasons for the slow uptake in both the research and design phases of adaptive building envelopes are presented in Table 2.3.

Table 2.3: Reasons for limited use of adaptive building envelopes in buildings (e.g. Loonen, Trčka et al., 2013; Hensen, Loonen et al., 2015; Attia, Bilir et al., 2018).

	Reason	Explanation
R&D stage	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.
Stages of building project	Performance evaluation	A lack of benchmarks, standards and test procedures hinders the measurement and evaluation of adaptive building envelope performance.
	Capital costs	Making the building envelope adaptive requires additional components, which entails more raw materials and higher investment costs than for static building envelopes.
	Operating 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.
	Failure costs	Sufficient budget and resources must be provided for properly maintaining adaptive building envelopes throughout their life cycle to prevent malfunction or failure of components.
	Lack of payback information	The risks of disproportionately long payback periods due to higher investment and/or failure costs discourage designers and clients from implementing adaptive building envelopes.
	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.

However, taking risks during the design and operation of adaptive building envelopes also offers opportunities, such as saving energy and improving comfort, but such ambitious goals need to be supported by sound planning decisions. In order for adaptive building envelopes to evolve from an abstract concept to a viable design alternative, tools are needed that can predict the operational performance at the design stage of a building. This may increase transparency on how the performance benefits during operation may outweigh the initial cost arguments. A promising tool, which needs further development, however, is the simulation of the building performance (Loonen, Trčka et al., 2013).

2.4 Performance prediction of adaptive building envelopes in design process

To make use of adaptive building envelopes in the built environment, practitioners need to be able to predict the performance of adaptive building envelope proposals in the design decision-making process (Giovannini et al., 2018). Performance prediction estimates the interactions and processes within a building system by taking into account numerous dynamic interactions and constantly changing processes of heat, light and mass (Raslan and Davies, 2010), with the aim of obtaining a complete understanding of the system's behaviour (Hensen and Lamberts, 2011). A key requirement for a holistic approach in the design decision-making process is the consideration of active and passive technologies for adaptive building envelopes to allow practitioners to examine all possible design alternatives and assess the benefits of each. Among the most powerful tools today to achieve a robust building envelope solution that fulfils all operational requirements are whole-building BPS tools (Wilde, 2018). They 'act as a virtual laboratory' (Loonen, Klijn-Chevalerias and Hensen, 2019, p. 272) and assist, for example, in:

- effectively exploring design space parameters;
- sizing and fine-tuning of the interactions between adaptive building envelopes and building services, such as Heating, Ventilation and Air-Conditioning (HVAC) systems;
- 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 number of studies have examined general tool capabilities for an effective use of BPS tools in supporting design decisions by practitioners, i.e. the end users of the tools (e.g. Loonen, Hoes and Hensen, 2014; Loonen, Favoino et al., 2016; Attia, Bilir et al., 2018; Taveres-Cachat, Favoino et al., 2021). The capabilities have been classified by Attia, Hensen et al. (2012) as follows:

1. **Usability and information management of Graphical User Interface (GUI):** BPS tools should support end users in using presentation techniques to achieve communicative purposes (e.g. creation of comparative reports) and in performing their tasks (e.g. input representation).
2. **Integration of intelligent design knowledge base:** BPS tools should provide guidance to influence design decisions, e.g. through preset building templates, evaluation of complex design strategies and optimisation of design solutions.
3. **Accuracy of tools and ability to simulate complex building components:** BPS tools should be capable of providing validity and quality assurance of simulation outputs and of simulating complex building components with high model resolutions.
4. **Interoperability of building modelling:** BPS tools should enable multidisciplinary storing and sharing of information with one model representation spanning all design phases to facilitate collaboration, achievable e.g. through Building Information Modelling (BIM).
5. **Integration of tools in building design process:** BPS tools should adapt to the different purposes by multiple users and design phases in order to integrate them into the whole building design process.

While existing BPS tools are capable of predicting the thermal performance of building design proposals, not all have fully implemented the capabilities discussed above (Clarke and Hensen, 2015). BPS tools have also not fully implemented capabilities to represent the real-world complexity of adaptive building envelopes, which presents a challenge to predicting and thus evaluating adaptive building envelope performance in the design decision-making process (Attia, Bilir et al., 2018). In particular, BPS tools are rather limited in their capability to provide insights into building-integration issues of adaptive building envelopes and their operation strategies (Loonen, Favoino et al., 2016), reasons for which are discussed in detail in Chapter 3.

The shortcomings, however, 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, which quite often result in unintended and undesirable modelling artefacts (Loonen, Klijn-Chevalerias and Hensen, 2019). A possible workaround is to split the simulation period into a number of simulations with shorter periods, each with different building characteristics, and combine the predictions into a single representation of the adaptive building envelope behaviour (Loonen, Favoino et al., 2016).

2.5 Chapter summary and implications for study

Adaptive building envelopes actively and efficiently use the resources around them by negotiating inter-connected and intelligent decision-making strategies in the control mechanism during operation. Recent evidence suggests that the thermal performance of adaptive building envelopes, whether active or passive, is largely dependent on the control logic defined in this mechanism (Matin and Eydgahi, 2019b). The reason is that the control logic influences the behaviours and characteristics of the adaptive building envelope through changes in movement patterns or geometry, or through interactions with occupants or the environment (Loonen, Trčka et al., 2013). Because of the importance of the control mechanism for the thermal performance of adaptive building envelopes, their investigation is a continuing concern within research and industry, also in order to meet sustainability and GHG emission reduction targets globally.

The objective of improving thermal performance is pursued by the control mechanism, consisting of sensor, control and actuator technologies, through its (i) adaptability for a deliberate response to environmental conditions, (ii) multi-functionality for flexibility in control actions and (iii) evolvability for consideration of changes (Wyckmans, 2005). However, not all of the reviewed technologies used in adaptive building envelopes have these abilities. Passive technologies, for example, may have problems in considering changes in their own performance due to their either uncontrollable response or fixed, limited and not programmable response. In contrast, active technologies offer a much more complex response that integrates heuristic methods and are therefore more likely to adapt, be multi-functional and evolve. This suggests that active technologies are more responsive to environmental conditions and occupants' preferences compared to passive technologies, and are hence better able to influence the thermal performance of adaptive building envelopes.

The expected role that adaptive building envelopes can play in achieving emission targets requires that designers can consider active and passive adaptive building envelopes in the design decision-making process, contributing to their widespread adoption in the building sector. When the term adaptive building envelope is used in the remainder of this thesis, it refers to both active and passive adaptive building envelopes. A powerful tool to achieve robust building envelope solutions is BPS tools. Given the importance that the technologies used in adaptive building envelopes have on their operation, it seems crucial that BPS tools can accurately consider the previously identified technologies, especially the sensor, control and actuator technologies:

Sensor technologies: BPS tools need to be able to consider the measurement of information, the translation of the information into control signals and the documentation of environmental and building envelope states. For the measurement of information, it is key that they can detect the following data:

- environmental data, such as environmental conditions and interactions of the building envelope with the environment;
- occupancy data, such as occupants' preferences and manually entered information; and
- historical data, such as internal backup and restored information.

Control technologies: BPS tools need to be able to consider the maintenance of the required level of performance by adjusting the operation of the building envelope to a changing environment (Aste, Manfren and Marenzi, 2017). This is dependent on the tools' capability to:

- manage, optimise and change priorities and performance criteria;
- anticipate the effect of a control action on the task a building envelope must perform; and
- detect faults and other unfavourable events.

Actuator technologies: BPS tools need to be able to consider the operation of components at building envelope level and at whole building level. At building envelope level, it is key that they can manipulate the properties and movement patterns of adaptive building envelopes and fine-tune their operation. At whole building level, it is key that they can integrate the adaptive building envelope with the operations of other building systems (e.g. HVAC systems, lighting) and occupant behaviour, which is beyond the scope of this research.

In general, it seems that while existing BPS tools 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 and their operation strategies (Loonen, Favoino et al., 2016). Because of the limitations, a considerable amount of literature has been published on the thermal building simulation of adaptive building envelopes. The literature, however, has 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. It is therefore not clear which specific practical improvements are needed for future tool developments in current design practice for the thermal building simulation of adaptive building envelopes. As a consequence, further work is required to take the end user perspective and understand their needs.

3 Integrated modelling of control and adaptive building envelope

Performance prediction of the operation strategies of adaptive building envelopes in BPS tools is a major challenge in the design decision-making process (Attia, Bilir et al., 2018). This chapter therefore seeks to examine the capabilities of different simulation approaches to accurately represent adaptive building envelopes together with their control. The first part of this chapter investigates the area of integrated modelling and highlights the relevance of developing all-inclusive models that are able to predict the interaction of multiple components and technologies used in adaptive building envelopes. In the second and third part of this chapter, simulation approaches for control and adaptive building envelope simulation are discussed by exploring (i) mono-simulation approaches in BPS tools and (ii) co-simulation approaches. The chapter concludes with a summary of evidence from the literature.

3.1 Background: integrated modelling

A model is the representation of a real system reduced 'to an idealized form on some desired level of abstraction' (Augenbroe, 2004, p. 5). To answer questions related to adaptive building envelope performance, practitioners may need to address complex issues at control, building envelope and even whole-building level. The modelling of adaptive building envelopes thus requires the prediction of the interactions of multiple components and technologies (Mazzarella and Pasini, 2009). This in turn requires the development of models that allow these components to be linked (Riddick et al., 2017), commonly referred to as integrated modelling.

Developing all-inclusive models is challenging as individual models that represent specific components or technologies must be integrated. To facilitate the integration of model components, Belete, Voinov and Laniak (2017) have identified strategies for an efficient development and execution of integrated models during simulation. They have grouped the different strategies into five phases that software developers can employ to integrate models. The phases of model integration are shown in Table 3.1.

Key to integrated modelling is the exchange and manipulation of data, which is in many cases constrained by technical challenges (Belete, Voinov and Laniak, 2017). For example, a challenge is that models should be able to automatically exchange data and to identify and, if possible, bridge semantic differences. To overcome the challenges, technical integration requires specific simulation approaches that prepare model components for a linked execution within a setup designed to execute the integrated model.

Table 3.1: Phases of model integration (adapted from Belete, Voinov and Laniak, 2017).

Phase	Description
1. Pre-integration assessment	Combining knowledge-based requirements with computer technologies to create an initial integrated software system workflow design.
2. Model preparation for integration	Preparing a component for integration depending on, for example, the way inputs and outputs are organised (e.g. use of files or databases).
3. Orchestration of models during simulation	Enabling the interactions between components by identifying the components to be included, defining the overall workflow to be implemented and managing the execution of the workflow.
4. Data interoperability	Ensuring that data exchanged between workflow components are correctly interpreted by being semantically and structurally interoperable.
5. Testing	Verifying and validating whether a system meets certain specified requirements and improves the quality of the integrated system.

Potential approaches for simulating building performance can be seen from Table 3.2. It is apparent from this table that parallel simulation is primarily used to speed up the simulation runtime, e.g. for parametric analyses (Garg et al., 2014), and hybrid simulation is used to test the not yet fully understood part of a system model based on model fitting (error minimisation) or monitored data, e.g. for calibration (S. Lee and Hong, 2017). Therefore, parallel and hybrid simulation are not expected to overcome the challenges associated with the modelling of adaptive building envelopes. Since the aim of the research is to improve the modelling of the operation strategies of adaptive building envelopes to enable better prediction of their performance, only mono- and co-simulation are considered in this work. This approach is supported by the fact that previous works have exclusively used mono- and co-simulation for predicting the performance of adaptive building envelopes (Loonen, Favoino et al., 2016), but not parallel and hybrid simulation. Consequently, only mono- and co-simulation are discussed in detail in this thesis.

3.2 Mono-simulation of control and adaptive building envelope

Most of the existing BPS tools apply the mono-simulation approach, where all components are modelled, simulated and analysed in a monolithic way (Trčka, Hensen and Wetter, 2009). This holistic approach to design and analysis (CIBSE, 2015a) may be attributed to the evolution of BPS tools, which can be summarised over four generations (Table 3.3).

Although most BPS tools are still based on the second generation of BPS tools (Wetter and Treeck, 2017), each generation marked a shift towards the improvement of coupling of the various calculation steps, underlying calculation methods, tool interoperability and, as a consequence, transferability of results (Clarke, 2001). Achievements to enhance the capabilities of these methods have resulted in a more widespread adoption of BPS tools in

Table 3.2: Overview of methods for simulating building performance (Trčka, Hensen and Wetter, 2009; Schloegl et al., 2015).

	Description and aim	Application examples
Mono-simulation	Representation of a system by one model executed within a dedicated runtime environment or solver → **Aim:** Quantification and comparison of competing cost and performance attributes of proposed designs in a realistic way and at relatively low effort and cost	• Thermal load and energy performance prediction (Spitler, 2019) • Performance prediction of dynamic windows (J. Wang and Beltran, 2016) • Building simulation for operational optimisation (Claridge and Paulus, 2019)
Parallel simulation	Representation of a system by one model split and run in parallel on multiple solvers → **Aim:** Reduction of simulation runtime	• Parametric analyses (Zhang, 2009; Wetter, 2016) • Speed up of single simulation runs (Garg et al., 2014)
Hybrid simulation	Representation of a system by multiple models integrated into a single runtime environment → **Aim:** Testing of the not yet fully understood part of the system based on model fitting or monitored data and simultaneous simulation of the remaining system using a numerical model	• Calibration of targeted model inputs (S. Lee and Hong, 2017) • Integration of AI techniques (Mui et al., 2021)
Co-simulation	Representation of a system by multiple models executed or solved in individual runtime environments. → **Aim:** Combination of heterogeneous modelling environments and solvers of specialised tools	• HVAC systems performance prediction (Trčka, Hensen and Wetter, 2009) • Performance prediction of an external shading system (Taveres-Cachat and Goia, 2020) • Implementation of occupant behaviour in building energy simulation (Li et al., 2017)

Table 3.3: Evolution of BPS tools (adapted from Clarke, 2001).

Generation	Main method	Characteristics
First generation (until mid-1970s)	Manual calculations and rules of thumb	• Handbook-oriented • Simplified and fragmented calculation steps • Familiar to practitioners
Second generation (from mid-1970s)	Traditional physical calculations	• Based on standard theories • Consideration of building dynamics • Less simplified but still fragmented calculation steps
Third generation (from mid-1980s)	Correlation-based methods	• Shift to numerical methods • Beginning of integrated modelling • Partial interoperability enabled
Fourth generation (from mid-1990s)	Building performance simulation	• Intelligent and knowledge-based • Fully integrated • Network compatible/interoperable

the design process (Attia, 2010), and an up-to-date list of whole-building BPS tools can be found on the Building Energy Software Tools directory website[1] by the U.S. Department of

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[1] https://www.buildingenergysoftwaretools.com/

Energy (DOE). The BPS tools mentioned most in this thesis are listed and briefly described in Table 3.4.

Table 3.4: BPS tools mentioned in thesis.

BPS tool	Description
EnergyPlus	EnergyPlus is a free, open-source and cross-platform console-based BPS tool. The EMS scripting feature of EnergyPlus uses the ERL, a simple scripting language, to describe control algorithms (DOE, 2018a). Wetter, Benne et al. (2020) prototype the next-generation EnergyPlus simulation engine, called Spawn.
IDA ICE	IDA ICE (EQUA Simulation, 2018) uses symbolic equations stated in the NMF and/or Modelica modelling language to describe physical systems from several domains. It offers an integrated API for programming.
IES VE	IES VE (Integrated Environmental Solutions, 2019) is a commercial BPS tool with integrated suites of applications linked by a common GUI and a single integrated data model. An API with Python (Python Software Foundation, 2019), a general-purpose programming language, was recently introduced to improve flexibility (Integrated Environmental Solutions, 2018).
TRNSYS	TRNSYS (Klein et al., 2017) is a modular, component-based BPS tool to analyse complex electrical and thermal energy system problems. It allows to add new mathematical models to embed components from other software and to run parametric studies.

3.2.1 Integration of adaptive building envelope control in BPS tools

Existing BPS tools are a useful tool for the design of adaptive building envelope control, as they allow for the integrated modelling and simulation of control and adaptive building envelope (Loonen, Favoino et al., 2016). For their design, BPS tools offer different levels of control development and integration into the simulation code (Buonomano et al., 2016). According to Cetin et al. (2019), control strategies, which provide a link between sensed variables and actuator actions through a control logic in BPS tools, can be divided into (i) predefined, (ii) flexible and (iii) user-specific control strategies, as explained in the next sections. A broader overview of the adaptive building envelope modelling capabilities in five existing BPS tools, including EnergyPlus, IDA ICE and TRNSYS, is provided by Loonen, Favoino et al. (2016).

3.2.1.1 Predefined control strategies for adaptive building envelopes

Predefined, system-based control strategies are already implemented in a given BPS tool and can be accessed directly via the GUI by filling mandatory fields. For example, the control thresholds of PCM can be controlled through temperature-based changes in specific heat capacity, and the control thresholds of thermochromic glazing through temperature-based changes in the refractive index (i.e. how fast light travels through the material) of the thermo-optical properties (Loonen, Favoino et al., 2016).

3.2.1.2 Flexible control strategies for adaptive building envelopes

Some BPS tools offer a little more flexibility in specifying control strategies for adaptive building envelopes via the GUI. Their flexible control strategies usually translate sensor signals into actions through simple IF-THEN statements: IF a condition is verified, THEN an action is triggered (Péan, Salom and Costa-Castelló, 2018). IF-THEN statements can also integrate simple algebraic operators, i.e. any of the common arithmetic operations such as addition and subtraction, and Boolean operators, i.e. AND, OR and NOT operators that result in an expression that is either TRUE or FALSE (Loonen, Favoino et al., 2016).

When defining flexible control strategies, tool users can usually select the sensor type and the control threshold for actuating the adaptive building envelope technology from a limited number of fixed presets. Following Loonen, Favoino et al. (2016), the type of sensor can be part of either a Rule-Based Control (RBC) strategy or a time-scheduled control strategy:

- **RBC strategy:** A RBC strategy monitors a specific trigger parameter, such as a boundary condition (e.g. outside weather conditions) or a simulation state variable, associated with a predefined threshold or setpoint. Once this value is reached, the RBC strategy triggers a control action and changes the operation of the adaptive building envelope according to the predefined control strategy.
- **Time-scheduled control strategy:** A time-scheduled control strategy has many features in common with the RBC strategy. Where it differs, however, is that the control actions are applied at predetermined times.

An example of a BPS tool that allows the modelling of flexible control strategies for adaptive building envelopes is EnergyPlus, in particular due to its EMS scripting feature, which is used, among other things, to represent more complex control strategies (Favoino, Cascone et al., 2015). However, EnergyPlus and other BPS tools, such as IES VE, are not suitable for simulating other than rule-based supervisory control strategies, which ensure the overall building performance through two levels of control: (i) local control guarantees robust operation and tracks the setpoint considering the dynamic characteristics of the local process environment, and (ii) supervisory control uses global optimisation techniques to find optimal control settings (e.g. operation mode and setpoints) for all local controllers to optimise the operation of the entire system under control (S. Wang and Ma, 2008). The reason why EnergyPlus and other BPS tools are not suitable for simulating other than rule-based supervisory control strategies is because of their input/output routines. These routines have rigidly organised inputs and outputs that are semantically different from sensor signals and actuator commands, which makes the simulation of other control strategies much more difficult (Wetter, Nouidui, Lorenzetti et al., 2015; Aste, Manfren and Marenzi, 2017).

For the design of a building with a BMS, a consequence is that rule-based supervisory control strategies, which consist of a set of simplified rules, offer a simple design and low computational cost (Drgoňa et al., 2018). However, they are not optimal, adaptive or predictive, leading to significant shortcomings in appropriate control and performance, as the control thresholds used are usually empirical and do not correspond exactly to the optimisation control problem at hand (Michailidis et al., 2020).

3.2.1.3 User-specific control strategies for adaptive building envelopes

Only few BPS tools allow users to specify customised local controllers. Among these tools are IDA ICE and TRNSYS:

- **IDA ICE:** By using equation-based modelling approaches, IDA ICE allows users to define custom control macros by manually developing a script for the control strategy (Tällberg et al., 2019).
- **TRNSYS:** By decomposing a complex problem into a series of smaller components, TRNSYS allows users to model complex control strategies through an external editor and influence the input/output connection of components during simulation runtime (Loonen, Favoino et al., 2016).

Another way to implement a control system in a BPS tool was presented by Buonomano et al. (2016) with DETECt 2.3, a bespoke BPS tool developed in MATLAB (MathWorks, 2018a), a proprietary multi-paradigm programming language. DETECt 2.3 was adopted to propose a novel Enhanced Model Reference Adaptive Control scheme for PCMs integrated in the building envelope. Buonomano et al. (2016) used measured variables of the actual system under control to describe the Enhanced Model Reference Adaptive Control scheme through more than 70 differential equations. This approach required detailed knowledge of the non-linear dynamics of the physical system, which also helped to increase the robustness of the approach with respect to e.g. external disturbances and parameter uncertainty.

3.2.2 Suitability of control strategies for adaptive building envelopes in BPS tools

The previous section demonstrated how control strategies for adaptive building envelopes may be implemented in existing BPS tools. In view of all that has been mentioned so far, one may suppose that mono-simulation approaches are generally suitable for the integrated modelling of control and adaptive building envelope.

However, given the predefined, flexible or user-specific ways that allow users to integrate control strategies for adaptive building envelopes, BPS tools offer different levels to flexibly develop and integrate the operation strategies of adaptive building envelopes. This makes it difficult to determine whether BPS tools are capable of accurately representing the technologies used in adaptive building envelopes to operate them (Section 2.1). Table 3.5 seeks to shed light on this by comparing the different levels of control system development and integration into the simulation code of BPS tools with the different technologies used in adaptive building envelopes. From this, it can be seen that user-specific control strategies allow for a flexible integration of technologies in BPS tools and a more accurate prediction, especially when there is no other modelling option. In contrast, flexible and predefined control strategies may be more limited in representing certain components of adaptive building envelope technologies. Only if all components can be represented in the BPS tool, flexible and predefined control strategies ensure the accuracy and stability of the solution by preserving integrity of the system model.

Table 3.5: Representation of adaptive building envelope technologies in BPS tools: shown for each control strategy (Mazzarella and Pasini, 2009; Cetin et al., 2019; Wetter, Benne et al., 2020).

	Representation of technologies in model	Example of BPS tool
Predefined control strategy	• System-based representation of technologies using a limited number of fixed presets in BPS tool → **Potential implication on prediction:** Assurance of accuracy and stability of solution by preserving integrity of the system model → **Potential implication on design:** Easy and quick implementation of technologies and assured level of accuracy	• EnergyPlus • IES VE
Flexible control strategy	• Flexible representation of technologies supported by BPS tool → **Potential implication on prediction:** Assurance of accuracy and stability of solution by preserving integrity of the system model → **Potential implication on design:** Relatively easy and quick implementation of technologies and assured level of accuracy	• EMS feature of EnergyPlus
User-specific control strategy	• Custom representation of technologies due to extendibility but with risk of generating an insoluble problem → **Potential implication on prediction:** Possible affect on accuracy and stability of the system model due to combination of different modules, but more accurate prediction of technologies in case of no other modelling option → **Potential implication on design:** Flexible yet potentially sophisticated implementation of technologies	• IDA ICE • TRNSYS

While BPS tools are generally able to model adaptive building envelopes, not all may be able to predict the behaviour of adaptive building envelopes, especially the behaviour of emerging adaptive building envelopes (Loonen, Favoino et al., 2016). This is due to the different levels of control development and integration into the simulation code of BPS tools. Users may therefore be more productive if they rely on a range of tools from which they may choose the tool the most appropriate modelling capabilities (Crawley et al., 2008). However, there are also other challenges that may be associated with predicting the thermal performance of adaptive building envelopes, which were identified as part of the literature review and are discussed in the next section.

3.2.3 Challenges associated with BPS tools

Most of the existing BPS tools are based on the second generation of BPS tools, which were primarily developed to consider the use case of building energy performance assessment to assist in building design and energy policy development (Wetter and Treeck, 2017). The second generation of BPS tools was developed before the implementation of modular software approaches and the availability of powerful computer algebra tools. Instead, they were developed by means of imperative programming through the use of C or Fortran programming languages (D. Ritchie et al., 2018; J. Backus and International Business Machines Corporation, 2018). In imperative programming, the software developer explicitly specifies in the source code what the tool should do, step by step, to achieve the output. Because BPS tools still formulate models using imperative programming languages, they 'assign values to functions, declare the sequence of execution of these functions and change the state of the program' (Wetter and Treeck, 2017, p. 38). The tools thus integrate the numerical solution procedure into the actual model equations, which tightly intertwines the model equations with the numerical solution methods.

This tight coupling of calculation procedures raises a number of challenges that may be associated with the capabilities of BPS tools to accurately and representatively simulate systems and controls with a fast, dynamic response, such as adaptive building envelopes. The challenges identified in the literature are summarised in Table 3.6 and discussed below.

Table 3.6: Challenges associated with BPS tools.

Challenge	Potential implication on adaptive building envelope simulation
Adaptation to new models and functionalities	Poor integration of solvers for new models with the existing solver → Limited development of models and functionalities for specific adaptive building envelope technologies
Understanding of model interactions	Tight integration of numerical solution methods in model equations → Difficult understanding of interactions of component models with other model parts
Representation of control sequences	Semantic difference of input/output routines from actuator commands and sensor signals → Limited types and ranges of control systems to be modelled in BPS tools
Design decision support	Solving of a non-convex optimisation problem involving continuous and discrete parameters → Rare integration of SA, UA and optimisation methods

3.2.3.1 Adaptation to new models and functionalities

As a result of the tight coupling of the numerical solution procedures with the model equations, solvers for new models and functionalities can be poorly integrated into the existing solvers of BPS tools (Taveres-Cachat, Favoino et al., 2021). This makes it difficult to extend them and to add new models and functionalities beyond the use case of building energy performance assessment and energy policy development for which they were tailored (Wetter and Treeck, 2017). For the design of adaptive building envelopes, this is particularly critical as other use cases recently gained importance that BPS tools need to support just as much as the use case of building energy performance assessment and energy policy development. Examples of use cases that recently gained importance are:

- **Time-varying building envelope specifications:** To take into account the dynamic behaviour of smart soft materials, like electroactive polymer, and geometric components, BPS tools need to be able to change material properties and to integrate architectural form-finding tools during simulation runtime (Loonen, Favoino et al., 2016; Taveres-Cachat, Favoino et al., 2021).
- **Multi-domain integration:** BPS tools need to be able to solve the equations of different physical domains (e.g. thermal, visual, air, moisture) in a coupled way to evaluate the interactions between adaptive building envelope, indoor environment and building services in different physical domains (Clarke and Hensen, 2015; Loonen, Favoino et al., 2016).
- **Interactions with occupants:** To address the effect of occupants' activities on the adaptive building envelope (Wyckmans, 2005), BPS tools need to be able to integrate models for the stochastic nature of interactions between adaptive building envelope and occupants (Bakker et al., 2014).
- **Product development:** BPS tools need to be able to integrate models of emerging technologies (Favoino, Cascone et al., 2015) in order to assist in product development from early R&D phases to marketing and sales support (Hensen, Loonen et al., 2015).

3.2.3.2 Understanding of model interactions

Due to the tight integration of the numerical solution methods into the model equations, it can be difficult for users of BPS tools to understand the interactions of component models with other model parts, like control sequences (Wetter and Treeck, 2017). If users do not understand the interactions between component models and control sequences, they may not use the software correctly and differently than the software developers intended, which can affect the accurate representation of adaptive building envelope control in BPS tools.

3.2.3.3 Representation of control sequences

As was mentioned in Section 3.2.1, BPS tools allow the modelling of control strategies for adaptive building envelopes in a predefined, flexible or user-specific way. While the flexibility of the ways to model control strategies for adaptive building envelopes varies depending on the BPS tool, the tight coupling of numerical solvers with the individual building component models imposes rules that determine where the internal data structure of the tool provides inputs to functions to compute building or control equipment. These rules have shown to make it difficult to extend the tools to a specific control sequence, limiting the modelling of certain types and ranges of control strategies (Widl et al., 2014).

For example, BPS tools are limited in representing discrete events, which occur in a simulation when a value in the state variables of a model changes. However, actions of an adaptive building envelope, together with the control, constitute a hybrid dynamical system, whose mode selection occurs at irregular time instances (Schaft and H. Schumacher, 2000). The simulation of adaptive building envelopes is therefore a discrete problem, where the values of state variables change at discrete points in time. To accurately represent adaptive building envelopes in a BPS tool, a model must be able to take into account events that occur at a particular instant in time and mark a change of state of the adaptive building envelope. But most BPS tools use continuous models whose system states are continuously changed over time based on a set of differential equations that define the rates of change of the state variables (Figure 3.1). The continuous models are appropriately discretised as part of the numerical integration process, but the discretisation points may not align with the points at which the relevant variables change state (Ożadowicz and Grela, 2016). Many BPS tools may consequently be limited in affecting state transitions. This may make it difficult to accurately predict the influence of control decisions on the dynamic behaviour of the building envelope (Mazzarella and Pasini, 2009), resulting in a loss of information in the modulation range of adaptive technologies (Favoino and Overend, 2015), or, at worst, invalidating the generality of the model (Gunay, O'Brien and Beausoleil-Morrison, 2013).

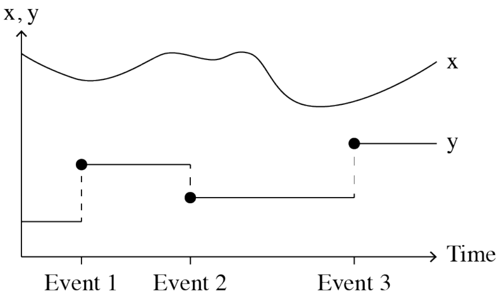

Figure 3.1: Continuous-time versus discrete-event variables (adapted from Fritzson and Bunus, 2002).

For an optimal design and operation of adaptive building envelopes, BPS tools should also be able to integrate methods for designing appropriate control and monitoring schemes and diagnostic systems for performance tracking to reduce commissioning and operation errors (Aste, Manfren and Marenzi, 2017).

3.2.3.4 Design decision support

There is a great need for the integration of tools to support the design decision-making process (Section 2.4). According to Loonen, Favoino et al. (2016), tools for design decision support include tools for carrying out a Sensititvity Analysis (SA), a Uncertainty Analysis (UA) or an optimisation, all of which are currently not often implemented in BPS tools:

SA: The purpose of a SA is to determine the influence of design parameters of e.g. adaptive building envelopes on relevant performance indicators (Chong and Menberg, 2018). SA can be performed according to the *local* and the *global* approach. Local SA assumes a linear relation between input and output variables and takes no account of interactions between input variables (S. Yang et al., 2016). Global SA is considered to be the more reliable approach because input variables are varied simultaneously over the whole input sample space, thus accounting for interactions between variables (Tian, 2013).

UA: To measure the acceptable level of model accuracy, i.e. the degree to which tool outputs conform to the correct value, is the purpose of a UA (American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), 2014b). This may be useful for validating adaptive building envelope models (Taveres-Cachat, Favoino et al., 2021). Validation is defined as the process of determining the degree to which a numerical model accurately represents the real world.

Optimisation: An optimisation can help in the design process to assess the performance and design alternatives of adaptive building envelopes. Although optimisations offer an effective way to establish fast and reliable workflows that are less prone to human errors (W. Wang, Zmeureanu and Rivard, 2005), design teams rarely benefit from them (Donato et al., 2016). A possible reason for this is that most BPS tools do not integrate optimisation algorithms because they contain adaptive integration meshes, iterative solvers and IF-THEN logics that cannot achieve the required smoothing of the objective function in an optimisation algorithm (Wetter and Wright, 2004). However, to enable structured design space explorations, BPS tools can be coupled with an external optimisation algorithm to form a so-called simulation-based optimisation (Nguyen, Reiter and Rigo, 2014).

3.3 Co-simulation of control and adaptive building envelope

Only a few studies use mono-simulation approaches for the simulation of adaptive building envelopes together with the control because of the identified challenges (e.g. Favoino, Cascone et al., 2015). Aste, Manfren and Marenzi (2017) even suggest that mono-simulation should rather be seen 'as a complementary tool' (2017, p. 323) in terms of control applications. As a result, researchers have shown an increased interest in using co-simulation approaches to predict the performance of adaptive building envelopes. The reason for this is that they provide a way to simulate the adaptive building envelope along with the control, possibly represented by specialised control-oriented software, to perform an integrated analysis (Loonen, Favoino et al., 2016; Taveres-Cachat, Favoino et al., 2021).

3.3.1 Principles of co-simulation

Co-simulation, which stands for *cooperative simulation*, refers to the joint simulation of separate models, developed in different tools. The models are executed in individual simulators and allowed to cooperate (Trčka, Hensen and Wetter, 2009; Hafner et al., 2012). While the tools communicate and synchronise outputs, such as variables or status information, at certain points in time, each tool independently solves one part of the coupled problem between the communication points.

A particular challenge in co-simulation is the time synchronisation and orchestration of the heterogeneous models and their individual solvers. To enable synchronisation and interactions across sub-simulators, co-simulation uses a coordinator-worker concept, as shown in Figure 3.2. The worker simulates sub-problems and the coordinator initiates the start of the simulation and is responsible for coordinating the overall simulation and the data transfer between the tools (Broman et al., 2013).

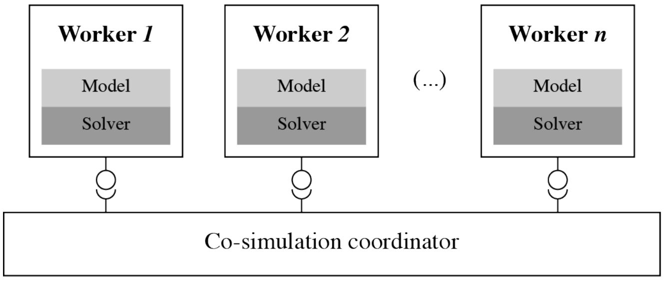

Figure 3.2: Coordinator-worker structure of co-simulation.

A possibility for simultaneous simulation of the sub-models is to deploy tool integration platforms or protocols that provide a standardised definition of interface variables to facilitate data exchange between tools (Kossel et al., 2006; Bastian et al., 2011). Such platforms or protocols, called Interprocess Communication (IPC) mechanisms, can make co-simulations more flexible and modular (Wetter, 2011) by considering multiple execution semantics to perform a global simulation (Nicolescu et al., 2007). Table 3.7 shows the IPC mechanisms commonly used in building performance simulation studies.

Table 3.7: Commonly used IPC mechanisms in co-simulation.

Interface	Description
BCVTB (Wetter, Nouidui and Haves, 2016)	A modular, open-source software environment based on Ptolemy II (Eker et al., 2003), an open-source software framework for experimentation with actor-oriented design, used to (i) link different simulation tools during simulation runtime, (ii) couple simulation tools to hardware through its analogue/digital interface or its BACnet interface (Nouidui and Wetter, 2014) and (iii) perform simulation-based optimisations (Evins, Pointer and Vaidyanathan, 2011).
FMI Standard (MODELISAR, 2014)	First released in 2010 by the ITEA2 MODELISAR project, the FMI Standard is an open middleware to facilitate information exchange between heterogeneous tools in co-simulation contexts using a combination of XML-file, C-code and shared libraries. A model conforming to the FMI Standard can be encapsulated and shared as an FMU that can be integrated with other standard-compliant FMUs (Broman et al., 2013). Attempts have been made to make the most common BPS tools (e.g. EnergyPlus and TRNSYS) FMI-compatible.
Grasshopper (Robert McNeel & Associates, 2014)	Grasshopper is a visual programming language (Myers, 1990) that was developed to enable architects and engineers without expert programming skills to build generative algorithms. It uses add-ons, visually connected through simple input-output relations, each of which executes a script, function or simulation programme, thus allowing Grasshopper to perform energy simulations with EnergyPlus or daylight simulations with Daysim.
MATLAB/Simulink environment (MathWorks, 2018a,b)	MATLAB is a proprietary multi-paradigm programming language, and Simulink is a MATLAB-based graphical programming environment for multi-domain dynamic systems. The MATLAB/Simulink environment is often used as coordination layer in co-simulation setups to manage the information exchange between simulators and the simulation runtime (Favoino, Fiorito et al., 2016).

Other principles to consider when implementing a co-simulation strategy are summarised below and discussed in detail by Trčka, Hensen and Wetter (2009) and Taveres-Cachat, Favoino et al. (2021):

- **Coupling data:** The data that are exchanged between the simulators.
- **Coupling strategy:** The strategy for coupling different models with each other, based on the data exchange over time and the iteration between the simulators. It can be distinguished between strong coupling, where the coupled simulators need to meet predefined convergence criteria before moving to the next timestep, and loose coupling, where the coupled simulators use the coupling data from previous timesteps with no iteration between the coupled simulators.
- **Coupling timestep:** The frequency with which data are exchanged, depending on the time constant of the states exchanging flow variables (i.e. heat or mass flow) and the rate of change of inputs acting on the state variables (i.e. control actions). It

significantly influences the stability and accuracy of a co-simulation, especially when there are iterations between the simulators (Bastian et al., 2011).

3.3.2 Co-simulation for adaptive building envelope simulation

The coupling of domain-specific tools for an integrated analysis while maintaining their individual features is one of the main benefits of co-simulation. According to Trčka, Hensen and Wetter (2009), co-simulation thus enables (i) the use of disparate tools that support individual domains, (ii) the translation of a model to code that can be uploaded to control hardware and (iii) the development of control strategies in tools with richer semantics for expressing models than what is found in BPS tools. These also make co-simulation highly beneficial for adaptive building envelope simulation to obtain a more accurate characterisation of their integrated performance, as adaptive building envelopes have no fixed designs or operation strategies and are specified on a case-by-case basis.

It is therefore not surprising that researchers have recently shown an increased interest in adopting co-simulation for the simulation of adaptive building envelopes. In the literature, however, it was found that only the BCVTB (e.g. Coffey and E. Lee, 2014), Grasshopper (e.g. Smith and Lasch, 2016) and the MATLAB/Simulink environment (e.g. Favoino, Fiorito et al., 2016) have been used to study adaptive building envelope performance. The FMI Standard has not yet been used. Originally developed as part of the ITEA2 MODELISAR project, which involved 29 partners and was initiated by Daimler Chrysler, the FMI Standard was sought to encapsulate and link models and simulators for co-simulation of different domains by standardising the API for C. It is an open standard that facilitates collaborative development. The first version was released in 2010 and the second in 2014 and is now supported by more than 80 tools, including EnergyPlus and TRNSYS (Nouidui and Wetter, 2014). As development of FMI-based tools accelerates in the field of building performance simulation, the FMI Standard is well positioned to become the de facto standard for co-simulation.This development towards the standardisation of the FMI Standard and thus the replacement of mechanisms such as the BCVTB is also strengthened in an international research project under the umbrella of IBPSA as IBPSA Project 1 (Wetter and Treeck, 2017). Hence, it is well positioned to become the de facto standard for co-simulation. IBPSA Project 1 benefits from the standardisation of the FMI Standard, thereby letting go of mechanisms such as the BCVTB, to carry out extensive work on the design and operation of control of energy systems based on Modelica (Modelica Association, 2017).

Modelica is an object-oriented, equation-based modelling language that can be used to create schematic model representations and efficient simulation codes (Wetter and Treeck, 2017). Compared to imperative programming languages used in BPS tools, equation-based languages do not need specification of the sequence of computer assignments necessary to simulate a model. This is because when a model is developed, the mathematical equations are specified, packaged into graphically represented components and stored in a hierarchical library. When these components are then assembled into a system model in a schematic editor for connection diagrams (Fritzson and Bunus, 2002) and a simulation environment analyses these equations, it (i) optimally rearranges them through computer algebra, (ii) translates them into executable code and (iii) links them to numerical solvers (Wetter and Treeck, 2017). The advantages of object-oriented, equation-based modelling languages have been discussed by Zimmer (2010) and summarised in Table 3.8. As a result of these advantages, Modelica offers more flexible and modular modelling and simulation methods for building and control systems than what is utilised in existing BPS tools (Wetter, Benne et al., 2020). These methods may offer users the possibility to easily combine models of new adaptive building envelope subsytems without having to modify the entire system model. In this way, adaptive building envelope models may be more easily replaced or improved, making the models' predictions more accurate and reliable.

Table 3.8: Advantages of object-oriented, equation-based modelling languages.

Advantage	Impact on modelling process
1. Well-specified modelling language	Facilitation of the actual modelling process, as the modeller can focus on the creation of the model without worrying about the underlying simulation engine.
2. Support of organisation of knowledge	Decomposition of complex models into easily readable and understandable sub-models, which can be effectively organised in a hierarchical library and then shared, extended and reused. A free, open-source library developed in IBPSA Project 1 is the Modelica IBPSA Library (Modelica Association, IBPSA and contributors, 2018).
3. Consistency check	Check for consistency of components with the modelling language for early detection of modelling errors and facilitation of model validation.
4. Multi-domain modelling	Creation and interaction of sub-models from different domains to develop multi-domain models.
5. Modelling of hybrid systems	Convenient formulation of models for continuous, discrete and event-driven processes for modelling hybrid systems.

Although Modelica used in a co-simulation setup, and co-simulation in general, seem to be beneficial for simulating the behaviour of adaptive building envelopes, there is no standard systematic mechanism for data exchange between the coupled simulators (Taveres-Cachat, Favoino et al., 2021). This lack of standardisation results in three main challenges:

- **Accuracy:** The application of co-simulation may be uncertain in terms of accurate predictions. While each individual tool may be validated, ensuring the expected quality of its predictions, less work has been done to validate adaptive building envelope models created in co-simulation setups. This may be explained by the fact that co-simulation setups couple domain-specific tools whose data exchange and format conversion differs from setup to setup, thus complicating a comprehensive validation (Steinbrink et al., 2017).

- **Reusability:** There is a lack of a standard systematic approach for performing co-simulation, which is supported by the fact that there is no one-size-fits-all approach to co-simulation. This usually leads to a customised solution for the application and the tools used, creating the need for recommendations and best practice guidance.
- **Guidance and documentation:** What contributes to a limited awareness of the potential value of using co-simulation is the lack of widely available recommendations on how to approach co-simulation tasks and how to overcome the technical challenges, i.e. the correct definition of data exchange parameters, including the timing and frequency of the exchange, for a stable co-simulation.

3.4 Summary of evidence from the literature

Several attempts have been made in the literature to predict the thermal performance of adaptive building envelopes together with their control in an integrated modelling system using either mono-simulation or co-simulation. These attempts show that both approaches are suitable for predicting the performance of adaptive building envelopes. However, co-simulation seems to offer more flexibility in integrating the operation strategies of adaptive building envelopes and thus more opportunities for an accurate and representative prediction of their thermal performance. There are, nevertheless, challenges that may be associated with both of the approaches. For this reason, there is abundant room for further progress in determining and improving the application of the simulation approaches in research and industry. To answer questions related to the development of future tools, this section first derives requirements for future tool developments based on the findings of the literature review, followed by an identification of the knowledge gap in the field of study.

3.4.1 Requirements for simulation of control and adaptive building envelope

The challenges that can be associated with the simulation of control strategies for adaptive building envelopes imply that mono- and co-simulation approaches for the integrated modelling of control and adaptive building envelope need to be further developed. This development is particularly important to enable practitioners to consider adaptive building envelopes in real-world buildings to help meet sustainability and carbon emission reduction targets.

Each Software Development Life Cycle includes at least four phases, depending on the Software Development Life Cycle model, namely requirements, design, construction and testing. The first phase, the Software Requirements Specification (SRS), is a complete description of what a software should do without describing how it will do it. Its purpose is to provide a foundation for subsequent development phases to contribute to the success of a software development project (Sun, 2007). A common way of classifying requirements is to divide them into Functional Requirements (FRs) and Non-Functional Requirements (NFRs):

- **FRs:** The requirements that describe the specific functions that a tool must perform and that end users demand as basic features. A function is represented or stated in terms of inputs, its operation and outputs, which may be a calculation, technical details, data manipulation and processing, or any other specific functionality that defines what function a tool should perform.
- **NFRs:** The requirements that define the quality attributes of a tool. These attributes are a set of standards that can be used to judge the specific operation of a tool, rather than the specific functions. They are important to ensure the usability and effectiveness of the tool, so failure to meet NFRs can result in tools that do not meet end user needs.

Recent evidence suggests that FRs and NFRs differ little in terms of their behavioural characteristics, therefore they may be integrated into a common SRS (Eckhardt, Vogelsang and Méndez Fernández, 2016). One challenge of SRS is that requirements may change over the course of the project. However, beyond this, SRS offers the opportunity to define the boundaries of a project and create a shared vision of the software. More importantly, it has the potential to improve end user experience and satisfaction by ensuring that solutions fit the environment (Umar and Khan, 2011). In this regard, NFRs in particular may have an impact on the user experience, for example, in terms of interoperability that helps users avoid juggling applications (Hughes, 2021).

Table 3.9 presents the identified FRs and NFRs for future tool developments and reveals that there are mainly NFRs that future tool developments should take into account. NFRs were specified based on the metrics for measuring attributes of quality in use defined in *PD ISO/IEC TR 9126-4:2004* (International Organization for Standardization (ISO) and International Electrotechnical Commission, 2004). Using these metrics, the general tool capabilities identified by Attia, Hensen et al. (2012) (Section 2.4) and the challenges identified in the literature review were classified into usability and interoperability attributes. The FRs identified are the accuracy and adaptability of future tool developments. Even though more work seems to be needed on the NFRs, software developers rarely focus on them because they are difficult to address, often interacting in synergistic or competing ways (Umar and Khan, 2011). Nevertheless, the literature review has demonstrated that future tool developments should focus on NFRs in addition to FRs, as both are of key importance for end users.

Table 3.9: Requirements for future tool developments: requirements are based the capabilities identified by Attia, Hensen et al. (2012) and the challenges identified in the literature review.

Requirement	Attribute and explanation
FRs	**Accuracy:** Degree to which tool outputs conform to the correct value: • Accurate representation of operation strategies of adaptive building envelopes • Support of discrete-event simulation **Adaptability:** Ease with which a tool can be changed to fit changes in requirements: • Adaptation to new models (e.g. multi-domain integration) and functionalities (e.g. design decision support) • Integration of the operation of building systems (e.g. HVAC systems, lighting) and occupant behaviour
NFRs	**Usability:** Measure of the quality of a user's experience in interacting with a tool: • Usability and information management of GUI • Integration of intelligent design knowledge base • Understanding of interactions of component models • Reusability of simulation approaches **Interoperability:** Ability of a tool to share specific information according to agreed operational semantics: • Interoperability of adaptive building envelope modelling • Integration of tools in building design process

3.4.2 Gap in knowledge: accurate representation of control and adaptive building envelope

Practitioners need to be able to consider proposals for adaptive building envelopes in the design decision-making process to determine their benefits for the thermal building performance and hence contribute to their wider adoption in the building sector. To achieve a robust building envelope solution, building designers need BPS tools that are capable of accurately representing and predicting the interactions of the multiple components and technologies used in adaptive building envelopes. Potential approaches to adaptive building envelope simulation include (i) parallel simulation to speed up the simulation runtime, (ii) hybrid simulation to test the not yet fully understood part of a system model, (iii) mono-simulation to quantify performance attributes of proposed designs and (iv) co-simulation to combine heterogeneous modelling environments. Since the aim of the research is to improve the modelling of the operation strategies of adaptive building envelopes to enable better prediction of their performance, and parallel and hybrid simulation are not expected to overcome the challenges associated with the modelling of adaptive building envelopes, mono- and co-simulation are favoured over parallel and hybrid simulation in this research. However, mono- and co-simulation can be associated with challenges when it comes to accurately representing adaptive building envelopes along with their control:

- **Mono-simulation:** The different levels of control system development and integration into the simulation code of BPS tools may limit the flexibility to accurately represent some adaptive building envelope technologies, especially emerging ones.
- **Co-simulation:** The system decomposition approach may affect the accuracy of co-simulation. While each individual tool may be validated, ensuring the expected quality of its predictions, there is no common benchmarking procedure for co-simulation.

As a result, many open questions remain in the field of adaptive building envelope simulation, which justifies further explorations in this area. Additionally, the literature review points to three topics that would benefit from technical insight, the primary skill set of the author of this thesis:

1. **Understanding end user needs:** In design practice, the challenges associated with BPS tools for modelling adaptive building envelopes typically create a need for workarounds, which quite often result in unintended and undesirable modelling artefacts. While lots of research studies have been identified that address the thermal building performance simulation of adaptive building envelopes, far too little attention has been paid to the industry. Therefore, further work is required to take the end user perspective and understand their needs and implications of the needs for future tool developments that also meet end user needs.
2. **Developing a modelling approach:** Based on the understanding of end user needs, a natural progression of this work would be the development of an approach for the integrated modelling of adaptive building envelope and control. Due to the importance of accurately representing the behaviour of adaptive building envelopes, it is also particularly important to ensure that the proposed approach behaves with satisfactory accuracy within its domain of applicability.
3. **Testing the applicability:** While the proposed modelling approach may enable practitioners to consider adaptive building envelopes in the design decision-making process, it needs to be tested under conditions likely to be encountered in real design projects to ensure that the research result turns into a practical application that creates a lasting benefit for practitioners. One way to achieve this is to provide information about the quality of the modelling approach by executing it under real conditions to indicate the extent to which it meets the requirements that guided its design and development. However, testing all NFRs and FRs is beyond the scope of this research and may be an important issue for a software verification and validation process. Rather, further work should be done to determine the functionality of the modelling approach (i.e. the functions of the modelling approach to perform according to design specifications) in testing design alternatives of adaptive building envelopes.

Taken together, it seems evident that many studies on the thermal building performance simulation of adaptive building envelopes are currently not sufficiently concerned with the industry and the accuracy of simulation approaches. With this in mind, this research seeks to make its contribution by providing detailed insights into how to accurately represent control and adaptive building envelope in an integrated modelling approach that also meets end user needs. The research question and objectives as well as the methodology of the study are presented in the following chapter.

Part II

Analysis

4 Study methodology

This chapter defines the main areas of investigation of this study and outlines methodological considerations resulting from the research subject. Various possible research designs are explored, and a rationale for the selected research methodology based on a mixed-methods design is presented. The different research instruments used in the study are briefly discussed, followed by details on the data collection and the analysis methodology.

4.1 Areas of investigation for research

The literature review and the interview study (see Chapter 5 and Borkowski, Rovas and Raslan (2021)) suggest that current BPS tools hinder the accurate and reliable prediction of adaptive building envelopes. More flexible modelling approaches that allow for rapid prototyping and easy integration are required to enable researchers and designers to take full advantage of the benefits of adaptive building envelopes. To address this gap in knowledge, this research proposes the following research question, as outlined in Section 1.2:

> What requirements should future tool developments meet to represent the behaviour of adaptive building envelopes, and how can future tool developments contribute to an accurate prediction of the thermal performance of adaptive building envelopes?

In particular, the objectives of this study aim to:

1. Identify requirements for future tool developments for predicting adaptive building envelope behaviour.
2. Use the previously identified requirements to develop an approach for the integrated modelling of control and adaptive building envelope.
3. Test the accuracy and the representativeness of the proposed approach for predicting the thermal performance of adaptive building envelopes.
4. Analyse the applicability of the proposed approach to evaluate the thermal performance of design alternatives for adaptive building envelopes under conditions likely to be encountered in real design projects.

4.2 Proposed research approach: a mixed-methods strategy

For exploring the approach to inquiry, J. Creswell and J. Creswell (2018) describe a process in which the researcher brings together research assumptions, specific procedures of inquiry (i.e. research designs) and research methods of data collection, analysis and interpretation. To apply this process in practice, it is key to consider the nature of the research problem(s) in order to select a research approach and associated methods that are required (Morse and Niehaus, 2009).

In light of the aim of this study, a key aspect that had to be taken into account was the shortcomings of BPS tools described in Section 3.2.3, which have resulted over the past years in a significant number of publications related to the thermal building performance simulation of adaptive building envelopes (e.g. Attia, 2019). Recent work, however, has 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. This limited consideration of end user needs may be the reason why recent tool developments might not align with end user requirements. By taking the end user perspective and understanding their needs and workarounds used, it may be possible to better understand requirements for future tool developments that also meet end user needs.

To this aim, it was considered that qualitative measures would usefully supplement and extend this research by adopting a user-centred perspective through interviews with experts in adaptive building envelope simulation. Other aspects considered in the rationale for selecting the appropriate methodology were as follows:

- **Domain of study:** The present study was conducted in the domain of the built environment, which often uses strong quantitative methodologies. However, by focusing on events embedded in real-life contexts, this study also required the integration of qualitative methodologies to study underlying aspects like perceptions and opinions (Amaratunga et al., 2002).
- **Research objectives:** The objectives of this study suggested that the analysis involved data from various sources and samples. As a result, the study adopted different research methods for data collection.
- **Nature of research subject:** The aim of this research was to gather timely and specific information on the building performance simulation of control strategies for adaptive building envelopes in this emergent area. There was consequently little information widely available due to novelty. Also, the research subject was dynamic in nature with ongoing developments and regular updates of the tools. This posed a challenge on the selection of the research design, which sought to ensure the maintenance of the relevance of the study findings in the ongoing developments in industry and research.

Following a comprehensive review of the literature in the area of research methodologies, the alternative strategies of inquiry outlined in Table 4.1 were taken into account. In considering the aforementioned aspects, especially the emergent and dynamic nature of the research subject, the approach to inquiry was based on the following points:

- **Philosophical assumption:** The pragmatic research philosophy, as described by J. Creswell and J. Creswell (2018), was considered most appropriate as it is problem-centred, pluralistic and real-world oriented.
- **Research design:** In establishing a research design, a mixed-methods strategy was adopted that included both qualitative and quantitative methods and combined them into a single method. In built environment research, a mixed-methods strategy is sometimes preferable as 'the weakness in each single method will be compensated by the counter-balancing strengths of another' (Amaratunga et al., 2002, p. 23), thus creating a more complete picture of the phenomenon under study (Ihantola and Kihn, 2011).
- **Implementation:** An iterative approach was utilised in the data collection phase to use emergent insights gained in one phase to develop or inform the method in other phases (Gibson, 2017).

Table 4.1: Summary of qualitative, quantitative and mixed-methods approaches (adapted from J. Creswell and J. Creswell, 2018).

Research approach	Use of practices as researcher
Qualitative approach: • *Philosophical assumption:* Constructivist/transformative knowledge claims • *Strategy of inquiry:* Phenomenology, grounded theory, ethnography, case study and narrative • *Method:* Open-ended questions, emerging approaches and text or image data	• Positions him- or herself • Collects participant meanings • Focuses on a single concept or phenomenon • Brings personal values into the study • Studies the context or setting of participants • Validates the accuracy of findings • Makes interpretations of the data • Creates an agenda for change or reform • Collaborates with the participants • Employs text analysis procedures
Quantitative approach: • *Philosophical assumption:* Postpositivist knowledge claims • *Strategy of inquiry:* Surveys and experiments • *Method:* Closed-ended questions, predetermined approaches and numeric data	• Tests or verifies theories or explanations • Identifies variables to study • Relates variables in questions or hypotheses • Uses standard of validity and reliability • Observes and measures information numerically • Uses unbiased approaches • Employs statistical procedures
Mixed-methods approach: • *Philosophical assumption:* Pragmatic knowledge claims • *Strategy of inquiry:* Sequential, convergent and transformative • *Method:* Both open- and closed-ended questions, both emerging and predetermined approaches and both quantitative and qualitative data and analysis	• Collects both qualitative and quantitative data • Develops a rationale for mixing • Integrates the data at different stages of inquiry • Presents visual pictures of the procedures in study • Employs the practices of both qualitative and quantitative research

4.3 Research design

A mixed-methods approach come with different classification schemes, commonly referred to as typologies (e.g. Guetterman et al., 2019). To determine the most appropriate typology, this study followed the process developed by Nastasi, Hitchcock and L. Brown (2015) and selected a multi-strand typology. The present study was consequently implemented over different strands, each comprising several stages, as shown in Figure 4.1.

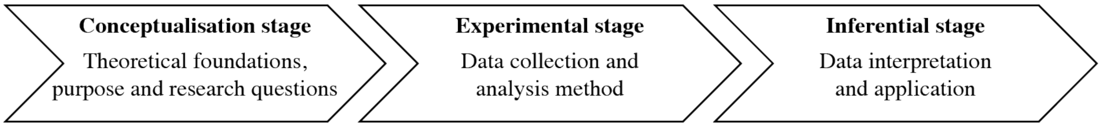

Figure 4.1: Stages of research process.

Further characteristics of the study were:

- **Sequencing of data:** This study used a sequential design, where a dimension of the phenomenon being investigated was used to inform one or more strategies drawn from a different method, thus employing exploratory/confirmatory questions that unfolded as more was known about the phenomena under study (Nastasi, Hitchcock and L. Brown, 2015).
- **Priority of data:** Quantitative and qualitative components used in the study had equal status (Morse and Niehaus, 2009).
- **Mixing of data:** This study merged data in the findings section with the findings of each component presented in a separate chapter (Morse and Niehaus, 2009).

4.3.1 Implementation of the research: methods and instruments

Mixed-methods research combines both quantitative and qualitative methods in a single study (Morse and Niehaus, 2009). The idea is that data are collected using different research strategies and methods in such a way that the resulting combination offsets the weaknesses of each method to take advantage of the strengths of both (e.g. Gibson, 2017).

The different instruments that were incorporated into the mixed-methods research strategy in this research study are illustrated in Figure 4.2. The conclusions drawn based on the findings of the first strand led to the conceptualisation, data collection and data analysis of the other research strands. These strands were then used to confirm or disconfirm the initial inferences, i.e. the results of a process of meaning-making (Collins, 2015). Meta-inferences were developed based on the combined and linked results from the three stands. A key benefit of separating the strands is that this type of research design is easier to control, as studies unfold more slowly and predictably (Nastasi, Hitchcock and L. Brown, 2015).

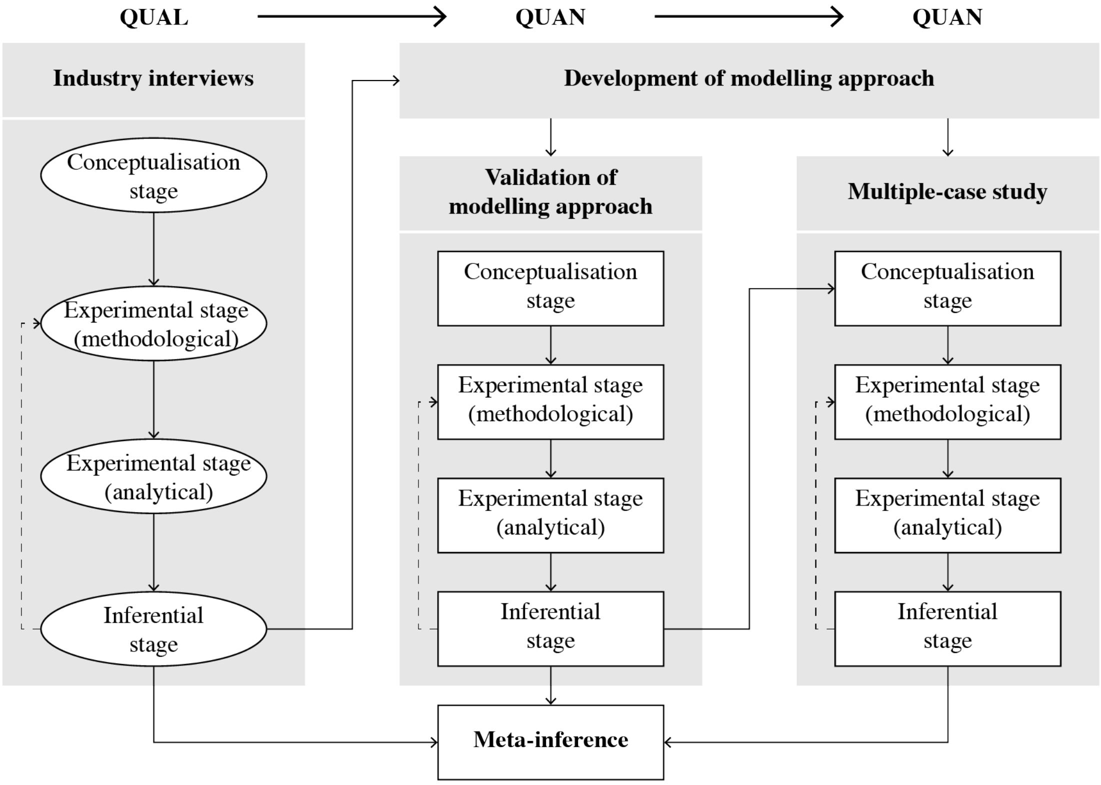

Figure 4.2: Sequential, multi-strand, mixed-methods research strategy.

With regard to the mixed-methods design adopted in this study, an industry-based interview study was first conducted utilising a qualitative research instrument. The findings from the interview study served as the basis for proposing an approach for the integrated modelling of control and adaptive building envelope for thermal performance prediction. The development of the proposed modelling approach, which aimed to predict adaptive building envelope performance using mono- and co-simulation setups, followed the five phases of model integrated proposed by Belete, Voinov and Laniak (2017). To manage and automate the workflow integrated in the modelling approach, it was packaged and stored in a Python package called `cosim`. Following the development, the proposed modelling approach was (i) validated to ensure that the predictions of the modelling approach were meaningful (quantitative instrument) and (ii) applied to a case study to determine to what extent it is suitable for completing the tasks that end users need to be able to complete with it (quantitative instrument). The sections below describe aims, methods and instrumentation and implementation approaches of each component of the research design. The following chapters provide a more detailed description of the process that contributed to the development and implementation of each component and the findings.

4.3.1.1 Industry interviews

Aim of study

The main aim of the in-depth interviews was to produce qualitative data that describe participants' individual perceptions of the limitations of current methods and tools used to simulate adaptive building envelopes in design practice. In addition to an in-depth analysis, the data produced in this phase of the study were used to guide the research and to inform the development of the modelling approach.

Description of method

An interview in qualitative research is a structured and purposeful conversation, where the interviewer asks questions to elicit information (Alshenqeeti, 2014). Because of its flexibility and its ability to produce data of great depth, in-depth interviewing is the most commonly used qualitative method in built environment research (Amaratunga et al., 2002).

Instrumentation and implementation approach

This part of the study used an interview guide with pre-specified topics to guide participants on what to talk about (Kallio et al., 2016). Interviews were conducted via Skype or face-to-face with the participants who were selected by following the key informant technique (DiCicco-Bloom and Crabtree, 2006) and had recent experience in thermal building performance simulation of adaptive building envelopes.

4.3.1.2 Validation of modelling approach

Aim of study

A key issue identified in the interview study was the need for high accuracy in tool predictions. The proposed modelling approach was therefore validated to determine the extent to which it could representatively capture the dynamic behaviour of adaptive building envelopes and whether it could accurately predict the thermal performance of adaptive building envelopes.

Description of method

There are various techniques to check for errors or inaccuracies in a BPS tool (Judkoff and Neymark, 2006). The strategy developed for the validation of the modelling approach combined empirical and non-empirical validation techniques. Specifically, empirical validation was used to evaluate the ability of the modelling approach to analyse real physical behaviour, and comparative testing to help identify and diagnose sources of error or inaccuracy in the modelling approach.

Instrumentation and implementation approach

The validation used empirical data from the Mobile Adaptive Test Experimental Lab (MATELab), a bespoke test cell in Cambridge, United Kingdom (UK), that was built to validate the effect of adaptive building envelopes on office-like environments and occupants. Since MATELab was designed to test different adaptive building envelope technologies quickly and easily, hence allowing for the implementation of a well understood test case, it was considered particularly valuable for this part of the study.

4.3.1.3 Multiple-case study

Aim of study

The present study used a sequential research design that unfolded as more became known about the phenomena under investigation. Although user feedback on the modelling approach was provided via informal presentations and discussions with industry representatives, further testing of the proposed modelling approach is required. While this was not undertaken during this study due to time constraints, the functionality of the modelling approach was tested through the multiple-case study to determine (i) how useful it is for evaluating the thermal performance of design alternatives for adaptive building envelopes under conditions likely to be encountered in real design projects and (ii) how suitable it is for completing the types of tasks that end users need to be able to complete with it.

Description of method

To account for the exploratory nature of this research study, the present work adopted a case study that examines a contemporary phenomenon in its real-world context (Yin, 2014). Although the simulation of a case study is not the same as reality, it is ‘a method (. . .) to model the operation of "real-world" processes, systems or events’ (J. Davis, Eisenhardt and Bingham, 2007, p. 481). This makes it highly relevant for a project-driven industry like the built environment (Proverbs and Gameson, 2008).

Instrumentation and implementation approach

This part of the study adopted an embedded multiple-case study design to add opportunities for extensive analysis and to improve the insights into the single case. The embedded units of analysis were the control strategies for the adaptive building envelopes in each case study building. Two case study buildings with two distinct control strategies were simulated in the modelling approach over a whole year.

4.3.2 Data analysis procedures and interpretation methods

A crucial stage in a mixed-methods research design is the integration of the sets of inferences generated by the various strands of the study, thus requiring the application of different data analysis methods (Guetterman et al., 2019). A general overview of the methods used in this study are briefly described below and in greater detail in the relevant chapters. To form the data analysis strategy in this thesis, micro- and macro-scale data analysis methods were used.

4.3.2.1 Micro-scale data analysis methods

Micro-scale analysis methods are applied with respect to a specific phase of research (Creamer, 2018). The present study adopted the following analysis methods at this scale:

Theory development: the content analysis approach

A qualitative content analysis approach was used for the interpretation of the interview data. This approach provides knowledge and understanding of the content of text data through a systematic process of coding and identification of themes or categories (Vaismoradi, Turunen and Bondas, 2013). Compared to other qualitative 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 seems appropriate for the interview study. Mayring (2000) identified the following advantages of the content analysis approach:

1. Drawing conclusions from some sort of recorded communication to other sources in their context.
2. Analysing data step-by-step by following rules of procedure and arranging the data into content analytical units.
3. Carefully constructing categorises for the various aspects of the interpretation within the analysis process.
4. Performing reliability checks by comparing findings with other data.

Statistical analysis

Statistical methods were used in the analysis of the quantitative data of the validation and the case study to summarise the collected data and to make inferences about these data (Mills, Durepos and Wiebe, 2012). The following methods were considered appropriate to perform the statical analysis:

- **Descriptive statistics:** The application of statistics to describe, summarise and explain a set of data, which is comprised of numeral facts or observations, in a meaningful way so that patterns emerge from the data. These include measures of central tendency and measures of spread.
- **Inferential statistics:** The use of statistics to make inferences (or predictions) about the population from which the data were drawn. To make correct inferences, some

kind of randomisation is used, such as estimation of parameters or testing of statistical hypotheses.

Measurement of model accuracy: Uncertainty Analysis (UA)

In analysing the results of the validation, there could be large discrepancies between simulation-predicted and measured data points. An UA was therefore used to quantify how well the simulation model describes the variability in the measured data, thus decreasing the uncertainty of the model and increasing the level of confidence in the model. A UA can be described as 'the process of determining the degree of confidence in the true value when using a measurement procedure(s) and/ or calculation(s)' (ASHRAE, 2014b, p. 10). It measures the acceptable level of model accuracy through the use of uncertainty indices, being the NMBE and the CV-RMSE indices in the validation study.

4.3.2.2 Macro-scale methodological and analytical integration

Macro-scale analysis methods are generally applied to the synthesis of data from different research phases (Creamer, 2018). The primary analysis method used at this scale was the framework by Fetters, Curry and J.W. Creswell (2013), which adds value to mixed-methods research through its generality, specificity and pragmatism.

The framework involves the collection of data through the adoption of different methodological approaches (O'Cathain, Murphy and Nicholl, 2010). By combining the data, the research findings of one of the methods can be explained by another method. As a consequence, the use of this framework is generally seen as a crucial method to use the findings from the different data sources to differentiate and extend 'insights of the phenomenon of interest by addressing different aspects of a single phenomenon' (Fetters, Curry and J.W. Creswell, 2013, p. 2144).

Integration can occur at three levels: (i) at the study design level, (ii) at the methods level and (iii) at the interpretation and reporting level (Fetters, Curry and J.W. Creswell, 2013). In this study, integration was achieved at the level of the study design when the quantitative and qualitative approaches were intentionally integrated in an exploratory sequential design, and at the level of interpretation and reporting when the quantitative and qualitative findings were described in the thesis.

4.4 Quality of the research: issues of validity

The validity of mixed-methods research studies can be evaluated according to inference quality, which is the same as internal validity in quantitative literature and credibility in qualitative literature. Inference quality determines whether valid conclusions can be drawn from a study given the research design and controls used (Ihantola and Kihn, 2011). It is a combination of:

- **Design quality:** Quality of data, design and data analysis procedures.
- **Interpretive rigour:** Process of making inferences based on study findings.

The use of a mixed-methods research design necessitates the application of measurement techniques for constructing validity for all quantitative and qualitative components of the design to pertain the quality of inferences in mixed-methods studies (Onwuegbuzie and R. Johnson, 2006; Ihantola and Kihn, 2011). In case qualitative or quantitative components are equally dominant, Teddlie and Tashakkori (2009) suggest using inference quality to ensure the quality of the inferences. To achieve the required inference quality, the issues outlined in Table 4.2 were considered in the data analysis of this study. Given the research design and controls used, this study primarily considers internal validity rather than external validity. Therefore, while valid conclusions can be drawn from the study, these are only transferable to situations outside of this study but not generalisable.

Table 4.2: Integrative framework for inference quality (Teddlie and Tashakkori, 2009).

Research criterion		Description
Design quality	Design suitability	Appropriateness of methods to answer research questions.
	Design adequacy	Adequate implementation of the components of the design.
	Analytic adequacy	Appropriateness and adequacy of data analysis techniques to answer the research questions
	Within-design consistency	Consistency of the study design from which the inferences are drawn.
Interpretive rigour	Interpretive consistency	Consistency of inferences with each other and findings of data analysis.
	Theoretical consistency	Consistency of each inference with theory and state of knowledge in the field.
	Interpretive agreement	Consistency of interpretations across scholars and participants.
	Interpretive distinctiveness	Distinctive difference of inferences from other possible interpretations of the findings.
	Integrative efficacy	Effective integration of inferences made in each strand into a theoretically consistent meta-inference.

4.5 Data protection and ethical practice

Considerations of the ethical use of personal data was particularly important in the interview study. To make sure that participants were not adversely affected by the interview study, guidance from the British Sociological Association (BSA) (2017) was consulted in the interview setup phase. The following criteria were implemented in the interview study:

- **Participant anonymity and confidentiality:** Confidentiality in research implies that personal data that may identify subjects are not reported (Kaiser, 2012). In line with the Data Protection Policy of UCL, the interview study was registered under the EU's General Data Protection Regulation and the UK Data Protection Act 2018 (UCL Data Protection Registration No: Z6364106/2018/10/88). Under UCL's policy, the interview study fulfilled the obligation to adopt appropriate measures to use pseudonymised personal data and to securely store interview data.

- **Informed consent:** According to BSA (2017), participation in a research study 'should be based on the freely given informed consent of those studied' (2017, p. 5). This involves informing potential participants in appropriate detail of the nature and procedures of the research and of possible risks and benefits, which may influence their decision to participate. In the interview study, potential participants were fully informed at any contact phase through a participant information sheet (Appendix A.1) and then gave their written consent to take part in the research.

4.6 Summary of methodology

The main objective of this research project was to develop a solution to accurately and representatively predict the dynamic behaviour of adaptive building envelopes. A mixed-methods research strategy was adopted to compensate the weakness of each method with the strengths of another. This strategy was implemented over three phases, with conclusions from the findings of the first phase leading to the carrying out of the other phases. The three phases were (i) an industry-based interview study, the findings of which served as the basis for the development of a modelling approach, (ii) a validation of the modelling approach and (iii) a multiple-case study. Meta-inferences were then developed on the basis of the combined and linked findings from the three phases.

5 Industry interviews

A shortcoming of existing BPS tools is their limited extensibility that is often partly overcome by the use of scripting. This implies that the accurate prediction of adaptive building envelope performance remains challenging and requires *ad hoc* approaches. This challenge has made practitioners reticent in considering the use of adaptive building envelopes, which in turn has led to a slow uptake of these building envelopes in the built environment. The interview 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, this part of the study adopts a user-centred perspective through interviews with experts in adaptive building envelope simulation.

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5.1 Context and justification of interviews

The shortcomings of BPS tools identified in Section 3.2.3 have led to a significant number of publications discussing the thermal building performance simulation of adaptive building envelopes in recent years. However, previous work focused on developing a research roadmap paid less attention to the needs of designers and how they use simulation as an exploratory tool for designing and tuning the operation of adaptive building envelopes. For this reason, this part of the study takes the perspective of the end users to better understand requirements for future tool developments that also meet end user needs.

The interview study adopts a user-centred perspective 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. This is to ensure that this research project is guided by an attempt to address the key issues and priorities.

The interview 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 part of the research 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.

Finally, the research project, which included the interview study, used the findings of the interviews to inform the development of a potential solution for the prediction of adaptive building envelope behaviour.

5.2 Interview methodology: design, procedures and implementation

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). As part of a quantitatively driven mixed-methods research project, an interview guide approach was adopted in this part of the study, as suggested by Teddlie and Tashakkori (2009) (Figure 5.1).

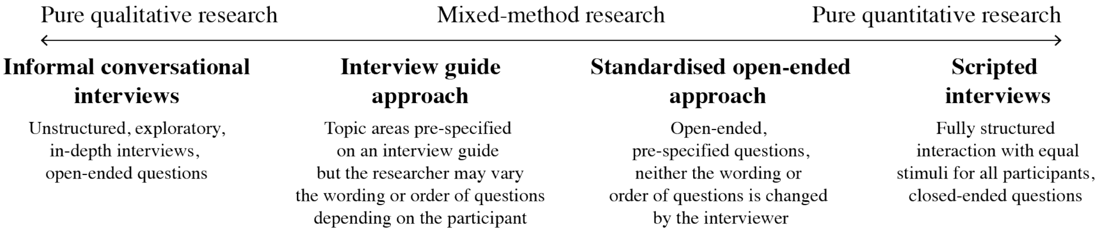

Figure 5.1: Types of research interviews (Teddlie and Tashakkori, 2009).

5.2.1 Interview question types and structure

A clear benefit of the interview guide approach is that it provides guidance to participants on what to talk about (Kallio et al., 2016) and that it covers the topics under investigation completely (Taylor, Bogdan and DeVault, 2015). In an interview guide, topics are specified, but the researcher may change the wording or the order of questions according to the feedback from participants during the interview.

According to the practical guidance on how to design and carry out a study using interviews outlined by King (2004), the interview guide was structured into two sections: an introductory section followed by a section with sets of questions. The sets of questions, commonly referred to as *interview schedule*, combined both closed- and open-ended interview questions:

- **Closed-ended questions:** Questions that produce short and finite answers (i.e. ‘yes’ or ‘no’), which are quantifiable and hence easy to analyse.
- **Open-ended questions.** Questions that generate descriptive answers, which need to be coded (i.e. tagged or labelled). Leaving questions open-ended may encourage

participants to engage in more in-depth descriptions, and probing questions can be used to gain more insights into participants' experiences and perceptions (Whiting, 2008).

The interview schedule was composed of two levels of questions: (i) main topics that dealt with the main content of the study subject and (ii) follow-up questions that were used to enable the participants to understand easier the main themes and to direct the interview towards the research subject. The interview guide that was used during the interviews is presented in Appendix A.2 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.

5.2.2 Sampling strategy and selection criteria

Samples must be representative of the population to maximise the applicability of the findings to the broader context in qualitative research. 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 part of the study, the selection was achieved by following the key informant technique (DiCicco-Bloom and Crabtree, 2006). According to this method, 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 to be likely to provide focused information on the research question. The goal of this strategy is to generate new concepts by gaining new insights into the question under study. Unlike random sampling that selects cases without any prior stratification, purposive sampling is a non-random sampling technique, in which the researcher chooses strategically key informants based on their potential to 'yield a depth of information or a unique perspective relative to the phenomenon of interest' (Collins, 2015, p. 360). As a consequence, key informants are selected based on predetermined criteria relevant to the research objective (Guest, Bunce and

L. Johnson, 2006). Selection criteria for the interview study and how they were intended to achieve the interview objectives are shown in Table 5.1.

Table 5.1: Selection criteria for key informants.

Selection criteria	Intention of criteria to achieve interview objectives
Recent experience in thermal building performance simulation of adaptive building envelopes.	Identify current methods for adaptive building envelope simulation in design practice.
Deep understanding of strengths and weaknesses of BPS tools.	Gain insights into the problems and limitations experienced by participants in adaptive building envelope simulation and derive information on future methods for adaptive building envelope simulation.
Hands-on experience in the development of workaround solutions.	Acquire knowledge of methods to overcome the challenges associated with BPS tool capabilities in adaptive building envelope simulation.

5.2.3 Selection bias, validity of results and sample size

The use of purposive sampling allows the researcher to study information-rich cases (i) to learn about key issues for the purpose of the study and (ii) to yield in-depth insights and understanding to illuminate the phenomenon under investigation (Patton, 2002). However, a major problem with purposive sampling is that sample recruitment is significantly influenced by the background, location and connections of the researcher (Robinson, 2014). Although this problem is substantial, Morse and Niehaus (2009) argue that selecting a key informant with specific knowledge is the intention and purpose of a purposive sampling strategy. Nevertheless, purposive selection of cases may lead to ‘biased’ samples, which subsequently affects the internal validity (control of cause and effect) of the results. To mitigate bias, key informants with somewhat different experiences were sought to understand the variation in the phenomena of interest in the population. When different cases are represented within the population of interest, they become valid across the realm they represent (Morse, 2011).

Among the most common objections to interviews are their reliability, validity and transferability (Kvale, 1994). In principle, however, interviews may lead to valid scientific knowledge if they focus on the quality of the craftsmanship of the interview researcher throughout an entire interview inquiry, continually checking, questioning and theorising the interview findings. This may lead to evident findings and intrinsically convincing knowledge claims and conclusions (Brinkmann and Kvale, 2018). To enhance the reliability, validity and transferability of the present interview study, several methods were adopted, including using open-ended questions, obtaining feedback from participants e.g. on the transcripts and critically reviewing the analysis by e.g. fact-checking interviewees’ statements with the literature.

To justify adequate sample sizes in purposive samples, Hagaman and Wutich (2017) suggest the concept of theoretical saturation, which emerged from grounded theory and can be defined 'as the point at which no new insights, themes, or issues are identified for a particular data category' (2017, p. 25). Several authors (e.g. Guest, Bunce and L. Johnson, 2006; Hagaman and Wutich, 2017) found that the minimum number of interviews needed to reach data saturation in purposive samples is between seven and twelve interviews when there is (i) a relatively homogeneous sample, (ii) fairly narrow study objectives and (iii) an interview guide. Since these three conditions were met in this part of the study, it was assumed that between seven and twelve interviews were sufficient to reach a point where data saturation was likely. As key informants were expected to be highly specialised, 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 interview participants were contacted via personal email or LinkedIn message, and 41 % responded to the interview request. Two potential interview participants did not meet the selection criteria, so that a total of seven participants were interviewed. Descriptive information about the participants is presented in Table 5.2.

Table 5.2: Information about interview participants.

Participant	Country of workplace	Experience*	Current role	Size of company†	Educational background	Highest qualification
P01	Denmark	Senior level	Engineer	Large	Environmental engineering	PhD
P02	UK	Senior level	Director	Large	Mechanical engineering	BSc
P03	UK	Senior level	Director	Large	Architectural engineering	PhD
P04	Sweden	Senior level	Director	Small	Environmental engineering	PhD
P05	UK	Mid-level	Engineer	Large	Architectural engineering	MSc
P06	UK	Mid-level	Engineer	Large	Architectural engineering	MSc
P07	UK	Entry level	Engineer	Mid-sized	Architectural engineering	MSc

* Entry level: 4-5 years, Mid-level: 6-10 years, Senior level: 11+ years

† Small: 1-50 employees, Mid-sized: 51-250 employees, Large: 251+ employees

5.2.4 Interview recording and transcription

Interviews are used in qualitative research as a data collection method, and the researcher has to make choices of how to 'record' the human interaction. It is possible to use field notes, a recording device or both. While field notes, which include the content of an interview as well as non-linguistic data (Flick, 2018), are an essential method, one of their main disadvantages is that they cannot be replayed. This may result in a loss of information and valuable details, consequently making the field notes incomplete and biased (Tessier, 2012). In this part of the research, the interviews were therefore audio recorded using a digital voice recorder to assist the interviewer with filling in blank spaces in the field notes and with checking the relationship between the notes and the actual responses. The audio file of each interview was transferred to a secure UCL file store for storage. Following data protection and ethical practice (Section 4.5), permission from each participant to audio record the interview was sought during the interview setup phase.

A frequently asked question when it comes to data collected through interviews is ‘what counts as data and when does the data analysis process start?’ (Tessier, 2012, p. 447). Although differences of opinion still exist, there appears to be some agreement that a transcript describes a form of representation of spoken discourse (e.g. Lapadat, 2000; Tessier, 2012), and transcripts are hence a form of analysis rather than data. The reason for this is that the transcription process is inherently theoretical and subjective, inevitably losing information as the interview recording is translated into written language (Lapadat, 2000). As a result, Markle, West and Rich (2011) recommend to code the actual data (i.e. audio recordings) and transcribe only what is needed later for publications and what is illustrative of the core aspects of the research.

The main advantage of coding the recordings is that researchers can repeatedly revisit the original data and maintain a greater sense of the interviewees’ perspectives. Working from audio recordings directly is, however, only possible due to technology advancements (e.g. Neal et al., 2014; Crichton and Childs, 2017). Instead of transcribing interviews and working with the resulting text, researchers can code, classify and annotate sections of audio sources directly in the audio track. By listening and re-listening to the recorded interactions, data are selectively reduced so that they preserve the possibility of various analyses and interpretations (Lapadat, 2000).

However, a clear benefit of transcription is that it enables the readers, without the same first-hand experiences as the researcher, (i) to fully understand the research setting and the participants’ perspectives, (ii) to interpret and understand the study and (iii) to make relevant links (Crichton and Childs, 2017). To facilitate transferability and to increase the trustworthiness of this qualitative inquiry, gisted transcriptions, a form of summarisation, were derived from each interview (Dempster and Woods, 2011). A reflexive, iterative process of interview data management was adopted to develop the gisted transcriptions, as proposed by Halcomb and Davidson (2006) and outlined in Appendix A.3. The gisted transcriptions were written in a narrative form and organised based on the key themes of the interview guide. To seek validation of the transcripts from participants (Gibbs, 2007), transcripts were sent to the participants for review, feedback and approval. The interview transcripts from this part of the research are included in Appendix A.4.

Quotations that were needed for publication and illustrative of the core aspects of the research were transcribed using pragmatic transcription, a verbatim (i.e. word for word) transcription format with nonverbal information (Evers, 2011). For the transcription of the nonverbal information, the transcription keys by Jefferson (2004) were used, as presented in Appendix A.5. To avoid disclosing the interviewee's identity, individually-identifiable details were replaced with more generic phrases in [brackets].

5.3 Data analysis methodology

A qualitative content analysis method (Mayring, 2000) was adopted for the interpretation of the interview data. 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 E.-H. Lee, 2014).

5.3.1 Qualitative content analysis

The aim of a qualitative content analysis it 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 transcripts (Vaismoradi, Turunen and Bondas, 2013). A qualitative content analysis was chosen because it is not only possible to analyse data qualitatively, as in a thematic analysis, for instance, but also to quantify the data at the same time (Vaismoradi, Turunen and Bondas, 2013). Moreover, a qualitative content analysis is a common method used when existing research literature on a phenomenon is limited (Hsieh and Shannon, 2005).

Compared to other qualitative methods, such as grounded theory, a weakness of qualitative content analysis is its limitation in theory development as 'both sampling and analysis procedures make the theoretical relationship between concepts difficult to infer from findings' (Hsieh and Shannon, 2005, p. 1281). However, Hsieh and Shannon (2005) highlight that the results of qualitative content analysis are concept development or model building at most, which seemed sufficient for determining and focusing the areas of investigation.

5.3.2 Implementation of analysis methodology

The process developed to implement the analysis strategy included NVivo (QSR International, 2018), a Computer Assisted Qualitative Data Analysis Software (CAQDAS). Compared to manual methods, which are considered time-consuming and inefficient, a CAQDAS allows for a more rapid and rigorous analysis process of qualitative data (Seale, 2011). For example, a CAQDAS allows the researcher to attach codes to segments of audio data to facilitate later retrieval of relevant data segments (Weitzman, 2000). Compared to managing the qualitative data by hand, the drawbacks associated with using a CAQDAS are the complexity of the software and the training time (N. Davis and B. Meyer, 2009).

After considering different software packages available for the purpose of qualitative data analysis, NVivo was chosen for the capabilities identified by N. Davis and B. Meyer (2009):

- **Simple and flexible coding:** Highlighting units of analysis, data or meaning and choosing between different coding options.
- **Categorisation of data into emergent themes:** Categorising codes into broader themes as they emerge from the interview data.
- **Linking of memos and codes:** Using the memo option to write notes about the analysis process and linking them to the codes.

The interview study used NVivo for data coding, which refers to the categorisation of data through splitting, analysis, comparison and conceptualisation. In this way, data can be converted into meaningful units, providing an overview of a large amount of recorded data and assisting in connecting ideas and concepts and rethinking theoretical associations (DeCuir-Gunby, Marshall and McCulloch, 2011). Breaking down data into meaningful categories also makes it possible to quantify their frequency of occurrence and to compare and correlate them with other data (Kvale, 2004).

The categorisation of simple codes into more encompassing categories was undertaken *ad hoc*, following the qualitative content analysis method by Hsieh and Shannon (2005), rather than developing codes beforehand. The coding process was simplified by the field notes with descriptions of the phenomena to be coded or categorised obtained through the interview process (Kvale, 2004). The coding and categorising process in this qualitative content analysis was guided by Hsieh and Shannon (2005) and Neal et al. (2014) and is summarised in Appendix A.3.

As a result of this process, numerous themes emerged that corresponded with the main questions under study. The node structure on which the categories were based is set out in Appendix A.6. The main themes that were subsequently defined are shown in Figure 5.2.

5.4 Discussion of key results from interviews

This section discusses the themes that emerged from the in-depth interviews with practitioners in thermal building performance simulation of adaptive building envelopes in current design practice. Where applicable, data tables outlining participant feedback were generated to

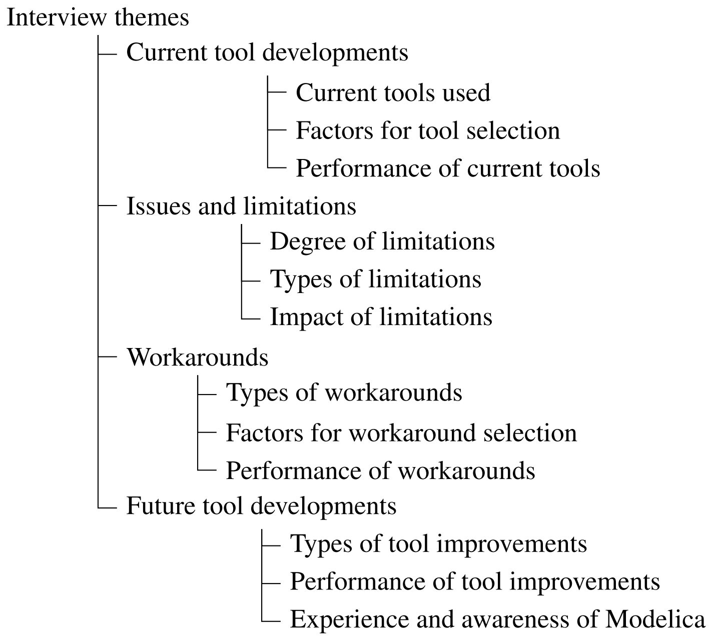

Figure 5.2: Main themes and subthemes of interviews.

assist in content clarification. To provide a useful tool for the evidence on which the results were drawn, full tables are included in Appendix A.7 and referenced where relevant. When referring to specific interview participants, an interview code was applied to differentiate between the interviews and to maintain participant anonymity. The code 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).

A pilot interview, a small-scale implementation of the complete research plan, was conducted in November 2018. After sorting out problems, e.g. with the wording of questions and the matching with available data, the final interviews were carried out between January and April 2019.

5.4.1 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 (Table A.2). The interview study found that:

- six out of seven participants use IES VE;
- three out of seven participants use EnergyPlus; and
- one out of seven participants uses IDA ICE.

While there are many other BPS tools that can be used for the thermal building performance simulation of adaptive building envelopes (see Loonen, Favoino et al. (2016) for further details), the experience of the practitioners interviewed in this part of the 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, 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 performance of BPS tools were particularly prominent (Table 5.3). As such, 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).

This response suggests 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). Under the term usefulness, the participants understood the following:

- **User-friendliness:** The usefulness of a BPS tool depends on its user-friendliness. While some participants perceived a BPS tool as user-friendly if it is capable of producing fast results and graphical outputs for presentation to clients (P03, P05), others perceived it as user-friendly if it can help produce accurate and reliable predictions for thermal analyses (P04).
- **Project suitability:** The usefulness of a BPS tool depends on whether it is suitable for projects involving adaptive building envelopes.
- **User-dependency:** The usefulness of a BPS tool depends on the user's experience, knowledge and understanding of that tool.

A BPS tool was perceived as useful by the participants if it either provided quick results with presentable graphical results (P03, P05), or if it allowed control and understanding over the input variables and calculation procedures (P02, P04). This satisfaction is mainly due

Table 5.3: Usefulness, reliability and modelling and computation time of BPS tools used.

Type	Description
Usefulness	• **User-friendliness:** Participants are generally satisfied with the user-friendliness of the tools (P05, P06, P07) despite mixed opinions about the meaning of user-friendliness: fast results and graphical outputs presentable to clients (P03, P05) vs accurate and reliable thermal analyses (P04). • **Suitability for projects:** Tools are highly suitable for the purpose of the participants' analyses and projects (P01, P04, P06). • **User-dependency:** The usefulness of the tools depends on the user's experience, knowledge and understanding of the tool (P01, P02, P04).
Reliability	• **Transparency:** – **IES VE:** IES VE limits users' knowledge about its inner algorithms and procedures (P02, P04, P05, P06) as it is a 'bit of a black box' (P05) despite the recent integration of a Python API for better flexibility (P06). – **EnergyPlus:** Participants have high confidence in pure calculation engines like EnergyPlus due to more transparent calculation procedures (P02, P04, P05). – **IDA ICE**: Participants have high confidence in IDA ICE calculation procedures as users can understand its codes and algorithms (P04). • **User-dependency:** The accuracy of the tools depends on the user's experience, knowledge and understanding of the tool (P01, P02). • **Dissemination in industry:** Participants have confidence in IES VE predictions as it is an industry standard (P05). • **Time step handling:** Participants perceive IDA ICE predictions as highly accurate as it has no fixed time step, but determines the time step depending on changes in the model (P04). • **Validation:** There is a good agreement between predicted data from IES VE and measured data (P06).
Time	• **Time requirement:** Traditional models need less time for modelling and simulation than bespoke models (P01, P03, P05, P07), on average between 100 and 200 hours per project (P03). • **Reasons for time requirement:** The most common reasons are: – correct implementation of the required level of detail (P02, P04); – geometry setup (P05, P06); – detailed input possibilities of some tools (P01); and – time step handling of tools (P04).

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 5.4. 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 they perceive IES VE as an industry standard.

Table 5.4: 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)

5.4.2 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). Generally, however, participants expect three main capabilities from BPS tools for modelling adaptive building envelopes, namely (i) flexibility in modelling building envelope systems, materials and controllers, (ii) transparency in calculation procedures to ensure reliability of predictions and (iii) short modelling and simulation time (Table 5.5). These expectations were cross-checked with the literature to compare them with what is available in existing BPS tools and what remains for future tool developments. After the cross-check, it became clear that existing BPS tools lack capabilities across all three expectations, leaving ample room for future tool developments.

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 5.6). Four participants rated IES VE, two IES VE and EnergyPlus and one IDA ICE. Participants rated all the BPS tools they use in an overall rating, without distinguishing between individual BPS tools. Therefore, the table shows the overall rating for all BPS tools used by each participant, not for an individual BPS tool. Interviewees rating IES VE rated it without considering the recently launched Python 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

Table 5.5: Comparison of participants' expectations with available BPS tool capabilities.

Expectations regarding BPS tool capabilities	Available BPS tool capabilities, indicated with the missing BPS tool capabilities
Flexibility in modelling building envelope systems, materials and controllers (P01, P02, P03, P05, P06, P07)	• Tight coupling of numerical solvers with individual models (Widl et al., 2014) • BPS tool-dependent development and integration levels of models into the simulation code (Buonomano et al., 2016) → Limited flexibility in adapting BPS tools to represent some adaptive building envelope systems, materials and controllers
Transparency in calculation procedures to ensure reliability in predictions (P02, P03, P04, P05, P06)	• Use of default values and templates to facilitate data entry (Attia, Hensen et al., 2012) • Integration of an adaptive GUI to enhance the human-computer interaction and the simulation's effectiveness (Attia, Hensen et al., 2012) → Difficult understanding of interactions of component models with other model parts for users
Short modelling and simulation time (P01, P03, P05, P07)	• Modelling mainly dependent on complexity of use case • Use of continuous models in BPS tools (Wetter, Bonvini and Nouidui, 2015) → Limited influence on state transitions that hinder prediction of the influence of control decisions on the dynamic behaviour of adapting building envelopes

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 due to the EMS feature, which opens up the capabilities of EnergyPlus, especially for custom control strategies. Because IDA ICE is highly programmable, its capabilities were rated as three, similar to EnergyPlus.

Table 5.6: Participant's rating of the capabilities of BPS tools.

Participant	P01*	P02†	P03†	P04‡	P05*	P06*	P07*	*Min*	*Max*	*M*	*SD*
Rating	3.0	5.0	6.0	3.0	–	5.0	4.0	3.0	6.0	4.3	1.1

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

The participants identified several challenges that can be associated with the capabilities of BPS tools to predict the thermal performance of adaptive building envelopes (Table 5.7). The challenges mentioned most often by interviewees were an accurate representation of building envelope systems, materials and controllers, as shown in Table 5.8. The challenges they reported were compared with the BPS tool capabilities found by Loonen, Favoino 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 5.9 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, Favoino et al., 2016). Second, Loonen, Favoino et al. (2016) 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 tools 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.

Table 5.7: Limitations of BPS tools used.

BPS tool	Reported limitation
All BPS tools	• **Materials:** Innovative materials, such as PCM in glass (P01), varying U-values (P01), varying g-values (P03), reflective materials (P04), façades with thermal resistors, bimetals and variable permeability surfaces (P05) and EC glazing (P07) • **Shading systems:** Solar shading including solar control strategies (P02, P03, P05, P06); Solar shading that changes e.g. its geometry based on solar radiation (P03) • **Controllers:** Custom control strategies to control adaptive façade behaviour (P01, P03, P05); Implementation of the actual controller in a building, such as predictive controllers (P01) • **Methods:** Testing of different design configurations by running parametric analyses (P03); Support of custom adaptive building envelope models (P04)
IES VE	• **Shading systems:** Different solar control strategies except a single ON/OFF step function (P02, P06); Selection of sensors (P02) measuring e.g. daylight illuminance (P05) or weather conditions (P06) • **Façade systems:** CCFs (P02, P05) • **Geometry:** Curvy façade and building elements (P06, P07)
IDA ICE	• **Geometry:** Sloped walls (P04) • **Shading systems:** Solar shading that collects dust or bacteria (P04)

Table 5.8: Challenges of BPS tools mentioned most often by participants.

Type	Quote
Building envelope system	'There's no, you know (0.3), CCF module in IES. You need to kind of (.) take what's there and appropriate it to kind of match what you wanted to do.' (P02)
Material	'We can only use the material (.) properties that are set as an input in IES. So, for instance, if we want to use phase change materials within glass, we can't model that.' (P01)
Controller	'For instance, () the control, I think that would be quite a challenge (.) to (.) simulate them (.) with the tools that are available to use.' (P05)

The use of one BPS tool for any given use case may mean that certain adaptive building envelopes cannot or can only partially be modelled, which may ultimately lead to uncertain

Table 5.9: Challenges associated with BPS tool capabilities reported by participants: shown against BPS tool capabilities found by Loonen, Favoino et al. (2016).

Type	Reported challenge	Agreement between challenges reported by participants and tool capabilities found by Loonen, Favoino et al. (2016)		
		IES VE	EnergyPlus	IDA ICE
System	DSF (P02, P06)	No	No	–
	Curvy façade element (P06, P07)*	Yes	–	–
	Sloped façade element (P04)*	–	–	Yes
Material	PCM (P01, P03, P05)	Yes	No	–
	Dynamic insulation (P01)	Yes	–	–
	Material motions by changes in e.g. volume or shape (P05)*	Yes	–	–
	Photochromic glazing (P07)	No	–	–
Controller	Custom control logic (P01, P02, P05)			
	Sensor	Yes	No	–
	Actuator	Yes	Yes	–
	Control logic based on weather conditions (P03, P06)			
	Air temperature	Yes	Yes	–
	Solar radiation	Yes	Yes	–
	Wind speed	Yes	Yes	–
	Shading with slat angle control (P06)	Yes	–	–

* Based on information in user manuals and forums

predictions and incomplete design decisions. Interestingly, most interview participants who have multiple BPS tools available for their projects have more professional experience. Although this finding may not be generalised due to the small sample size, it may suggest that the additional experience of the participants may lead to a greater knowledge of BPS tools, such as their limitations and capabilities, which in turn may lead to a greater knowledge of which BPS tool is best suited for which use case. However, it may also be possible that this finding has little to do with the experience of the participants, as it is often a company-wide decision for or against a particular BPS tool or set of BPS tools. In P01's company, for instance, the whole company works with IES VE because it is particularly useful for Part L compliance calculations in the UK, even though the participant works in Denmark and IES VE offers similar benefits for projects in Denmark as other BPS tools.

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. Loonen, Favoino et al., 2016; COST Action TU 1403 adaptive facade network, 2018a). 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, Favoino et al., 2016). This limitation, 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 5.10). 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 output because there are also many other aspects in a model affecting the predictions. Other participants believed 'if you would 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.

Table 5.10: Participants' rating of the effect of the BPS tool capabilities on the predictions.

Participant	P01*	P02†	P03†	P04‡	P05*	P06*	P07*	Min	Max	*M*	*SD*
Rating	5.0	4.5	5.0	7.0	7.0	8.0	4.0	4.0	8.0	5.7	1.5

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

5.4.3 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

(Table 5.11). 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. General capabilities that participants felt are missing in existing BPS tools were cross-checked with the literature and are listed in Table 5.12. The decision to use a workaround usually follows a thorough checking of inputs and outputs, as can be seen from Figure 5.3. 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.

Table 5.11: Workarounds applied by participants.

Workaround	Description
Scripting methods	• Participants use the following scripting tools: – Grasshopper with add-ons (P02, P03, P04, P06); – Python (P02, P05); – the EMS scripting feature (P02); and – MATLAB (P02). • Scripts are developed either by the participants themselves (P02, P03) or by in-house coders (P02, P03, P04, P05). • Advantages of scripting methods are the great flexibility to customise control strategies (P02) and the possibility to link scripts with tools like EnergyPlus and Radiance (but not with IES VE) (P05). • A disadvantage of scripting methods is the limited application in some companies due to users who are inexperienced in running e.g. IF-statements (P02).
Post-processing	• Post-processing refers to the manual interpolation of simulation outputs, usually in an Excel spreadsheet (P01, P02, P05, P07). • Examples of adaptive building envelopes that have already been modelled by post-processing are simple ON/OFF blinds automatically controlled by daylight illuminance (P05) and translucent panels, where daylight penetrated through a panel depending on the sun (P07). • A major drawback of post-processing is the introduction of human error (P02), the limited possibility of repetition (P02) and the limited consideration of the benefits of the adaptable component (P06).
Alternative model	• A suitable model is searched for in the following ways: – Identification of an alternative functionality within the tool used; – Testing of different configurations of similar systems to determine whether the model behaves appropriately (P02, P06) – Use of the worst case scenario to predict the thermal building performance (P06); and – Request to software developers of the tool used to develop a new model (P04).
Assumptions	• Participants often use reasonable assumptions and adjustments based on e.g. available data sheets from product manufacturers as a workaround (P05, P07).
Alternative tool	• A participant use another or a combination of other tools as a workaround (P04).

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

Table 5.12: Comparison of participants' perceived and actual BPS tool capabilities.

Area	Participants' perceived BPS tool capabilities	Actual BPS tool capabilities
Flexibility	Limited flexibility in creating adaptive building envelope models (P04, P06, P07)	Limited flexibility in developing models for specific adaptive building envelope technologies (Loonen, Favoino et al., 2016)
Scripts	Different capabilities in linking BPS tools with scripts; EnergyPlus is linkable, but IES VE is not (P05)	Poor integration of scripts into the existing solvers of most BPS tools (Taveres-Cachat, Favoino et al., 2021)
Customisation	Limited support for customising control strategies (P02)	Limited support for representing different types and ranges of control strategies (Widl et al., 2014)
Parametric analysis	Limited testing of different design configurations through parametric analysis (P03)	Rare integration of SA, UA or optimisation methods in BPS tools for design decision support (Loonen, Favoino et al., 2016)

> '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).

While Python and MATLAB are used by two of the seven participants (P02, P05), the interview data suggest that the most widely used scripting method employed by participants is Grasshopper. 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 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).

Another workaround mentioned is post-processing, as most participants called it. By contrast with scripting, this workaround may introduce human error and be less repeatable (P02) but can also be conducted in IES VE. As shown in Figure 5.4, 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 a Microsoft 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

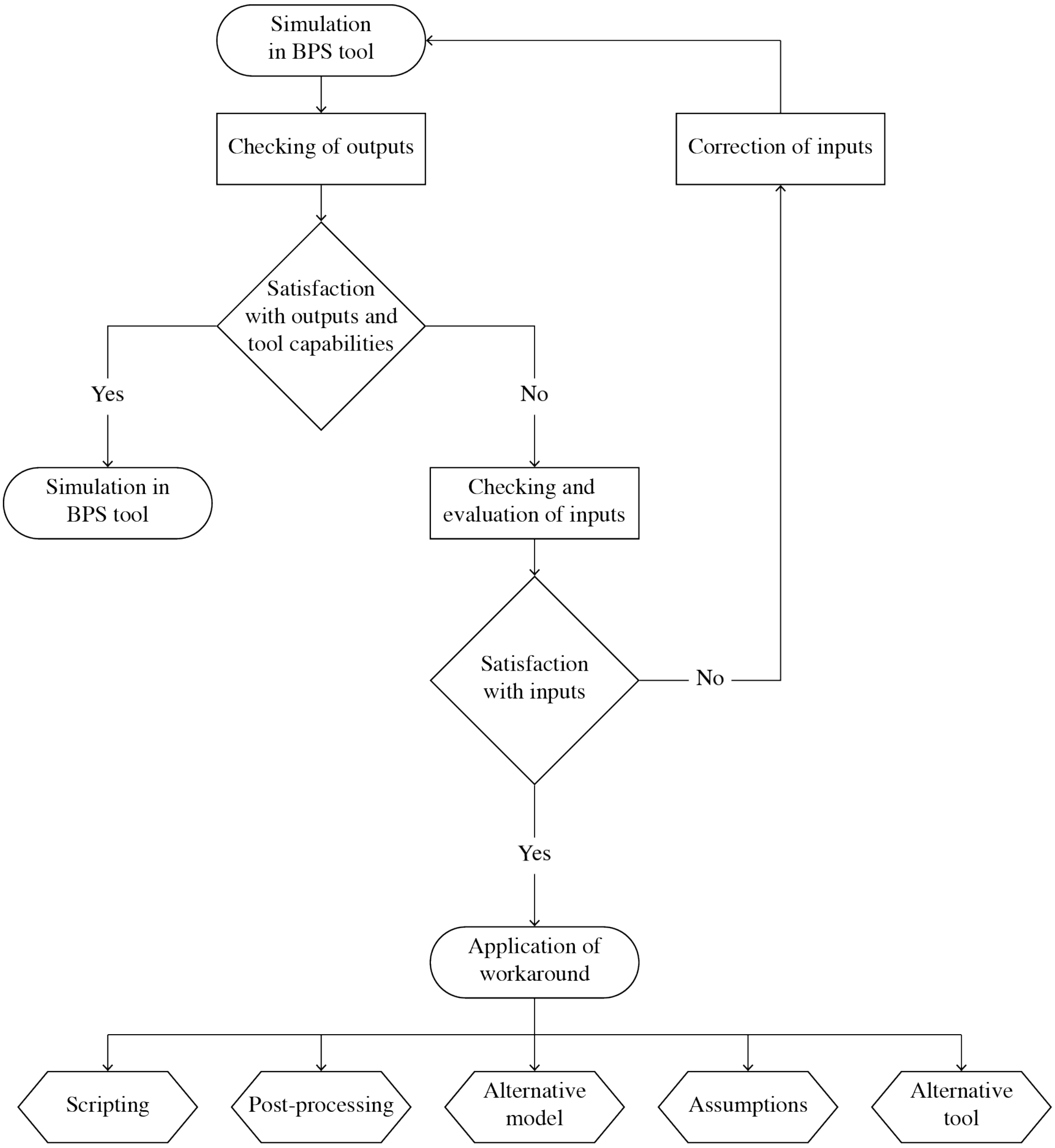

Figure 5.3: Process until decision for workaround is reached.

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).

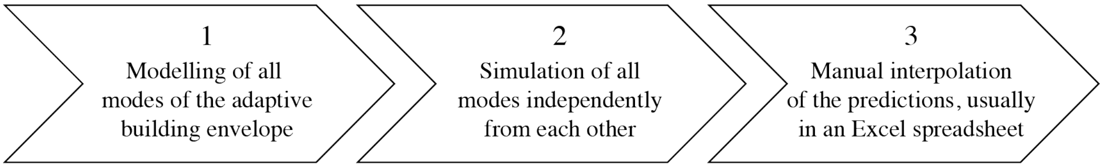

Figure 5.4: Steps of post-processing as workaround.

A workaround that has not been reported by participants is co-simulation. This method has been widely investigated in recent years (e.g. Loonen, Favoino et al., 2016; Borkowski, Donato et al., 2019) and 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. For more details on the performance of workarounds solutions, see Table 5.13.

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 interview 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 part of the 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

Table 5.13: Usefulness, reliability and modelling and computation time of workarounds.

Type	Description
Usefulness	• Previously applied workarounds are considered useful because they solve questions that cannot be answered with current BPS tools (P01, P02, P03). • Practitioners depend on the successful implementation of workarounds as they need them to obtain the analysis results required for the purpose of a project (P02). • A non-functional workaround would mean that the benefits of the adaptive components of the building envelope cannot be taken into account in the predictions (P06). • Adaptive building envelopes and workarounds should be implemented at the earliest possible design stage, as a project is always a compromise between flexibility and the client's needs, and flexibility in the early design stages outweighs the client's needs (P03).
Reliability	• Participants verify predictions of workarounds in the following ways: – **Four-eyes-principle:** Predictions are cross-checked with senior colleagues or specialists (P02, P05). – **Knowledge and experience by user:** Predictions are evaluated based on prior knowledge and experience (P01, P02, P03, P04, P05). – **Quality assurance of data:** Inputs and outputs are checked for quality (P02, P04, P05, P07), for example by checking inputs, plotting outputs to investigate relationships of variables and performing a sensitivity check (P05) or by ensuring that the correct information from product manufacturers is implemented in the tool (P07). – **Validation of workaround:** Workarounds are rarely validated in business organisations (P02) although they are perceived as uncertain and unreliable (P01, P03).
Time	• Even if developers create a workaround, it takes a long time to set it up and run it (P02). But the time required also depends on: – what needs to be calculated (P01, P04); – the level of complexity of the adaptive building envelope (P04); and – the building (P04). • Post-processing only slightly increases the time required, as the geometry input takes up most of the modelling time (P04).

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.

5.4.4 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 were of secondary importance (Table 5.14). 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) (Boeke, Knaack and Hemmerling, 2019).

Table 5.14: Detailed analysis of future tool developments.

Type	Description
Models for control systems	• Adequate models for control systems are required so that practitioners can better control the adaptive components of the building envelope in the model (P01, P02, P05, P06, P07). • Models for control systems are particularly important because of pressing building regulations that make the design of building envelopes more critical and that lead to an increased awareness of building performance (P01, P02). • Visualisations and animations would make it easier for practitioners and clients to understand the movable parts of a building envelope (P07).
Exchange and interoperability	• Future tool developments should offer improved possibilities for exchange and interoperability: – **Between design tools:** This includes efficient import/export possibilities for geometry or other relevant information, live updates between different tools such as BIM and BPS tools, and open source capabilities that allow project team members to remotely access and check a model (P05, P06, P07). – **Between BPS tools:** This includes efficient interoperation between tools used at different design stages, such as Sefaira for early design stages and IES VE for later design stages, or a tool that can be used in all design stages by providing different levels of accuracy (P01, P05).
Scripting	• Grasshopper and visual plug-and-play tools may influence the simulation of adaptive building envelopes in the future (P02), which may result in control systems that are flexible and applicable to more façade and building elements (P06, P07). • This assumption could soon become reality as companies hire more and more people capable of coding and scripting, and as widely-used tools like IES VE are opened up for scripting (P03, P06).
Tool capabilities	• Capabilities of future tool developments may provide: – flexibility to create different types of models (P04, P06, P07); – a good user manual to fully understand the physics behind a tool (P04); – transparency to be able to pay attention to every parameter during the simulation process (P04); – open source code (P04, P05); and – an error range in the predictions to show if something in a model goes wrong (P02).
Models for material and façade systems	• BPS tools already offer models for adaptive building envelopes to a certain extent, but not all components are currently supported in the same way, so they need to be integrated in more detail (P01, P02). • BPS tools need to implement additional models for adaptive building envelopes (P02, P03).
Tools	• Future tool developments may also include tools that are developed from scratch, such as suites of tools that address the various interactions of occupants, BMS, sensors, actuators, etc. (P02, P03) or tools specialised only in the analysis of the building envelope (P03), which could pave the way for a wider application of co-simulation (P04).
Parametric modelling and optimisation	• Another potential development in the future may be the introduction of parametric modelling and optimisation into common design and BPS tools (P01, P05).

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 E. Lee, 2011). For example, co-simulation allows to plug and play different simulators to identify optimised controller parameters for an adaptive building envelope. Graphical plug-and-play modelling is also promoted by tools like Modelica, 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:

- **Interoperability and adaptability:** Integration of different data and models, preferably from different design stages, into tools (P01, P02, P05, P06, P07), and implementation of parametric modelling and optimisation to enable users to understand model parameters (P01, P05).
- **Usability:** Accessible training and detailed documentation to facilitate understanding of tool capabilities (P02, P04), and tracking of parameters the tools use in modelling and simulation processes to enable users to understand codes and algorithms (P01, P04).
- **Performance:** A short model setup and simulation runtime to allow for quick results and decision-making (P02).

5.4.5 Implications of findings for future research and practice

This part of the 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 the interview 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 part of the research used the concept of software requirements (i.e. FRs and NFRs), which was already used in the literature review

(Section 3.4.1). The FRs and NFRs were subdivided following the same procedure as the FRs and NFRs in the literature review.

Figure 5.5 reveals that there are mainly NFRs and not FRs that future tool developments should take into account according to the feedback from participants. Although software developers tend to focus less on NFRs because they are difficult to test and validate, the interview 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 represents an excellent opportunity to be used in research on adaptive building envelope simulation (e.g. Borkowski, Donato et al., 2019).

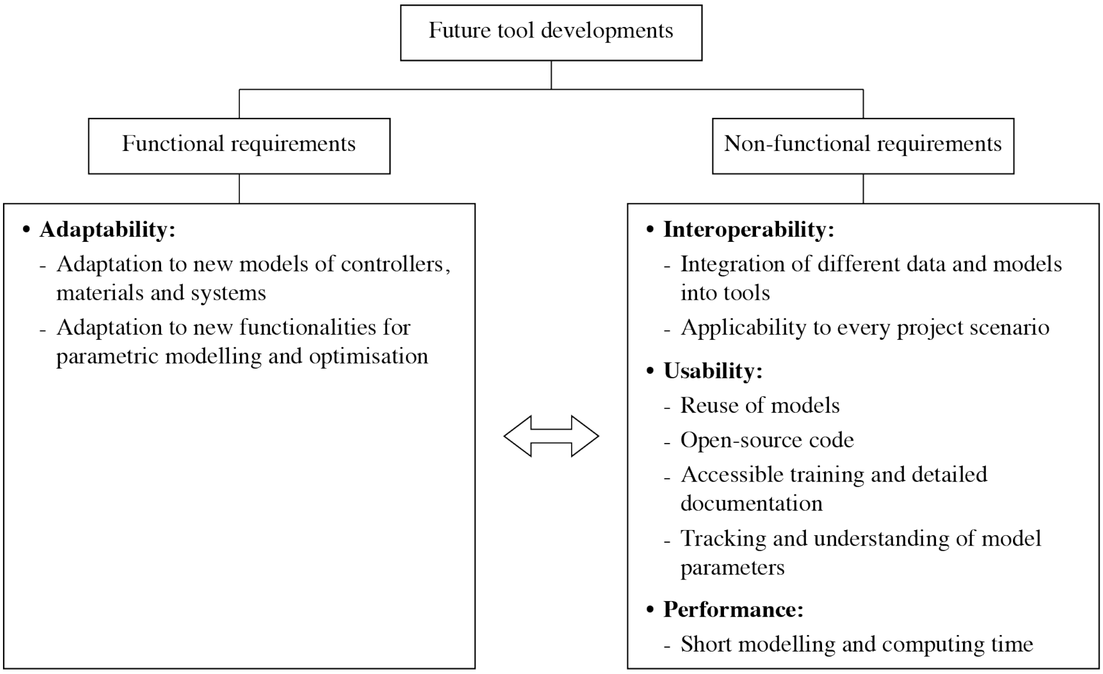

Figure 5.5: Implications for future tool developments.

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 part of the 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.

5.5 Chapter summary and implications for modelling approach

The interview 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 the findings, requirements for future tool developments were proposed that also meet the needs of the end users. The requirements identified overall support previous research, yet this work enhances the understanding of the requirements for future tool developments for adaptive building envelope simulation in two ways.

First, some of the requirements proposed in the interviews were more specific than those identified in previous studies. For example, the understanding of the interactions of component models, which was defined as a usability attribute in the literature review, was refined in the interviews by finding that the participants were referring primarily to a better tracking of the parameters used in the calculation procedures. This underlines the need for future tool developments for adaptive building envelopes to be more transparent, not only in terms of the relationships between the models, but also in terms of the relationships between variables in the model.

Second, one requirement that has not been identified in previous work but in the interview study was the performance attribute of future tool developments, i.e. a short model setup and simulation runtime. A possible reason why this was found in the interviews and not in previous studies could be the practical focus of the interview study, emphasising the importance for industry practitioners to get results and make decisions quickly. This indicates a gap between the requirements identified in research and those identified in industry practice, and highlights the need for more research-industry collaborations to promote knowledge transfer for successful exploitation of R&D results.

The requirements identified in this part of the study consequently made the picture of the requirements for future tool developments more specific and complete. In the next step of this research, the findings were used to inform the development of a potential modelling approach for the prediction of adaptive building envelope behaviour. In particular, the findings of the interview study have the following important implications for the development of the modelling approach:

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. Specific requirements identified in the SRS are:

- adaptation to new models of controllers, materials and systems;
- adaptation to new functionalities for parametric modelling and optimisation;
- integration of different data and models into tools; and
- applicability to every project scenario.

More accurate modelling approaches: A common view among interviewees was that the predictions of the more flexible modelling approaches are less accurate than those of existing BPS tools. To improve the reliability of predictions (i.e. the degree to which predictions can be made accurately), future modelling approaches need an increased level of transparency in their calculation procedures and accessibility to training and documentation in order to give users the best possible understanding and support in using tools. Specific requirements identified in the SRS are:

- open-source code;
- accessible training and detailed documentation; and
- tracking and understanding of model parameters.

More rapid modelling approaches: Practitioners are part of business organisations whose success is largely determined by the ability to make and execute key decisions quickly. Therefore, practitioners need modelling approaches that do not take too long to model and compute, which can be achieved by e.g. reusing models. Specific requirements identified in the SRS are:

- reuse of models; and
- short modelling and simulation time.

6 An integrated modelling approach for control and adaptive building envelope

This chapter proposes a solution for the integrated modelling of control and adaptive building envelope for thermal performance prediction. The development of the modelling approach followed the five phases of model integration proposed by Belete, Voinov and Laniak (2017) (see Section 3.1). This chapter describes how the development, guided by the findings in Chapter 5, went through the first four phases of (i) pre-integration assessment, (ii) model preparation for integration, (iii) orchestration of models during simulation and (iv) data interoperability. The fifth phase, the testing, is covered in the following chapters.

6.1 Pre-integration assessment

The modelling approach aimed to establish a link between component models to accurately represent the whole-building simulation of the thermal performance of adaptive building envelope and control. Specifically, the objectives were to develop an integrated modelling approach to accurately predict the thermal performance of adaptive building envelopes and their operation strategies and to implement possibilities for conducting SA, UA and optimisation to test models and derive their accuracy. As the research progressed, it was equally important to validate (Chapter 7), further develop and test the proposed modelling approach (Chapter 8), thus using information from empirical and statistical approaches and to model and simulate the complex interactions and trade-offs based on problem-specific approaches.

The development of the modelling approach was guided by the FRs and NFRs identified in the literature review (Chapters 2 and 3) and in the interview study (Chapter 5), as shown in Table 6.1. When developing the modelling approach, it was also key to include capabilities that allow users to create adaptive building envelope models using either a mono-simulation or a co-simulation setup, depending on the building envelope's complexity. The reason for this was that previous studies have shown that both approaches are capable of modelling adaptive building envelopes. However, the creation of possibilities for co-simulation of adaptive building envelopes in the modelling approach was particularly important. Although the use of co-simulation is not new in itself, its capabilities for the integrated modelling of the phenomenon under study have not yet been sufficiently explored.

The whole-building simulation model for predicting the thermal performance of the adaptive building envelope together with the control was broken down into three component models to be included in the modelling approach, namely (i) the building model, (ii) the

Table 6.1: Requirements to be addressed by modelling approach.

Requirement	Attribute	Description
FRs	Accuracy	The modelling approach should ensure validity and quality assurance of simulation outputs.
	Adaptability	The modelling approach should be able to adapt to changing requirements and to accommodate different purposes by multiple users and design phases.
	Design decision support	The modelling approach should allow users to perform SA, UA and optimisation.
NFRs	Interoperability	The modelling approach should allow for low and high resolution models so it can be used in all design phases.
	Availability	The modelling approach should be operational and accessible when required through reusability.
	Usability	The modelling approach should enable users to understand the interactions of the component models through the decomposition of the building system into subsystems and to perform their tasks through documentation and online help.
	Performance	The modelling approach should have a short modelling and computing time.

building envelope model and (iii) the controller model. To represent the interactions between the component models, the modelling approach was built on different software that was measured against the list of requirements and then selected according to their capabilities to satisfy the list. The main pieces of software adopted were EnergyPlus, the FMI Standard and Modelica to deliver the following functions:

- **EnergyPlus:** Integration of EnergyPlus v8.9.0 to create the thermal model of the building and the building envelope.
- **FMI Standard:** Integration of the FMI Standard v2.0 to exchange information at each simulation timestep between EnergyPlus and Dymola.
- **Modelica:** Integration of Dymola v2020x (Dassault Systèmes, 2020), a commercial modelling and simulation programme that provides a graphical frontend for models implemented in the Modelica language v3.4, to create the model of the controller.

Reasons for their selection are listed in Table 6.2. With this selection, the proposed modelling approach also address the three gaps identified in the interview study in terms of (i) flexibility, (ii) accuracy and (iii) rapidness. However, in relation to these gaps, there are also some important limitations of the modelling approach that need to be taken into account and that are subsequently discussed together with how the modelling approach addresses these gaps:

- **Flexibility:** The use of the FMI Standard as a non-proprietary industry standard may enable the integration of other tools that are compatible with it. An up-to-date list of FMI-compatible tools can be found on the FMI Standard website[1]. However, BPS tools often lack interfaces, and currently there are only a two BPS tools that are compatible with the FMI Standard, namely EnergyPlus and TRNSYS. This may inhibit the integration of other BPS tools into the modelling approach, hence imposing a coupling barrier on the modelling approach and limiting its use in practice.

- **Accuracy:** The modelling approach integrates EnergyPlus, which is generally considered to be the current state-of-the-art in thermal building performance simulation. However, despite EnergyPlus' integration into the modelling approach, co-simulation setups may be uncertain in terms of accurate predictions as they couple tools whose data exchange and format conversion differ from setup to setup. Another potential shortcoming of the modelling approach is the use of Dymola and Python, which may be unfamiliar to many practitioners and require a high level of expertise. This may lead to diminished confidence in the predictions of the modelling approach in practice.
- **Rapidness:** No significant benefits of using the modelling approach in terms of rapidness were found. By contrast, a limitation of co-simulation may be an increase in computation time compared to mono-simulation, partially due to the communication overhead between the simulators (Sagerschnig et al., 2011). However, this crucially depends on the coupling strategy and timestep (Trčka, Hensen and Wetter, 2009). Another limitation of co-simulation setups may be the lack of a standard systematic approach, which may lower the efficiency in terms of time improvement.

Table 6.2: Key reasons for selection of software adopted in modelling approach.

Software	Reason for selection
EnergyPlus	• General acceptance of performance reflecting the current state-of-the-art in thermal building performance simulation. • Export of model as FMU through EnergyPlusToFMU (Nouidui, Lorenzetti and Wetter, 2020), providing an interface to external software through the FMI Standard. • Parsing of input files, i.e. IDD and IDF files, and their integration into the Python data structure.
FMI Standard	• A non-proprietary industry standard. • Elimination of additional socket-based transaction layer, introduced e.g. in the communication between different simulators in BCVTB that increases overheads (Sagerschnig et al., 2011). • Possible integration of other FMI-compliant tools.
Modelica	• The Modelica modelling language has many advantages (Table 3.8), two of which are: – Decomposition of complex models into easily readable and understandable sub-models. – Deployment of a graphical frontend for models to potentially improve usability for users without prior Modelica knowledge.

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[1] https://fmi-standard.org/tools/

In addition, the modelling approach integrated Python v3.8.5 to manage and automate the overall workflow. As the number of Python files grew over the course of this study, they were packaged and stored in a new Python package called `cosim`. Python was chosen as it allows modular programming, which means that a large, bulky programming task could be broken down into individual, smaller, more manageable sub-tasks or modules. Because of `cosim`, new functionality could not only be integrated more easily and less error-prone, but could also be easily reused by other parts of the modelling approach without duplicating code.

The `cosim` package in Python is composed of different sub-packages and modules, as shown in Figure 6.3. Each (sub-) package contains a __init__.py file to enable Python to consider a (sub-) package as a package. A technical overview of `cosim` is provided in Appendix B, and the source code of `cosim` has been published on Github through the data archiving tool Zenodo[2] (Borkowski, 2021).

Table 6.3: Structure of `cosim` Python package.

Sub-package	Module	Description
model	__init__.py	–
	simulate.py	This module contains the class `simulate(output_dir, s_start=0, s_stop=31536000, s_step=600)` that can be used to run a model from (i) a co-simulation in EnergyPlus and Dymola through the FMI Standard or (ii) a mono-simulation in EnergyPlus.
output	__init__.py	–
	export.py	This module contains two classes: (i) the class `idf_to_fmu` can be used to create an FMU for co-simulation from an EnergyPlus IDF file using the FMI Standard v2.0 and (ii) the class `mat_to_csv` can be used to export a .mat output file from a Dymola simulation to a .csv file.

The proposed modelling approach has been mainly tested on control strategies for multi-functional shading systems, which are commonly used in practice as they represent a cost-effective solution that is well in line with current building practices (Loonen, Favoino et al., 2016). However, it could easily be extended to other use cases, which will be further explained in the following sections.

6.2 Model preparation for integration

Preparing a model component for integration depends primarily on the way inputs are organised and distributed. The inputs of the modelling approach are the individual component models, and they should be 'syntactically interoperable, i.e., data produced by one model are converted and formatted to serve as input for a receiving model' (Belete, Voinov and Laniak,

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[2] https://doi.org/10.5281/zenodo.4710631

2017, p. 50). In order to create syntactically interoperable component models, two models have to be prepared: (i) the thermal model of building and building envelope in EnergyPlus and (ii) the model of controller in EnergyPlus, Dymola or a third-party tool. The preparation of the component models is discussed in detail below.

6.2.1 Thermal model of building and building envelope

The thermal model of the building and the building envelope is developed in EnergyPlus. In addition to the simulation specific parameters and weather data, the input data include thermal model input data (e.g. building geometry, constructions, internal loads) and airflow model input data (e.g. infiltration, ventilation). HVAC model input data (e.g. HVAC systems, operating strategies and schedules) and occupancy model input data (e.g. occupancy pattern and schedules) can be modelled either in EnergyPlus or in a separate tool to potentially benefit from the modelling approach that links modular problems.

Once the thermal model is created, it is recommended to run a simulation to check the model for errors and inconsistencies. This checking primarily aimed at ensuring that the model is properly set up (syntactic checking), not that it captures the building dynamics correctly.

If the modeller chooses to model the controller in Dymola and to perform a co-simulation, the external interface of EnergyPlus has to be activated, which allows an EnergyPlus model to be linked to an external model through the FMI Standard. With the `ExternalInterface` input object present, the values listed in the object exchange their input/output signals with the FMI Standard at each zone timestep. Figure 6.1 shows the EnergyPlus input objects to which the external interface can map input/output signals.

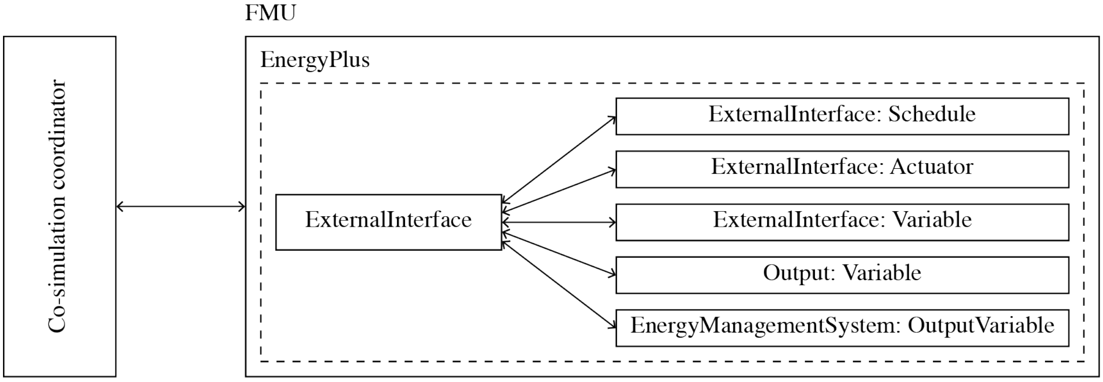

Figure 6.1: Mapping of input/output signals in EnergyPlus.

To override and set control actions elsewhere in the EnergyPlus model, the input signals can be written from the external interface to built-in EMS actuators. The overridable building envelope models in EnergyPlus can be seen from Table 6.4. New actuators are added from time to time or may be added through changes in the source code.

Table 6.4: EMS actuators to control thermal building envelope models in EnergyPlus.

Actuator	Control Type
Window Shading Control	Control Status [ShadeStatus] Slat Angle [°]
Surface Convection Heat Transfer Coefficient	Interior Surface Convection Heat Transfer Coefficient [W/m^{2}K] Exterior Surface Convection Heat Transfer Coefficient [W/m^{2}K]
Material Surface Properties	Surface Property Solar Absorptance [-] Surface Property Thermal Absorptance [-] Surface Property Visible Absorptance [-]
Surface Construction State	Construction State
Surface Boundary Conditions	Convection Bulk Air Temperature [°C] Convection Heat Transfer Coefficient [W/m^{2}K] Radiation Effective Temperature [°C] Radiation Linear Heat Transfer Coefficient [W/m^{2}K]

Another important decision in the EMS scripting feature is when to run the ERL script, which is done via EMS calling points. The recommended calling point for building envelopes is `BeginTimestepBeforePredictor`, which occurs near the start of each timestep but before the predictor is executed, i.e. the step in which the zone loads are calculated. It can thus be used to actuate components based on the results of the previous timestep. More information on the external interface and the EMS feature of EnergyPlus can be found in the EnergyPlus documentation (e.g. DOE, 2018a,c).

6.2.2 Model of controller

The controller model can be developed either in the EMS scripting feature of EnergyPlus, in Dymola or in a third-party tool. The `cosim` package currently only supports the first two options, although the code can be easily adapted or extended to the user's needs:

EMS scripting feature: If the controller model is developed in the EMS feature, the following EnergyPlus objects have to be defined: (i) the `EnergyManagementSystem:Sensor` object to retrieve information from elsewhere in the model for use in control calculations, (ii) the `EnergyManagementSystem:Actuator` object to initiate control actions, (iii) the `EnergyManagementSystem:ProgramCallingManager` object to specify when to execute an ERL programme and (iv) the `EnergyManagementSystem:Program` object to define control strategies with IF-THEN statements. The *Application Guide for EMS* provides a comprehensive overview of how to develop custom control routines for EnergyPlus models (DOE, 2018a).

Dymola: If the controller model is developed in Dymola, fundamental components can be taken from the Modelica Standard Library (Modelica Association, 2019), a free library developed by the Modelica Association and supplied with Dymola. It contains (i) components for modelling mechanical, electrical, thermal, fluid, control systems and hierarchical state machines, (ii) numerical functions and (iii) functions for handling strings and files. After creating the model, it is recommended to run Dymola's `check` command to perform some symbolic and syntactic checks on the model.

Third-party tool: If the controller model is developed in a third-party tool, it can be linked to the EnergyPlus model either directly or via Dymola. One possible way to interact with EnerygPlus is through the EnergyPlus API, which is available from EnergyPlus v9.3 and can be used from e.g. C and Python (DOE, 2020). It is also possible to use the co-simulation setup and go via Dymola. In this case, a source component, i.e. a block that generates a constant output signal (`Modelica.Blocks.Sources.Constant`), has to be created in Dymola. This block can then be overridden with a set of controller parameters obtained by the third-party tool.

6.3 Orchestration of models during simulation

To manage interactions between the components models, the overall workflow to be implemented had to be defined. In the mono-simulation, EnergyPlus handles the models automatically. EnergyPlus links many routines that are integrated and controlled by a solution manager that solves them simultaneously. It consequently interprets and executes the ERL script with the control strategy while the model is running (DOE, 2018b).

In the co-simulation, by contrast, the component models are orchestrated by the FMI Standard, as presented in Figure 6.2. The FMI Standard uses a component-based approach to integrate models (Belete, Voinov and Laniak, 2017). It is based on the principle that an all-inclusive model is decomposed into sub-models with standard interfaces. This means that a model, which implements the FMI Standard, can communicate with other FMI-compatible models. As a result, components that are written in different languages but support the standard can join the integrated simulation system.

Component models are imported into Dymola, the co-simulation coordinator, and then connected. When an FMU is imported into Dymola for the first time, it has to be connected manually to exchange variables or signals with another model part. This can be done by using Dymola's graphical frontend and plug-and-play approach. To load the FMU automatically when Dymola is called from Python, the personal setup file *startup.mos* in Dymola has to be modified as shown in Source code 6.1. This setup file ensures that Dymola always loads the FMU when opened. Otherwise, Dymola cannot find the FMU when called from Python and reports an error.

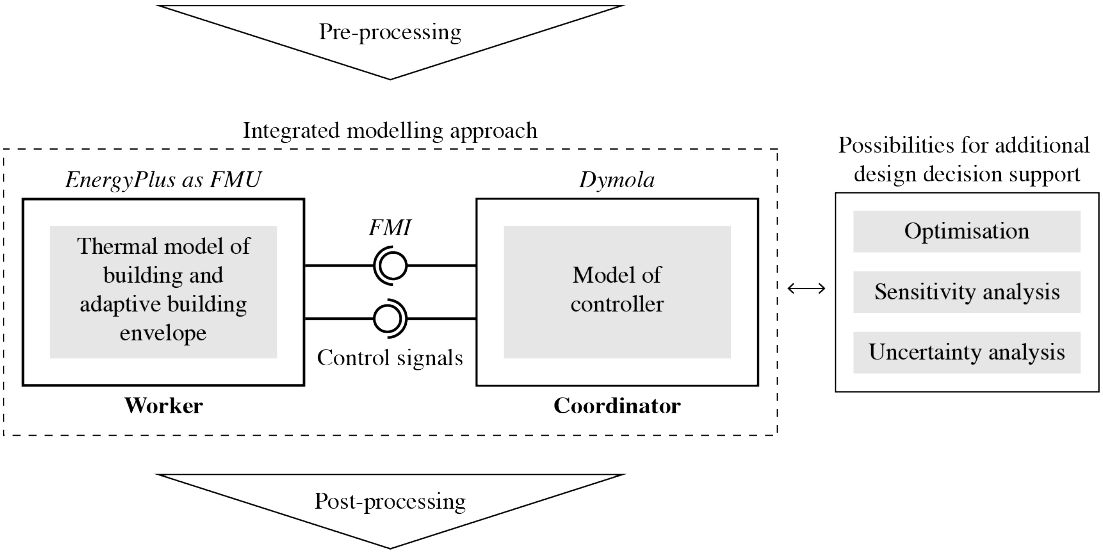

Figure 6.2: Co-simulation setup of modelling approach.

Source code 6.1: Personal setup file in Dymola to automatically load FMU.

```
importFMU("/etc/my_fmu.fmu", true, false, false, "");
```

The workflow is executed by calling either the `monosimulate` or the `cosimulate` function of the `model` class of the simulate.py module. On the one hand, the `monosimulate` function can be called as shown in Source code 6.2 and returns a eplusout.csv file to the output directory. On the other hand, the `cosimulate` function simulates the co-simulation model through the `Simulator.simulate()` method of the BuildingsPy package (LBNL, 2019). It can be called as shown in Source code 6.3 and returns a .mat file generated by Dymola to the output directory. The .mat file can then be exported to a .csv file using the `mat_to_csv` class of the `export` module of the export.py module.

Source code 6.2: Usage of `monosimulate` function of `model` class.

```
from cosim.model.simulate import simulate

m = {'eppy_path': '/etc/eppy', 'idd_file': '/etc/EnergyPlusV8-9-0/Energy+.idd',
↪  'epw_file': '/etc/my_weather.epw', 'idf_file': '/etc/my_model.idf', 'leap_year':
↪  True}

model = simulate(output_dir='/etc/my_output_dir', s_step=3600)
model.monosimulate(**m)
```

Source code 6.3: Usage of `cosimulate` function of `model` class.

```
from cosim.model.simulate import simulate

m = {'model_name': 'my_model', 'show_gui': True, 'exit_simulator': False}
```

```
model = simulate(output_dir='/etc/my_output_dir', s_step=3600)
model.cosimulate(**m)
```

6.4 Data interoperability

As explained earlier (Section 3.3.1), the FMI Standard ensures that data exchanged between workflow components are interpreted correctly by being semantically and structurally interoperable. The only component that has to be made compatible with the FMI Standard in the co-simulation setup of the modelling approach is the EnergyPlus model.

To encapsulate and share the EnergyPlus model, the modelling approach employs an FMU. An .fmu file is a distributed zip file containing (i) an XML file with, amongst others, the definition of the variables used by the FMU, (ii) all equations used by the model and (iii) optional other data that are required by the model. The modelling approach uses the class `idf_to_fmu` of the export.py module in Python to invoke the software package EnergyPlusToFMU and to create an FMU for co-simulation. The `idf_to_fmu` class contains the function `export` to create the FMU from the EnergyPlus model. It can be called as shown in Source code 6.4 and returns an .fmu file written to the current working directory.

Source code 6.4: Usage of `export` function of `idf_to_fmu` class.

```
from cosim.output.export import idf_to_fmu

idf_for_export = idf_to_fmu('/etc/EnergyPlusToFMU.py',
↪  '/etc/EnergyPlusV8-9-0/Energy+.idd', '/etc/my_weather.epw', '/etc/my_model.idf')
idf_for_export.export()
```

Output data are stored in a .csv file for further use in an external data analysis programme or directly in Python. In Python, it is possible to use, for example, the Python packages Matplotlib (Hunter, 2007) for plotting, Scipy (Jones, Oliphant, Peterson et al., 2011) and Numpy (Oliphant, 2006) for scientific computing or Pandas (McKinney and PyData Development Team, 2019) for data manipulation and analysis.

6.5 Chapter summary

Guided by the previously identified FRs and NFRs, the aim of the modelling approach was to establish a link between component models to accurately represent the whole-building simulation of the thermal performance of adaptive building envelope and control in a mono-simulation or a co-simulation setup. For the representation of the interactions between the component models, the modelling approach was based on different software that was measured against the list of requirements and then selected according to their capabilities to fulfil the list. The main pieces of software adopted were EnergyPlus, the FMI Standard and Modelica, implemented in Dymola. In addition, Python was integrated in the modelling approach to manage and automate the overall workflow. As the number of Python files grew over the course of this study, they were packaged and stored in a Python package called `cosim`.

7 Validation of adaptive building envelope performance in modelling approach

A key issue identified in the interview study was that future tool developments need a high level of accuracy in their predictions. As a consequence, this chapter assesses the accuracy of the proposed modelling approach for predicting the thermal performance of adaptive building envelopes together with the control. For the assessment of the accuracy of the modelling approach, validation techniques were used. Validation may be defined as the process of determining the degree to which a numerical model accurately represents the real world. In the validation process, verification played a key role in order to confirm that the model was implemented correctly.

The work presented in this chapter was part of a collaboration with Alessandra Luna-Navarro, PhD Candidate at the University of Cambridge. The collaboration resulted in two journal articles (Borkowski, Luna-Navarro et al., 2021; Luna-Navarro, Borkowski et al., 2021), which are currently under review. The work included in this chapter was mainly carried out by this thesis' author. The only contribution of Alessandra Luna-Navarro was the collection, storage and sharing of the empirical data.

7.1 Background: validation methodology

To check for errors or inaccuracies in a BPS tool, Judkoff and Neymark (2006) suggested three validation techniques:

- **Analytical verification:** Comparison of tool outputs to outputs from a commonly accepted numerical method for an isolated physical phenomenon.
- **Comparative testing:** Comparison of tool outputs to outputs from another tool commonly accepted to represent the state-of-the-art.
- **Empirical validation:** Comparison of tool outputs to measured data from e.g. a test cell.

Table 7.1 compares the advantages and disadvantages of these techniques. While analytical verification 'is limited to simple cases for which analytic solutions are known' (2009, p. 63), it provides a mathematical truth standard that tests the solution process but not the appropriateness of a model (Judkoff and Neymark, 2006). Rather, it helps identify and diagnose sources of error or inaccuracy in a tool, similar to comparative testing.

To evaluate the ability of a tool to analyse real physical behaviour, empirical validation is required to establish a truth standard (Neymark et al., 2002). However, empirical validation

Table 7.1: Advantages and disadvantages of validation techniques (Judkoff and Neymark, 2006, p. 3).

Technique	Advantages	Disadvantages
Analytical *Test of solution process*	• No input uncertainty • Exact mathematical truth standard for the given model • Inexpensive	• No test of model validity • Limited to highly constrained cases for which analytical solutions can be derived
Comparative *Relative test of model and solution process*	• No input uncertainty • Any level of complexity • Many diagnostic comparisons possible • Inexpensive and quick	• No absolute truth standard (only statistically based acceptance ranges)
Empirical *Test of model and solution process*	• Approximate truth standard within experimental accuracy • Any level of complexity	• Experimental uncertainties • Expensive and time-consuming measurements • Only a limited number of practical test conditions

studies often exclude ‘the characterization of some of the more complex physical processes’ (Beausoleil-Morrison et al., 2009, p. 64) due to measurement difficulties and uncertainties. In fact, empirical validation only tests the solution process and appropriateness of a BPS tool within (i) its domain of applicability (Sargent, 2013) and (ii) the range of experimental uncertainty (Coakley, Raftery and Keane, 2014).

7.2 Specification of validation strategy

The validation study was designed to determine whether the modelling approach can accurately predict the performance of control strategies for adaptive building envelopes. Prior to developing a validation strategy for this part of the study, the aspects of the modelling approach that needed to be tested were identified. This was done to ensure that each aspect of the modelling approach was investigated, and the aspects are shown in Table 7.2.

However, as three of the aspects of the modelling approach have already been investigated in previous studies (Table 7.2a), they were not tested again in this part of the study. Two of these already-tested aspects were, for example, (i) the numerical solver and (ii) the solver tolerance. The numerical solver is used by a Dymola simulation to perform a numerical integration by computing the state derivatives of the model. It is relevant for a Dymola simulation as it translates the model into an appropriate representation suitable for the numerical simulation (Matei and Bock, 2012). The solver tolerance is used by a Dymola simulation to determine the accuracy with which a model is solved (K. Wang et al., 2017). It consequently affects the numerical approximation of a simulation in Dymola, while the numerical solver only affects the computation time, but not the numerical approximation (Wetter, Zuo and Nouidui, 2011).

Table 7.2: Aspects of modelling approach requiring testing.

(a) Aspects tested in previous research.

Aspect	Description and relevance for present research of test
FMU generation	Nouidui and Wetter (2014) tested EnergyPlusToFMU to export an EnergyPlus model as an FMU for co-simulation: → **Relevance for present research:** Use EnergyPlusToFMU to export the EnergyPlus model as an FMU for co-simulation
Numerical solver	Wetter, Zuo and Nouidui (2011) tested the effect of the selected numerical solver in Dymola on the numerical approximation: → **Relevance for present research:** Ignore the selection of the solver, as it only affects the computation time, but not the numerical approximation
Solver tolerance	Wetter, Zuo and Nouidui (2011) tested the effect of the selected solver tolerance in Dymola on the numerical approximation: → **Relevance for present research:** As the solver tolerance affects the numerical approximation, follow the suggestion by Jorissen et al. (2018), who simulated different building models with Dymola, for the selection of the solver tolerance

(b) Aspects tested in present research.

Aspect	Description and expected outcome of test
Coupling data	Testing the data dependencies and the data transfer between the coupled simulators: → **Expected outcome:** Establishing the correctness of the implementation and execution of the coupling data
Subroutines	Testing the interconnections between subroutines at the whole building level: → **Expected outcome:** Establishing the accuracy of the modelling approach within its domain of applicability
Coupling frequency	Testing various time integration schemes, which depend on the rate of change of the inputs acting on the variables, to guarantee accuracy and stability of the modelling approach: → **Expected outcome:** Establishing the required coupling frequency for the domain of applicability

Finally, two important limitations needed to be considered when developing the validation strategy. First, there was no known analytic solution for the phenomenon under study[1], and it was therefore not possible to perform an analytical verification. Fortunately, this lack of an analytic solution could be ignored by using comparative testing, which helps to identify and diagnose sources of error or inaccuracy in a BPS tool, similar to analytical verification. Second, conducting comparative testing, which requires the use of a tool commonly accepted to represent the state-of-the-art, was complicated by the challenging representation of control strategies for adaptive building envelopes in existing BPS tools. In order to nevertheless perform comparative testing, only control strategies that could be modelled in existing BPS tools were used in the test procedures.

Following the identification of the aspects of the modelling approach that had to be tested and the limitations, a test plan was developed. It was designed to exercise a certain grouping of tests subdivided by the different aspects of the modelling approach. Table 7.3 presents the test plan developed by detailing the objectives, procedures and resources for each specific test required for the validation of the modelling approach.

Table 7.3: Test plan for validation of modelling approach.

Test	Objective	Procedure	Resources
1.	Testing the data dependencies and the data transfer between the coupled simulators	• Comparative testing • UA	• Computer with tools required by modelling approach
2.	Testing the interconnections between subroutines at the whole building level	• MCSA • Empirical validation • UA	• Empirical data • Computer with tools required by modelling approach • Research computing cluster
3.	Testing various time integration schemes	• Comparative testing • UA	• Computer with tools required by modelling approach

The validation strategy was subsequently developed based on this test plan. It combined empirical and non-empirical validation techniques to offset the disadvantages of one validation technique with the advantages of another (Judkoff and Neymark, 2006). The two-part strategy comprised empirical and comparative techniques and is shown in Figure 7.1. Empirical validation, while required for the analysis of real physical behaviour, often excludes the characterisation of some more complex physical processes. In this case, comparative tests

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[1] There is a test suite developed within IEA 34/43 Project C that contains analytical solutions for various window and shading combinations (Loutzenhiser, Manz and Maxwell, 2007). The only relevant test case for the validation study would have been case 6 with a glazing unit and an external venetian blind with a time-scheduled control strategy (from horizontal to tilted downwards at 45° on 15 August 2005 at 7:00). However, preliminary tests revealed identical or near-identical predictions of the modelling approach and the test suite. The reason for this could be that both tools had implemented similar mathematical models. While this highlighted that the modelling approach is generally correct and plausible, the test suite was considered insufficient to investigate control strategies for adaptive building envelopes in detail.

are more useful as they help to identify and diagnose sources of error or inaccuracy in the modelling approach by providing a truth standard using statistically based acceptance ranges that test the solution process. Empirical data were collected from MATELab, an outdoor test cell for occupant-façade interaction in Cambridge, UK (Luna-Navarro and Overend, 2021). In recent years, the performance of adaptive building envelopes has been increasingly tested in outdoor test cells (Cattarin et al., 2018). New test cells, in particular, have been developed to evaluate occupants' perception of and behaviour with building envelopes under real weather conditions and realistic indoor conditions (e.g. internal fittings and geometric dimensions). In this validation study, these types of test cells are referred to as *realistic* test cells. This new type of test environment provides better control than field studies in real buildings (Luna-Navarro, Borkowski et al., 2021) and allows the performance of the building envelope to be tested under real weather conditions and realistic interior features. However, the thermal performance of these realistic test cells is typically less accurate and controlled than traditional outdoor test cells because they are not calorimetric or guarded, but typically have a flexibly configurable building envelope that allows alternative building envelope technologies to be tested under different orientations and Window-To-Wall Ratios.

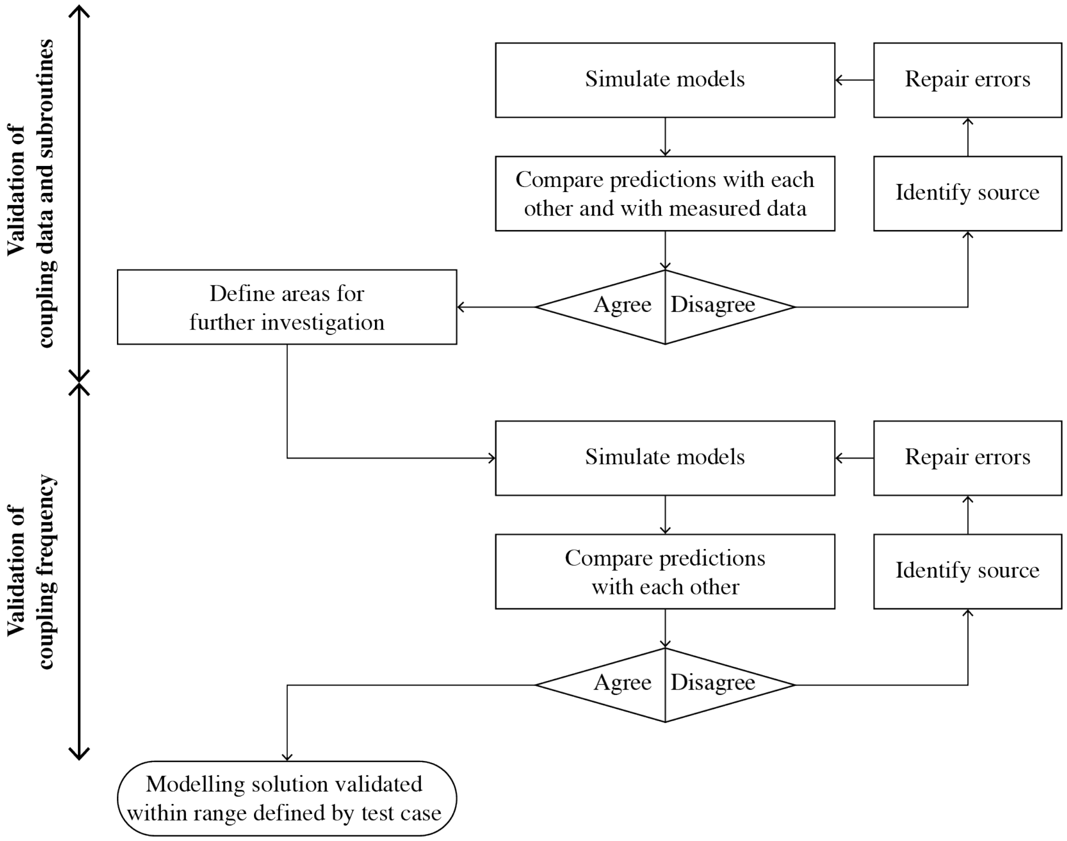


Figure 7.1: Validation strategy.

Each part was constructed to isolate a specific aspect of the modelling approach in order to examine, collectively, every aspect of the modelling approach. The first part tested the coupling data and subroutines (1. and 2. in test plan), and the second part tested the coupling frequency (3. in test plan):

Validation of coupling data and subroutines: The empirical validation aimed to test the implementation and execution of the data between the coupled simulators, thus helping to investigate the solution process and appropriateness of the modelling approach at the whole building level. This was achieved by comparing the simulation-predicted data points from the modelling approach and another tool, which is commonly accepted as the state-of-the-art, with the measured data points from MATELab. Also, the empirical validation was used to identify discrepancies in the predictions of the modelling approach in order to highlight areas for further investigation as the validation study progressed.

Validation of coupling frequency: The predicted data points from the modelling approach were compared with those from another tool that is generally accepted to represent the state-of-the-art to determine the required time integration scheme for an accurate and stable simulation of control strategies for adaptive building envelopes in the modelling approach.

This validation strategy allowed to test the solution process and the appropriateness of the modelling approach within the range of experimental uncertainty (Beausoleil-Morrison et al., 2009). Hence, it could conceivably be hypothesised that the model created in the modelling approach is valid for the set of experimental conditions if the accuracy of the model required for its intended purpose is within a satisfactory range of accuracy.

A research computing cluster was used in this part of the study. Although the use of the research computing cluster was not necessary for the cases studied in the validation study, its use was necessary for conducting a MCSA to inform the verification of the model of MATELab. Testing the modelling approach on the research computing cluster may also provide valuable insights for other use cases that may be tested in the future.

7.3 Methodology

Figure 7.2 presents the steps of this part of the study to validate the modelling approach. Firstly, the testing scenario was defined, and the experimental data were collected accordingly. The thermal model of MATELab, developed in EnergyPlus by Luna-Navarro, Borkowski et al. (2021), was then extended through including a control strategy for the building envelope in the form of an automation system for internal venetian blinds. The control strategy was implemented in Dymola and then linked to the existing model of MATELab in the modelling approach. The control strategy was also modelled in the EMS scripting feature of EnergyPlus to compare outputs of the modelling approach to outputs from another tool, which is commonly accepted to represent the state-of-the-art, and to identify and diagnose sources of error or inaccuracy in the modelling approach. After setting up the models, a MCSA was performed to inform the verification of the model of MATELab. The MCSA used the controller model developed in the EMS feature to keep the computational time as short as possible. The predicted data were then compared with the experimental data and the model was validated. Finally, areas for further investigation were identified and various time integration schemes were tested through inter-tool comparisons. The following sections give detailed information on each of the steps of the workflow.

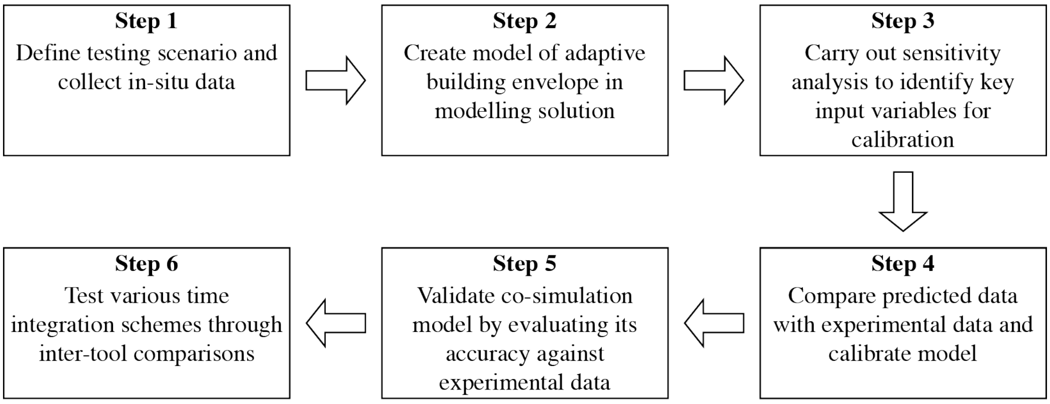
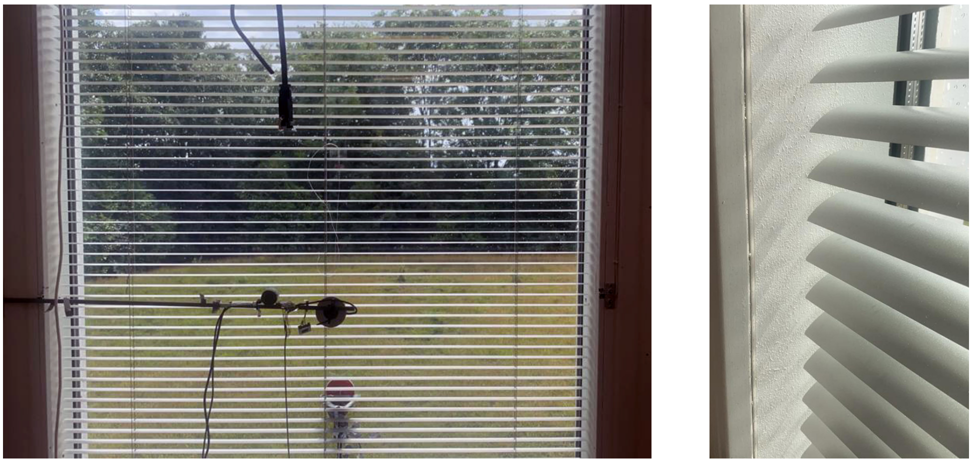


Figure 7.2: Steps involved in validation of modelling approach.

7.3.1 Description of test scenario

MATELab is a 30 m^2 office-like test facility, designed to investigate occupant responses to different adaptive building envelope technologies. It has a modular glazed building envelope oriented to the east, south and west providing the opportunity of testing three different façade bays per orientations. Each façade bay has a maximum dimension of 1.5 m by 2.3 m and has been designed to be easily installed and replaced so that different building envelope technologies can be investigated in a relatively short period of time. In addition, each of the façade bays can be covered with obscuring façade cover panels made of highly insulated external and corresponding internal plasterboard panels to generate a broad range of glazing orientation scenarios. For the validation study, the east and west glazing panels were covered with the obscuring façade cover panels internally and externally, thereby generating a south-facing glazed façade scenario. The south-oriented glazing consisted of two high-performance Double-Glazed Units and internal automated venetian blinds, as shown in Figure 7.3. This setup resulted in a Window-To-Wall Ratio of approximately 0.5 on the south-oriented façade.

The decision to cover the south façade instead of the east/west façade may have affected the monitored variables. For instance, solar gains were higher on the south façade than on the east/west façade. Since the control algorithm was based on the solar irradiance, this would mean that blinds on the east/west façade would be closed less often than blinds on



(a) View from inside to outside through blind with installed sensors.

(b) Detailed view of blind slats.

Figure 7.3: Views of blind installed in MATELab.

the south façade (assuming the control threshold is the same), which would increase indoor air temperatures. While indoor air temperatures are important for building designers to assess the thermal comfort of occupants, the assessment of other comfort aspects, such as visual comfort, are equally important for a successful façade design, e.g. to analyse glare and daylight levels.

A full description of MATELab can be found in Luna-Navarro, Borkowski et al. (2021), and Table 7.4 lists the physical parameters of MATELab, most of which correspond to those of Luna-Navarro, Borkowski et al. (2021).

Table 7.4: Physical parameters of MATELab.

Parameter	Condition
Glass façade	U-value: 1.1 W/Km^2
	Solar heat gain coefficient: 0.31
	Visible transmittance: 0.50
Opaque wall	U-value: 0.175 W/Km^2
Internal blinds	Slat width: 0.035 m
	Slat separation: 0.03 m
	Solar reflectance: 0.65
Occupancy	None
infiltration flow rate	0.0008 m^3/s per zone floor area
Internal heat gains	Lighting: 11.8 W/m^2
	Other equipment: 10 W/m^2

MATELab was unoccupied and operated in a free-running mode during the validation study, thereby eliminating uncertainties arising from occupant behaviour and operation of HVAC systems, respectively. This resulted in a simpler and more controlled testing scenario, hence making it easier to identify sources of inaccuracy or error in the building envelope and in the basic setup of the co-simulation.

7.3.2 Data collection procedures

Due to ongoing research work, MATELab was only available for a limited period of time for data collection, and data were collected between 8 and 16 August 2020. The validation study then used these data to verify and validate the model of MATELab calibrated by Luna-Navarro, Borkowski et al. (2021). During the measurement period, the following parameters were measured based on the available sensors for undertaking the model verification and validation: (i) outdoor environmental parameters, (ii) indoor environmental parameters and (iii) parameters related to the control actions of the blind automation system. After the data collection, the values were compiled and averaged over 1 min.

7.3.2.1 Outdoor environmental parameters

Outdoor environmental parameters were needed to create the weather file for the verification and validation of the model of MATELab. Weather data, specifically the dry bulb air temperature and the global horizontal solar irradiance were collected using the weather station of MATELab, located on its roof at a height of approximately 3 m above ground level. It was assumed that these data were of particular importance for predicting MATELab's performance, in particular the aspects listed in Table 7.5.

Table 7.5: Effects of outdoor environmental parameters on MATELab's performance.

Parameter measured	Measurement instrument used	Performance aspects affected by parameter
Dry bulb air temperature	Weather station	Exterior surface convection Infiltration/ventilation sensible heat transfer
Global solar irradiance	Weather station	Fenestration heat gains Exterior surface heat balance Control strategy

When values were missing in the weather data set, the data had to be interpolated. To verify the accuracy of the measured data, dry bulb air temperature data were compared with data from a nearby weather station located on the roof of the Cambridge Computer Laboratory (Digital Technology Group (DTG), n.d.).

Nonetheless, a larger weather dataset would have been preferable to accurately determine the local boundary conditions. Ideally, direct and diffuse solar irradiance data at weather station level should also have been measured since the control strategy relied on the solar irradiance data and, therefore, even short-term inaccuracies could lead to incorrect or time-shifted control actions.

7.3.2.2 Indoor environmental parameters

Indoor environmental parameters were needed to assess the accuracy of the model of MATELab during validation. An accurate prediction of the energy and thermal performance of adaptive building envelopes is important, as BPS tools are used in building design, and inaccuracies in these tools could have a negative impact on the use of adaptive building envelopes in design practice. Since MATELab was a thermally unconditioned space with no heating and cooling, this part of the study focused on the thermal performance of adaptive building envelopes. The thermal performance indicator used was the indoor air temperature, which was measured at the centre of the room by a 3 m high sensing station (1 in Figure 7.4).

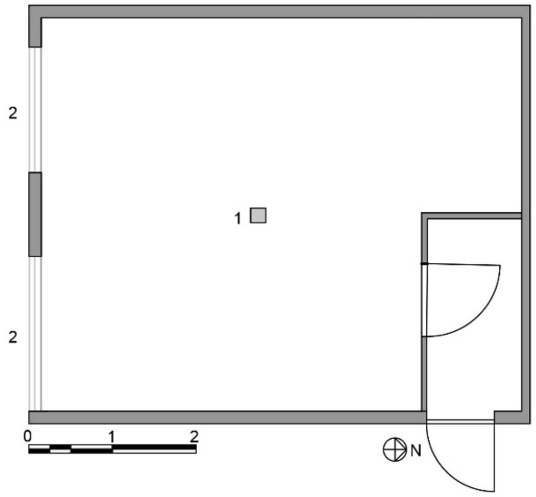


Figure 7.4: Floor plan of MATELab (1: location of the indoor air temperature sensor, 2: south-façade location).

As mentioned in the introduction to this thesis, the validation was affected by the COVID-19 pandemic in that it was only possible to access sensor data connected to the BMS system, resulting in a limited number of variables available for the validation. Of the accessible variables, the indoor air temperature was found to be the best available variable to test the control strategy of the building envelope, at least indirectly. The reason for this was that as soon as the blinds were closed due to the control threshold being exceeded, the solar radiation was blocked and the solar heat gain was reduced. Since the interior could now no longer catch the sunlight and absorb the radiation, the indoor air temperature rose less. To verify the accuracy of the indoor air temperature, control actions were also measured directly.

7.3.2.3 Parameters related to control actions

Another data point required for the validation was the control actions of the blind automation system, namely the position of the blind. It was important to collect this data, as the performance of adaptive building envelopes depends largely on the control strategy during operation. Table 7.6 shows the control strategy to dynamically operate the venetian blinds. It was a RBC strategy whose input and output were the solar irradiance, the time delay and the position of the blind.

Table 7.6: Control strategy for MATELab's blind automation system.

Input	$I_{\mathrm{sol,sky}}$: global horizontal solar irradiance in W/m^2 $I_{\mathrm{sol,south}}$: global vertical solar irradiance on south surface in W/m^2 t: time delay in s
Output	$u_{\mathrm{blind}} \in [0, 1]$: position of the blind (0 = open, 1 = closed)
Algorithm	

```
set $I_{\mathrm{sol}} = 1/3 \times I_{\mathrm{sol,sky}} + 1 \times I_{\mathrm{sol,south}}$
if $I_{\mathrm{sol}} > 250\,\mathrm{W/m^2}$ and $t > 900\,\mathrm{s}$ then
  $u_{\mathrm{blind}} = 1$
else
  $u_{\mathrm{blind}} = 0$
end if
```

The movements of the blinds were monitored by a control unit, which wrote a message in a log and stored it in an internal memory when an action of the actuator was registered, i.e. when the position of a blind changed. To evaluate the accuracy of the predicted control actions during validation, the data points related to the control actions of the blind automation system were downloaded and used directly from the computer that stored the actuator messages.

7.3.3 Modelling of the case study

The thermal model was based on the existing thermal simulation model of MATELab developed in EnergyPlus by Luna-Navarro, Borkowski et al. (2021). In the model, three zones were implemented: (i) a supply air plenum under the raised floor, (ii) a return air plenum over the suspended ceiling and (iii) an occupied space. The simulation parameters of the thermal model of MATELab were based on the physical parameters listed in Table 7.4.

As described in Section 7.3.2, the available weather station on MATELab's roof at the time of the experiment had collected data on the dry bulb air temperature and the global solar irradiance. This was supplemented with humidity and wind data from an existing weather file for Cambridge created with Meteonorm v6.0 (Meteotest, 2007). These data were then used to create a new weather file for the study period with Elements (Big Ladder Software and Rocky Mountain Institute, 2016), a free and open-source software tool for creating and editing custom weather files.

The diffuse and direct solar irradiance data was then derived from the measured global solar irradiance data. The diffuse solar irradiance $I_{\mathrm{sol,diff}}$ was approximated by the correlation model by Erbs, Klein and Duffie (1982), whose accuracy was confirmed by Dervishi and

Mahdavi (2012). This model calculates the ratio of the diffuse to the global solar irradiance as a function of the clearness index k_T, as shown in the following equation:

$$I_\mathrm{sol,diff} = (0.9511 - 0.1604\,k_\mathrm{T} + 4.388\,k_\mathrm{T}^2 - 16.638\,k_\mathrm{T}^3 + 12.336\,k_\mathrm{T}^4) \times I_\mathrm{sol} \qquad (7.1)$$

For the calculation of the diffuse solar irradiance, an average clearness index of 0.61 for London, UK, in August was used (Duffie and Beckman, 2013). Following this, the direct solar irradiance was derived from the difference between the global and the diffuse solar irradiance.

Figure 7.5 shows the durations of the measurement period (8 to 16 August 2020) and the simulation period (1 to 31 August 2020). It also highlights that the simulation period began seven days before the actual measurement period, which was necessary to ensure that the initial conditions produced by the simulations matched those of the measured data. To determine the appropriate number of days needed to produce similar initial conditions, simulations and comparisons with the measured data were carried out in advance. In addition to the simulation period, the model was warmed up between 6 and 25 days, which was automatically determined by EnergyPlus and continued until the temperatures and heat flows in each zone converged (DOE, 2018d). The simulation timestep was 300 s.

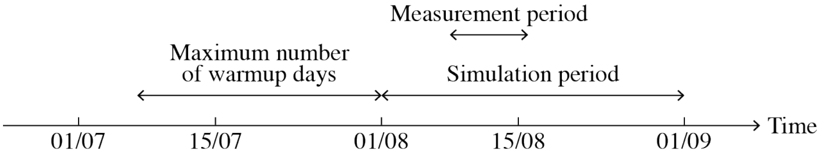


Figure 7.5: Schematic of simulation and measurement periods.

In order to model alternative dynamic controls, the EnergyPlus model of MATELab was connected to a controller model, which was developed in (i) the EMS feature of EnergyPlus and (ii) Dymola in the modelling approach. The controller model in the EMS feature was used, on the one hand, for the MCSA. On the other hand, it was used to generate outputs of a tool that is generally accepted as the state-of-the art to identify and diagnose sources of error or inaccuracy in the modelling approach. The model created in the modelling approach was then used to test the accuracy of the predictions of an adaptive building envelope model coupled in a co-simulation setup, an area that has not been sufficiently explored in the past.

7.3.3.1 Modelling of control strategy in EMS feature

The control strategy was modelled in the EMS scripting feature of EnergyPlus, prior to its modelling in Dymola. The EMS feature uses the ERL to describe control strategies.

EnergyPlus interprets and executes the control sequence implemented in ERL as the model is being run. In the validation study, the EMS feature was used to provide high-level, supervisory control to override the `WindowProperty:ShadingControl` object in EnergyPlus. Without the EMS feature, MATELab's control strategy could have only been modelled in fragments. A reason for this is that blind control strategies within EnergyPlus are preset or time-scheduled. To model a control strategy that is based on boundary conditions or simulation state variables instead, the EMS feature must be used. A well-tuned control strategy may have a positive impact on the model output (British Standards Institution (BSI), 2017).

Two aspects of the control strategy were particularly complex to model in the EMS feature. However, modelling these aspects was important in order to reduce the specification and modelling uncertainty and eventually obtain realistic predictions of the control actions for validation. Firstly, the monitored solar irradiance had to be used as an input to the control strategy to ensure that the information provided to the control system was the same for the real and the predicted setup. This was achieved by using the `Schedule:File` object in EnergyPlus as a schedule, which read sub-hourly values from an external CSV file. While the input file contained 15-minute interval data, the `Interpolate to timestep` field was set to interpolate values and use them at the appropriate minute in the hour. Secondly, the control strategy had a time delay; the blinds changed their position only when the solar irradiance was greater than 250 W/m^2 for more than 900 s (15 min). The time delay was modelled in the EMS feature through the use of trend variables, which are used to store the history of ERL variables.

Whenever the EMS controller model needed to be modelled over the course of this part of the study, the model was called from a script written in Python through the `idf.run()` function of the Eppy package (Philip, 2019). The data were then stored in CSV format for analysis.

7.3.3.2 Combination of thermal model with control model in modelling approach

Figure 7.6 shows the schematic of the co-simulation process. In the validation study, the data exchange between EnergyPlus and Dymola was orchestrated through the FMI Standard. This part of the study used Dymola as a coordinator simulation tool and EnergyPlus as a worker simulation tool. This means that the EnergyPlus model was encapsulated and shared as a FMU for co-simulation, which enabled EnergyPlus to exchange information at each timestep with Dymola. The measured solar irradiance was provided as an input to the model to compute the blind position. The blind position was then provided as an input for the FMU.

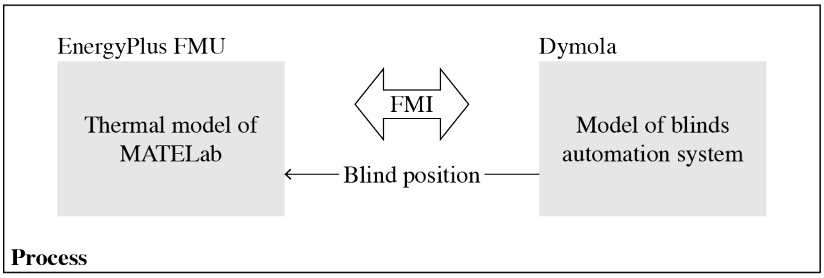


Figure 7.6: Schematic of the co-simulation process: the control strategy for the blind automation system in Dymola is coupled to the model of MATELab through the FMI Standard for information exchange at each zone timestep.

The external interface of EnergyPlus was activated in order to link the EnergyPlus model to the Dymola model. With the `ExternalInterface` object present, the values listed in the object received their inputs from the FMI Standard at each zone timestep. To export the EnergyPlus model of MATELab as an FMU for co-simulation, the software package EnergyPlusToFMU was used. The FMU was then imported into Dymola, where it appeared as input/output block and was connected to the controller model. Figure 7.7 represents the model of the control strategy in Dymola, where is (i) the input data of the monitored solar irradiance, (ii) the control strategy and (iii) the FMU.

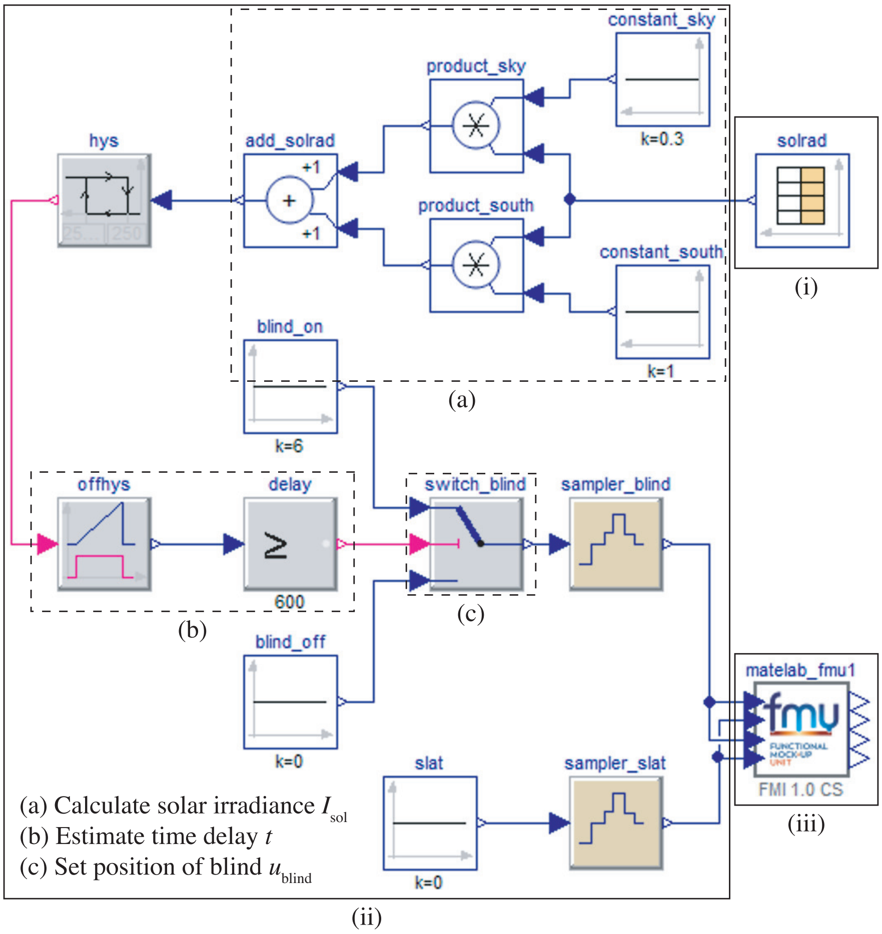


Figure 7.7: Graphical representation of the Dymola model: the model represents the control strategy for MATELab's blind automation system.

To equal the timestep of EnergyPlus to the sampling time of the FMU, a sampler (i.e. `Modelica.Blocks.Discrete.ZeroOrderHold`) was required. The sampler sampled the input signals and computed the output signals from the sampled input signals by a given sample period equivalent to the timestep. Dymola then synchronised the FMU every timestep.

The entire workflow was automated through a script written in Python, which covered three basic steps: (i) export of the thermal model of MATELab as an FMU through the `idf_to_fmu` function of the `export` module of the modelling approach, (ii) co-simulation of the entire model of MATELab through the `cosimulate` function of the `simulate` module of the modelling approach and (iii) extraction and storage of data in CSV format for analysis. All simulations required for the verification and the validation were performed using the standard Dassl solver of Dymola with the default solver tolerance of 10^{-4} on a 2015 MacBook Pro with a dual-core Intel Core i5 processor of 2.7 GHz running Ubuntu 20.04 in a virtual machine.

7.3.4 Sensitivity analysis to inform the verification process

Verification plays a key role in the validation process of simulation models. The objective of the verification was to confirm that the model of MATELab was implemented correctly. This was done by identifying and quantifying the degree of uncertainty around the most important input variables of the model of MATELab and then fine-tuning uncertain input variables to minimise discrepancies between predicted and measured data points. Possible sources of uncertainty in the model of MATELab were:

- **Specification uncertainty:** Inaccurate or incomplete building and system specifications, such as geometry, material and blind properties and internal heat gains.
- **Modelling uncertainty:** Simplifications and assumptions of the physical processes, such as infiltration and ground heat transfer.
- **Numerical uncertainty:** Errors introduced in the simulation of the model.
- **Scenario uncertainty:** External conditions imposed on the building, such as climate conditions and occupant behaviour.

To determine the most important input variables, the first step of the verification process consisted in undertaking a SA (Chong and Menberg, 2018). Figure 7.8 shows the schematic of the verification process.

This investigation used a the global SA approach as it is considered a more reliable method than the local SA (Tian, 2013). The approach to global SA adopted for this part of the study was a MCSA. MCSA is a variance-based method that measures the sensitivity of the output to the input variable by the amount of variance in the output caused by that input

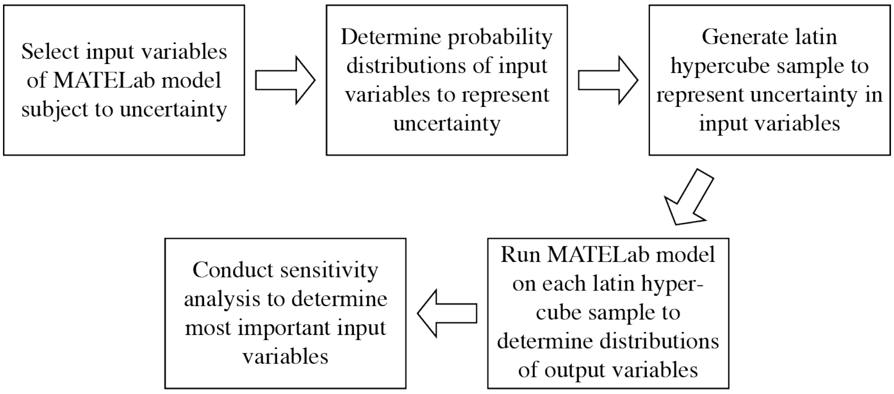


Figure 7.8: Workflow diagram showing the processes involved in the SA.

(Tian, 2013). It uses random samples from a given distribution, and the validation study selected the Latin Hypercube Sampling (LHS) method to generate the sample. LHS was chosen because of its efficient stratification properties. This means that LHS divides the input sample space into *n* equally spaced and non-overlapping regions (strata) and then selects a sample at random from each sample space (Macdonald, 2009). LHS thus outperforms simple random sampling techniques (Das et al., 2014).

Numerous sets of input-output variables were generated by running the model of MATELab on the input sample in the MCSA. Correlation-based methods were then applied to measure the strength of the input and output variables and to rank the input variables from 1 (the most important variables) to 8 (the least important variable). The two indices applied were S_{Pear} and S_{Spear}. While S_{Pear} measures the strength of the linear relationship between each of the input variables and the indoor temperature, S_{Spear} measures the strength of the monotonic relationship between each of the input variables and the indoor temperature. Both indices had to be applied to capture information in the case of a non-linear relationship between input and output variables. The validation study used the Python package Scipy to compute the correlation coefficients. Scipy's statistical function `scipy.stats.pearsonr` was used for S_{Pear} and `scipy.stats.spearmanr` was used for S_{Spear}.

Given that sensitivity indices are estimated based on a limited sample, SA methods are subject to uncertainty (J. Yang, 2011). To get good estimations nonetheless, Monte Carlo simulations require many iterations. A first indication of the number of Monte Carlo simulations needed was provided by Lomas and Eppel (1992), who found that 60-80 simulations could be sufficient to achieve convergence. However, depending on the complexity of the model and the number of the parameters, more iterations might be necessary. This is why the present work used the bootstrap technique (J. Yang, 2011), in which the estimated statistic is plotted against the gradually increasing base sample size. Convergence is assumed as soon as there is no significant variation for each sensitivity index.

A research computing cluster was used to run the MCSA as it required many iterations and thus a lot of compute power. In order to keep the computational time as short as possible, the MCSA only used the EMS model. This required the use of EnergyPlus alone, which helped to reduce the computational intensity of the MCSA. Since the thermal model was the same for both the EMS model and the Dymola model, it was assumed that the findings from the MCSA with the EMS model were transferable to the co-simulation model.

The MCSA was completely automated through a Python script by running the simulations in a ‘for’ loop, which iterates over a given sequence. The loop calls a function multiple times and stores the results at the end of the loop. After the computation of S_{Pear} and S_{Spear}, the sensitivity of the input variables was ranked from most to least important variable. The ranking was then used to generate the following plots for an initial qualitative evaluation of key input variables using the Python package Matplotlib: (i) tornado plots to compare the relative importance of the different input variables and (ii) scatter plots to show the relationships between the variables.

7.3.4.1 Uncertain inputs

The model of MATELab had many input variables that could vary as a result of specification and modelling uncertainty. However, the variables that were likely to have an impact on the indoor temperature – the performance indicator – were:

1. Infiltration flow rate
2. Density of façade cover panels
3. Specific heat capacity of façade cover panels
4. Separation of venetian blind slats
5. Solar reflectance of venetian blind slats
6. Internal heat gains of computer equipment
7. Time delay for control strategy
8. Solar irradiance for control strategy

The input variable 1 was measured by Luna-Navarro, Borkowski et al. (2021) but it could vary as a consequence of measurement uncertainty. The infiltration flow rate was based on measurements from a blower door test, and it was assumed that it follows a standard normal distribution. The inputs 2 and 3 were based on the manufacturer’s specifications in terms of nominal performance, which might differ from the actual performance in situ. Therefore, a standard normal distribution was assumed, and the minimum and maximum values found in the literature were used. The input variables 4 to 6 reflect variations in building specifications, for which only minima and maxima were known. They were also regarded as standard normal distributions where extreme values were less likely to be selected than values near the mean. Since the tails of a standard normal distribution extend indefinitely, the LHS method may generate negative numbers that are usually not supported by EnergyPlus. They represented only a very small proportion of the total number of samples and were thus set to zero.

The last two input variables (7 and 8) were design parameters, which were defined by the façade contractor and the authors and which could be changed through interventions. Therefore, they were assumed to be uniformly distributed as they may be regarded as being equally probable. The sources used to inform the shape of the distributions can be seen from Table 7.7.

Table 7.7: Input variables used in the MCSA.

Input variable	Symbol (unit)	Distribution assumed	Uncertainty type	Reference
Infiltration flow rate	Q_{inf} (m^3/sm^2)	*N(0.003,0.0008)*	Modelling uncertainty	Luna-Navarro, Borkowski et al. (2021)
Density of façade cover panels	p (kg/m^3)	*N(1500,333)*	Specification uncertainty	Technical sheet from manufacturer
Specific heat capacity of façade cover panels	c (J/kgK)	*N(5000,1000)*	Specification uncertainty	Technical sheet from manufacturer
Separation of venetian blind slats	h (m)	*N(0.50,0.17)*	Modelling uncertainty	No a priori information available
Solar reflectance of venetian blind slats	ρ (-)	*N(0.50,0.17)*	Modelling uncertainty	No a priori information available
Internal heat gains of computer equipment	Q_{int} (W/m^2)	*N(100,33.3)*	Modelling uncertainty	CIBSE (2015b, Table 6.2)
Time delay for control strategy	t (s)	*U(930,310)*	Specification uncertainty	Defined by façade contractor and authors
Solar irradiance for control strategy	I_{sol} (W/m^2)	*U(250,33.3)*	Specification uncertainty	Defined by façade contractor and authors

Luna-Navarro, Borkowski et al. (2021) found in a local SA that the infiltration flow rate and the internal heat gains were the most important input variables. They have been used again in the validation study, primarily to find out whether these variables were more or less important than the variables related to the control strategy for the blind automation system.

7.3.5 Testing of time integration schemes

The empirical validation indicated a need to further investigate the relationship between the required simulation timestep and the accuracy of the predictions. For this purpose, it was necessary to study various time integration schemes in detail.

The allowable choices for the simulation timestep in EnergyPlus are 3600, 1800, 1200, 900, 720, 600, 360, 300, 240, 180, 120 or 60 s. This part of the study implemented and examined each of them in the EMS feature of EnergyPlus and the modelling approach. However, a common problem with shorter timesteps is that the computation time increases (DOE, 2018d). Therefore, the validation study also investigated the duration of the simulations for each timestep. The computation time was measured using the wall clock time from the time the Central Processing Unit was initiated until the time the calculations were finished.

However, initial tests showed that the computation time per timestep was never the same. The reason for this was that it depended strongly on the utilisation of the Central Processing Unit in Ubuntu. In order to have confidence in the conclusions that can be drawn from the results of this part of the study, the following question had to be answered: How many simulation runs per timestep are required to be sampled to ensure that the results of the completed study have scientific significance? A common technique for estimating the minimum number of samples required for a study is the power analysis (Duffy, 2006). This is a method for determining statistical power, i.e. the probability that a hypothesis test correctly rejects the null hypothesis when it is false. The hypothesis test used in the validation study was a Student's *t*-test, which compares the means of two samples of Gaussian variables. The two samples were (i) the computation time in the EMS feature and (ii) the computation time in the modelling approach, each per timestep. The sample means were calculated based on 10 test simulation runs per timestep. Figure 7.9 shows an example of the normal (or Gaussian) distributions of the computation times in the EMS feature and the modelling approach for a timestep of 3600 s using a continuous probability density curve.

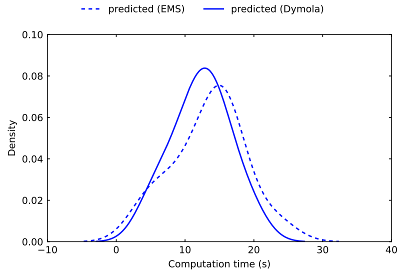


Figure 7.9: Distributions of computation times for a timestep of 3600 s.

The Student's *t*-test was implemented in Python using the `TTestIndPower` class of the statsmodels library (Seabold and Perktold, 2010). This test calculated a *p*-value, which is the probability that the difference between the samples could have occurred by chance only, and an effect size, which is the quantification of the size of the effect when comparing the difference in the means from the two samples. In estimating an appropriate sample size to determine how many simulation runs were required per timestep from each sample, the validation study was interested in detecting at least an effect of 0.80, with an 80 % chance of detecting the effect if it is true and a 10 % chance of detecting an effect if there is no such effect. The results of the Student's *t*-test for each timestep can be seen from Table 7.8. It shows that the minimum number of samples required for a timestep of 3600 s was 231 simulation runs. As a consequence, each timestep was simulated 231 times to ensure that the results of the completed validation study were scientifically meaningful.

Table 7.8: Results of Student's *t*-test for each timestep.

Timestep (seconds)	3600	1800	1200	900	720	600	360	300	240	180	120	60
p-value	0.58	0.031	0.47	0.050	0.060	0.063	0.11	0.16	0.077	0.16	0.15	0.048
Effect size	0.23	0.98	0.30	0.87	0.83	0.80	0.68	0.60	0.76	0.60	0.61	0.86
Sample size	231	13.6	141	17.1	18.9	20.1	27.1	35.3	21.9	35.4	33.5	17.3

7.3.6 Analysis of verification and validation results

In analysing the results of the verification and validation, there could be large discrepancies between measured and simulation-predicted data points. A UA was therefore carried out to quantify how well the model of MATELab described the variability in the measured data, hence decreasing the uncertainty of the model and increasing the level of confidence in the model. The validation study used the NMBE and the CV-RMSE indices, which are described in greater detail in Appendix C:

- **NMBE:** The NMBE index gives the global difference between measured and simulated data points by normalising the average of the errors of a sample space and dividing it by the mean of the measured data points.
- **CV-RMSE:** The CV-RMSE index measures the variability of the errors between measured and simulated data points, thereby giving an indication of the model's ability to fit the data.

Positive values of NMBE suggest that the model under-predicts measured data, and negative values suggest that the model over-predicts measured data. Although the NMBE index is a good measure of the accuracy of a model, its main problem is the cancellation error, where the sum of positive and negative values reduces the value of NMBE (Ruiz and Bandera, 2017). The use of this index alone is consequently not recommended, hence the CV-RMSE index was used as a further measure of model accuracy.

This part of the study adopted an UA to assist in the verification and validation process for better probabilistic predictions. As outlined in Figure 7.10, an iterative process was applied to reduce discrepancies between predicted and measured data points. The model's output variable of interest used to calculate the uncertainty indices was the indoor temperature, and the acceptable range of accuracy should be in accordance with *ASHRAE Guideline*

14-2014 (ASHRAE, 2014b). According to the guideline, the hourly NMBE index is required to be less than 10 % and the hourly CV-RMSE index is required to be less than 30 % to validate a model as verified. In order to approach the minimum NMBE and CV-RMSE indices, the model was adjusted by fine-tuning the most important input variables identified in the MCSA. Once the ASHRAE criteria were met, the model of MATELab showed that it fitted the measured data.

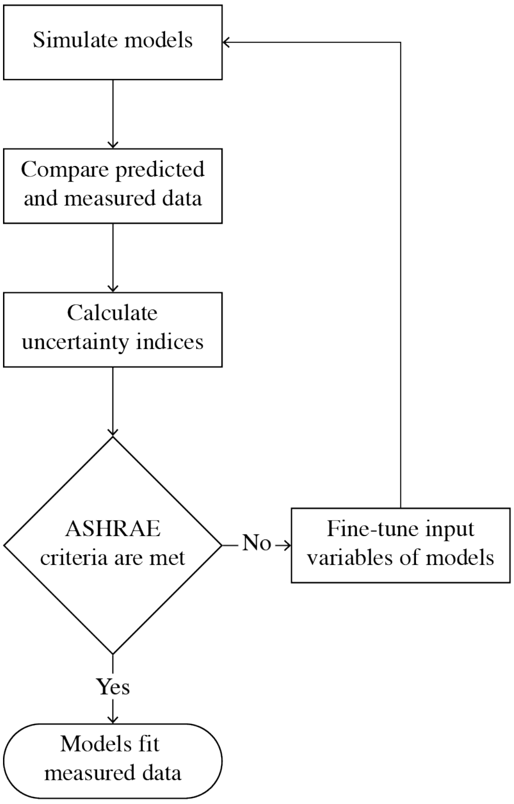


Figure 7.10: Iterative process to reduce discrepancies between predicted and measured data.

7.4 Test of coupling data and subroutines: results and discussion

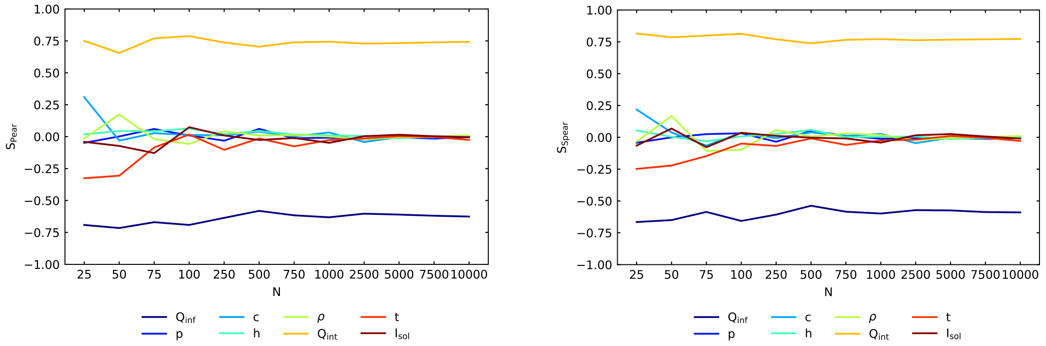
This section describes and discusses the results emerged from the empirical validation. It begins by presenting the results related to the MCSA and then moves on to examine the verification and validation of the model MATELab in relation to the indoor temperatures. The final part discusses in detail the validation of the control strategy for the blind automation system.

7.4.1 Monte Carlo sensitivity analysis

The aim of the MCSA was to determine the most important input variables by using the sensitivity indices $\mathrm{S}_{\mathrm{Pear}}$ and $\mathrm{S}_{\mathrm{Spear}}$ to evaluate the relationships between the input variables and the indoor temperature T_{i}.

7.4.1.1 Convergence testing

As discussed above, this part of the study adopted the bootstrap technique to achieve convergence. S_{Pear} and S_{Spear} were plotted against the gradually increasing number of iterations N, and convergence was assumed as soon as there was no significant variation for each sensitivity index. As can be seen from Figure 7.11, the indices provided a clear distinction between the two most important input variables — the internal heat gains Q_{int} and the infiltration flow rate Q_{inf} –- and the other six variables after a few hundred iterations ($N = 1000$). Internal heat gains describe the heat emitted within MATELab from internal sources, especially computer equipment, resulting in an increase in the temperature within the facility, and infiltration describes the unintended flow of outside air into MATELab, typically caused by cracks in the building envelope. The infiltration flow rate was provided as an input to the EnergyPlus `ZoneInfiltration:DesignFlowRate` object, in which the design flow rate was modified by temperature differences and wind speed.



(a) Convergence of S_{Pear}.

(b) Convergence of S_{Spear}.

Figure 7.11: Convergence of S_{Pear} and S_{Spear} for the input variables: the increasing base sample size is expressed as the number of iterations N.

While the indices started to converge at the base sample size of around 5000, only the two most important variables (Q_{int} and Q_{inf}) could be identified with certainty. Further tests could have been conducted to improve convergence. However, it was found that the other six variables (p, c, h, ρ, t and I_{sol}) had no noticeable effect on the model output compared to the internal heat gains and the infiltration flow rate. It can be seen from the data in Tables 7.9 and 7.10 that these six variables showed a negligible correlation with S_{Pear} and S_{Spear} ranging around zero. This indicated that the relationship was random or non-existent. It would thus have been computationally ineffective to increase the number of iterations further. As a consequence, convergence had been assumed, and converged results are discussed in the next section. Also, the internal heat gains and the infiltration flow rate were used to verify the model.

Table 7.9: Converged results for S_{Pear} from N = 1000 to N = 10000: shown with the ranking of the input variables, where 1 is the highest rank.

Number of iterations		Input variables							
		Q_{inf}	p	c	h	ρ	Q_{int}	t	I_{sol}
1000	Rank	2	7	4	6	8	1	5	3
	S_{Pear}	-0.63	-0.008	0.033	0.010	0.001	0.74	-0.027	-0.048
2500	Rank	2	4	3	7	5	1	6	8
	S_{Pear}	-0.60	-0.022	-0.042	0.006	-0.021	0.73	-0.014	0.004
5000	Rank	2	5	8	4	6	1	7	3
	S_{Pear}	-0.61	-0.005	-0.003	-0.013	-0.004	0.73	0.004	0.015
75000	Rank	2	3	4	7	8	1	6	5
	S_{Pear}	-0.62	-0.015	-0.006	0.002	-0.002	0.74	-0.003	0.003
10000	Rank	2	7	8	5	4	1	3	6
	S_{Pear}	-0.63	-0.004	0.003	0.007	0.010	0.74	-0.025	-0.004

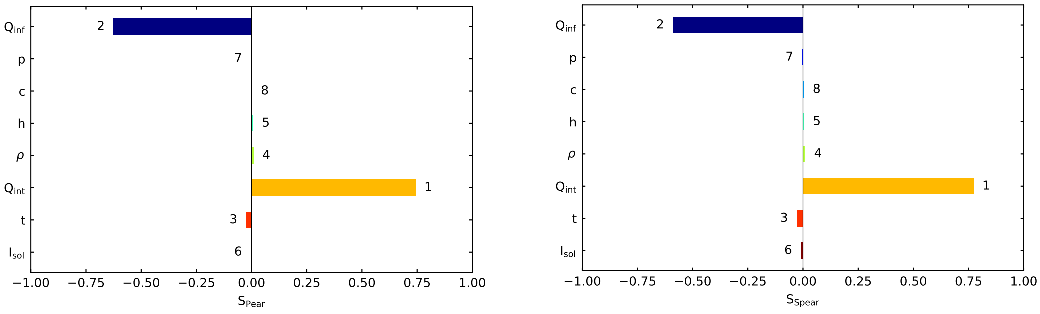
Table 7.10: Converged results for S_{Spear} from N = 1000 to N = 10000: shown with the ranking of the input variables, where 1 is the highest rank.

Number of iterations		Input variables							
		Q_{inf}	p	c	h	ρ	Q_{int}	t	I_{sol}
1000	Rank	2	7	4	8	6	1	5	3
	S_{Spear}	-0.60	-0.011	0.027	0.004	0.018	0.77	-0.025	0.042
2500	Rank	2	7	3	8	4	1	5	6
	S_{Spear}	-0.57	-0.007	-0.046	0.007	-0.022	0.76	-0.018	0.016
5000	Rank	2	6	8	4	7	1	5	3
	S_{Spear}	-0.57	-0.007	-0.002	-0.013	-0.005	0.77	0.011	0.026
75000	Rank	2	3	4	6	8	1	7	5
	S_{Spear}	-0.59	-0.013	-0.011	-0.005	0.001	0.77	-0.004	0.006
10000	Rank	2	8	7	6	4	1	3	5
	S_{Spear}	-0.59	-0.004	0.005	0.005	0.011	0.77	-0.029	-0.010

7.4.1.2 Relationship between input variables and indoor temperature

This part of the study applied two correlation-based methods to measure the strength of the input and output variables. From the data in Figure 7.12 it is apparent, however, that S_{Pear} and S_{Spear} were similar for each of the input variables, consequently leading to the same conclusions. The data also shows that the two most important input variables in relation to the indoor temperature were the internal heat gains Q_{int} and the infiltration flow rate Q_{inf}. Therefore, variations in the indoor temperature could largely be attributed to variations in the internal heat gains and the infiltration flow rate. Data from this figure can also be compared with the data in Tables 7.9 and 7.10.

The most surprising aspect of the data was that input variables related to the blind material (h and ρ) and the blind control strategy (t and I_{sol}) were less important for the model output than the internal heat gains and the infiltration flow rate. Although this finding, while



(a) Rank of input variables for S_{Pear}.

(b) Rank of input variables for S_{Spear}.

Figure 7.12: Comparison of the relative importance of the input variables for $N = 10000$: shown with the rank of each input variable given next to the bar, where 1 is the highest rank.

preliminary, is bound to the experimental setup of the MATELab test case, it implies that variations in the output variables may be less attributed to variations in the input variables related to the control strategy.

There were instead correlations between the indoor temperature and the internal heat gains and the infiltration flow rate respectively. With regard to the internal heat gains, the strong positive correlations of 0.74 for S_{Pear} and of 0.77 for S_{Spear} show that the correlated variables moved in the same directions indicating that as the internal heat gains increased, so did the indoor temperature. However, the amount by which the internal heat gains increased the indoor temperature was not consistent as it was unequal to one. Compared to the relationship between the infiltration flow rate and the indoor temperature, the relationship between the infiltration flow rate and the indoor temperature seemed to be weaker. The moderate negative correlations of −0.63 for S_{Pear} and −0.59 for S_{Spear} showed that the correlated variables moved in different directions, meaning that a high infiltration flow rate correlated with a low indoor temperature but again not by a consistent amount. This indicates that, as the infiltration flow rate increased, the internal temperature decreased. A likely explanation for this is that the experiment took place in summer, when indoor temperatures were higher than outdoor temperatures. As more ‘cold’ air came through the cracks, it cooled the air inside and lowered the indoor temperature. These relationships are also presented in the scatter plots in Figure 7.13.

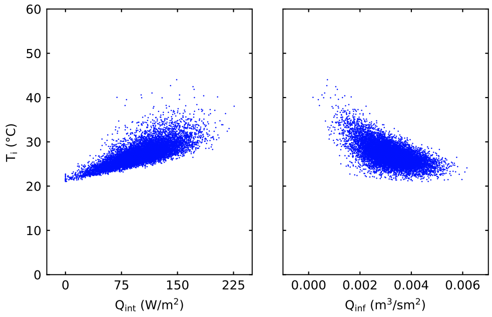


Figure 7.13: Relationship between T_i and the two key input variables for $N = 10000$.

Together the findings suggest that the MCSA succeeded in determining the most influential input variables. Despite the high number of input variables, the MCSA accelerated the investigation of the effect of input variables on the outputs of the model of MATELab. Given that a high number of simulations was necessary to achieve convergence in the MCSA, the use of a model that could be simulated in a mono-simulation setup, where an entire model is simulated by one and not by different simulators as in a co-simulation (Trčka, Hensen and Wetter, 2009) seemed crucial. Although the computation time of the MCSA was generally high due to the high number of iterations, adopting a mono-simulation model of MATELab, further simplified by disregarding Underfloor Air Distribution system and occupants, may have also reduced the time needed to compute the MCSA.

7.4.2 Verification of model of MATELab

The verification was undertaken to reduce the uncertainty of the model of MATELab created in the modelling approach. The control strategy was modelled, in addition to Dymola, in the EMS scripting feature of EnergyPlus to identify and diagnose sources of error or inaccuracy in the modelling approach. Since the parameters of the thermal model and the weather file were identical for both models, the main difference between them was that the control strategy was modelled in different tools. When initially comparing the predictions of the models of MATELab with the actual measured data, good agreement with the measured data was found. The data were analysed by descriptive statistics, and the summary statistics for the uncertainty indices NMBE and CV-RMSE before and after verification are compared in Table 7.11. From the data in the table, it can be seen that the NMBE minima (Dymola: –0.14 %, EMS: –0.14 %) and maxima (Dymola: 0.077 %, EMS: 0.074 %) were well below the ASHRAE requirement of 10 % for hourly empirical data. With median values of –0.010 % (Dymola) and –0.012 % (EMS) for the NMBE indices, both Dymola and EMS models had the tendency to slightly over-predict the measured data. The small discrepancies between the EMS feature and the modelling approach were expected based on earlier observations, e.g. by Trčka, Wetter and Hensen (2009), as the respective tools use different models and solution techniques. Similar to NMBE, the CV-RMSE minima (Dymola: 0.001 %, EMS: 0.002 %) and maxima (Dymola: 2.06 %, EMS: 2.10 %) were well below the ASHRAE requirement of 30 %, which was also suggestive of a good model fit.

While the first models of MATELab already had the ability to accurately represent the real facility, it was essential to improve the model so the allowable errors would not accumulate to be unacceptable at a later point. Therefore, the initial aim of the verification was to improve the model representation of the infiltration. Although the infiltration flow rate was less important for the model output than the internal heat gains in the MCSA, the infiltration was verified first. The reason for this was that the infiltration was the most

Table 7.11: Summary statistics for uncertainty indices applied before and after verification.

	Type of error	Median	Standard deviation	Minimum	Maximum
NMBE (%)	Before verification				
	Dymola	-0.010	0.052	-0.14	0.077
	EMS	-0.012	0.052	-0.14	0.074
	After verification				
	Dymola	-0.032	0.061	-0.19	0.060
	EMS	-0.031	0.061	-0.20	0.055
CV-RMSE (%)	Before verification				
	Dymola	0.63	0.40	0.001	2.06
	EMS	0.62	0.42	0.002	2.10
	After verification				
	Dymola	0.59	0.60	0.007	2.82
	EMS	0.61	0.66	0.005	2.89

uncertain input when creating the thermal model of MATELab due to measurement uncertainty. Adjusting the infiltration first could therefore help correct any potential modelling errors.

Prior to undertaking the verification, the thermal model of MATELab used the `ZoneInfiltration:DesignFlowRate` infiltration model for all zones, which used a design flow rate of 0.0008 m^3/s per zone floor area and resulted in a constant volume flow of infiltration under all conditions by default. By adjusting the infiltration model with proper selection of flow coefficients, it was expected to better represent infiltration, which is naturally driven by temperature differences and wind speed. To consider appropriate flow coefficients in EnergyPlus, the `ZoneInfiltration:FlowCoefficient` and `ZoneInfiltration:EffectiveLeakageArea` infiltration models can be used (DOE, 2018d).

The infiltration model was consequently changed from `ZoneInfiltration:DesignFlowRate` for all zones to `ZoneInfiltration:FlowCoefficient` for the main zone and the upper plenum and to `ZoneInfiltration:EffectiveLeakageArea` for the lower plenum in EnergyPlus. The `ZoneInfiltration:FlowCoefficient` model calculates infiltration as shown in Equation 7.2, where is $F_{Schedule}$ the value of the schedule that modifies the volume flow rate calculated by the model, c the flow coefficient, C_s the stack coefficient, ΔT the average difference between the zone air temperature and the outdoor air temperature, n the pressure exponent, C_w the wind coefficient and s the shelter factor. The flow coefficient used to calculate the unintended airflow from the outdoor environment directly into MATELab was based on the results of the blower door test by Luna-Navarro, Borkowski et al. (2021). All other values were taken from *2001 ASHRAE Handbook: Fundamentals* (ASHRAE, 2001).

$$\text{Infiltration} = (F_{\text{Schedule}})\sqrt{(cC_{\text{s}}\Delta T^{n})^{2} + (cC_{\text{w}}(s \times \text{Wind Speed})^{2n})^{2}} \tag{7.2}$$

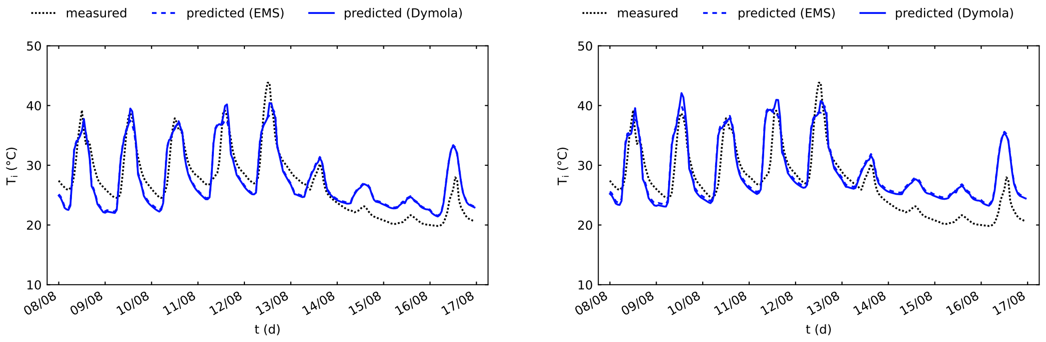
Since the blower door test only included the main zone and the upper plenum, the `ZoneInfiltration:FlowCoefficient` model was only selected for these two zones. The effective leakage area of the lower plenum was calculated using default values from *2001 ASHRAE Handbook: Fundamentals* (ASHRAE, 2001). In addition, the following changes were made to the model:

- Since infiltration highly depends on outside wind conditions, measured wind data from MATELab's weather station were added to the weather file.
- Since MATELab's weather data were not measured at World Meteorological Organization standard conditions, the `Site:WeatherStation` object was added to EnergyPlus to specify the measurement conditions for the climatic data, such as the height above ground of the weather station.

Once the infiltration model had been corrected, the MATELab model was fine-tuned by decreasing the internal heat gains from 10 W/m^2 to 0 W/m^2. Using the internal heat gains to fine-tune the model was found to be appropriate and straightforward because the internal heat gains had a great effect on the model output, as the analysis of the MCSA results showed.

The measured and predicted indoor temperature data after the verification are compared in Figure 7.14. It shows that, especially in the first days, there was an even better agreement between the data compared to the data before the verification. Although the median NMBE indices increased to –0.032 % (Dymola) and –0.031 % (EMS) as a result of the verification, NMBE indices close to zero indicate that there is only a small difference between the predicted and actual indoor temperature and that the model has a sound goodness-of-fit. Compared to the NMBE indices, the median CV-RMSE indices decreased to 0.59 % (Dymola) and 0.61 % (EMS) as a result of the verification, which also suggests that there is only a small variance in the simulated data points relative to the measured data points. The reason why the CV-RMSE indices improved compared to the NMBE indices by moving closer to zero might be due to a cancellation effect. This increased significantly as the regression line of the measured sample approached the simulated one.

One unanticipated finding was the discrepancies between measured and predicted data in the last three days, when the weather quickly changed from sunny to cloudy. A possible explanation for this might be inaccuracies in the thermal mass (e.g. due to equipment, furniture and books inside MATELab); if the real test facility was lighter than the model, it gave back more thermal energy and cooled down faster when the environment had cooler



(a) Before verification.

(b) After verification.

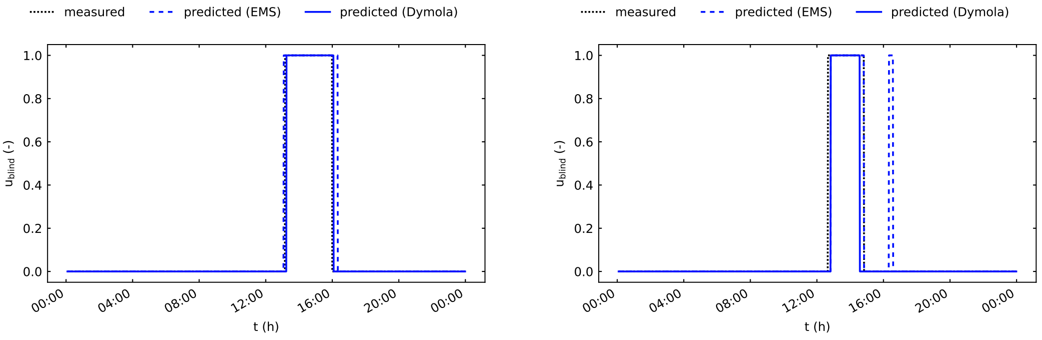
Figure 7.14: Comparison of T_i before and after verification.

temperatures than the thermal mass. Another explanation might be the inaccurate modelling of heat losses through the walls and glazing. As the indoor temperature was dominated by solar gains in the first days, it might have made it more difficult to identify other issues in the modelling. However, as a full investigation of this inaccuracy lies beyond the scope of this work, a further study with a stronger focus on it is suggested.

Interestingly, Dymola and the EMS feature predicted slightly different outputs. Since the weather file and the parameters of the thermal model were identical, it can be assumed that the differences may be due to the modelling capabilities supported by each of the tools to represent the control strategy. Whereas the commands of the ERL programming language, such as IF-ELSEIF-ELSE-ENDIF statements and trend variables, were used in the EMS feature, model components of the Modelica Standard Library (Modelica Association, 2019), such as `Modelica.Blocks.Logical.Hysteresis` and `Modelica.Blocks.Logical.Switch`, were used in Dymola. These different approaches to representing the control strategy in the respective tools may have resulted in differences in how the output of the control strategy was computed. A differently computed control strategy could then have led not only to discrepancies in the predictions of the blind movements, but also to discrepancies in the predictions of the indoor temperatures. Thus, the results show that, despite their different capabilities in representing the control strategy, both Dymola and the EMS feature were capable of accurately predicting the thermal performance of MATELab. However, a clear benefit of using Dymola in a co-simulation setup for higher accuracy could not be found in this validation, at least not for the prediction of the indoor temperature.

7.4.3 Validation of control strategy

The previous section showed that the model developed in Dymola performed slightly differently than the model developed in the EMS scripting feature. The reason for this could be the control strategy for the blind automation system. Figure 7.15 compares the predicted and measured blind positions for two representative days. On 11 August (Figure 7.15a), the blinds closed at 13:10 (measured) while in Dymola they moved at 13:15 and in the EMS feature at 13:05. This error could be linked to the averaging of the data during the analysis according to the 3600-s timestep of the simulation, but also to an inaccurate implementation of the time delay in either the real test facility or in the models. Furthermore, the EMS feature predicted to open the blinds at 16:15 (measured: 15:55, Dymola: 16:00). This inaccuracy could be due to the input data of the monitored solar irradiance for the control strategy, which contained 900-s interval data and was provided to EnergyPlus using values from an external CSV file as a schedule. The input data in Dymola were the same as in EnergyPlus. But while Dymola was able to interpolate the data so that they matched the measured data, EnergyPlus did not interpolate them but adopted the same value for 900 s. After 900 s, EnergyPlus moved on to the next value in the input file and adopted this value again for a period of 900 s.



(a) 11 August.

(b) 12 August.

Figure 7.15: Comparison of blind positions for two representative days (0: blinds open, 1: blinds closed).

The blind behaviour discussed above also appeared on 12 August (Figure 7.15b). The EMS feature predicted a spike in the movement of the blinds for 900 s between 16:20 and 16:35. The reason for this was again the interpolation of the solar irradiance data. While there was one occurrence where the solar irradiance was greater than the control threshold of 250 W/m^2, the blinds should not move given the 900-s time delay. Because of the interpolation error described above, the control strategy in the EMS feature assumed that the solar irradiance was above the threshold for more than 900 s, as a result of which the blinds were incorrectly closed.

Although the predicted control data slightly differed from the measured data, it may be assumed that their influence on the indoor temperature performance is negligible. This assumption is based on the MCSA result that the control strategy was not decisive for the model output. Nevertheless, the results can give some advice to other modellers on how to adapt the setup of similar models:

- Even though EnergyPlus was set to interpolate the values from the 900-s interval input data to the 300-s simulation timestep, this part of the study found that EnergyPlus did not correctly interpolate the input data, resulting in inaccurate predictions. Future work should take this error into account and debug the EnergyPlus model to completely determine its causes(s).

- A simple solution to solve this error could be to provide solar irradiation data at 300-s intervals to EnergyPlus. In this case, EnergyPlus would not need to interpolate the input data so that it could correctly (i) calculate the time delay and (ii) predict the positions of the blinds.

7.4.4 Identified areas for further investigation

The empirical validation has thrown up many questions in need of further investigation. One of the key questions, however, is whether the simulation timestep of 300 s was the reason why the predicted blind positions differed from the measured ones. This is because the required timestep of a simulation is strongly dependant on the rate of change of the inputs acting on the variables. Specifically, the two following further investigations in this area would be of great help.

Firstly, a major challenge in co-simulation is ‘to integrate the data exchange with the internal data structures, time integration algorithms and program flow of the individual simulators’ (Trčka, Wetter and Hensen, 2009, p. 725). As a consequence, there is no longer any guarantee of the stability and accuracy properties of the simulator’s original time integration scheme. In the modelling approach, Dymola controls the iteration process. While differences in the integrated results may be insignificant for smaller timesteps, the influence of the time lagging of the coupling data may be more significant for larger timesteps. As a consequence, it is suggested to further investigate the relationship between the required timestep and the accuracy of the predictions.

Secondly, both the control data predicted by Dymola and the control data predicted by the EMS feature of EnergyPlus differed slightly from the measured data. While it was uncertain whether the control strategy in MATELab worked correctly, it would be interesting to examine the effect of a changing timestep on the predicted positions of the blinds more closely. In particular, to examine whether the interpolation error persists, i.e. whether it is a numerical artefact in EnergyPlus that one should be aware of, or whether the inaccurate control predictions could be fixed by adjusting the timestep to e.g. 60 s.

7.5 Test of coupling frequency: results and discussion

This section describes and discusses the relationship between the required simulation timestep and the accuracy of the predictions. It begins by examining the effect of the time lagging of the coupling data in the co-simulation as the timestep gets larger. What follows is an account of the effect of a changing timestep on the positions of the blinds predicted by the EMS feature and Dymola.

7.5.1 Effect of time lagging of coupling data on co-simulation

Figure 7.16 compares the mean computation times of the EMS feature (mono-simulation) and Dymola (co-simulation) for each timestep. It shows that, for a timestep greater than or equal to 180 s, the EMS feature had a shorter computation time in contrast with Dymola. This is evident in a timestep of 3600 s, where the EMS feature was on average 17.1 % faster than Dymola (Dymola: 11.8 s, EMS: 9.78 s). Interestingly, for a timestep less than or equal to 120 s, the EMS feature had a longer computation time compared to Dymola. For a timestep of 60 s, for example, the EMS feature took 22.3 % longer than Dymola (Dymola: 55.7 s, EMS: 68.1 s).

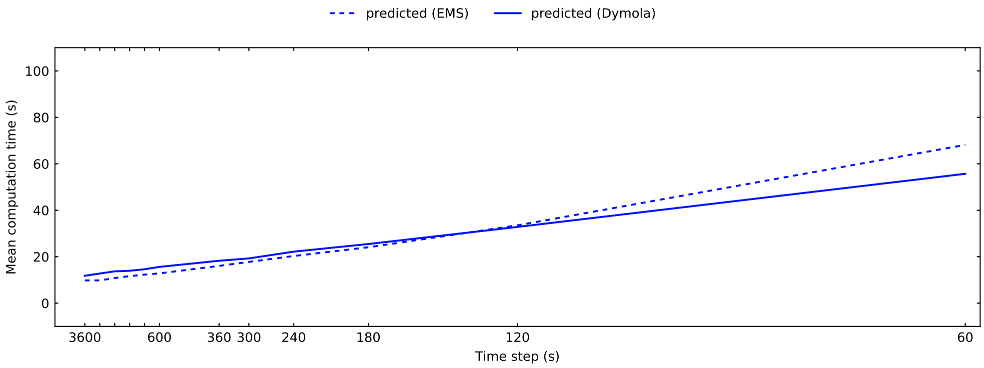


Figure 7.16: Comparison of mean computation times per timestep.

This finding has two important implications. Firstly, it suggests that the time lagging between the simulators in the modelling approach was not significant for either smaller or larger timesteps for the case studied, as initially assumed. This differs from earlier observations by Sagerschnig et al. (2011), who used the BCVTB to couple EnergyPlus with MATLAB to investigate controllers for radiant ceilings. The authors demonstrated that with a timestep of 600 s, depending on the model size, the computation time with co-simulation was about 2.5 times higher than with mono-simulation due to the synchronisation between the models. However, the long computation time of the co-simulation by Sagerschnig et al. (2011) may be due to the Ptolemy II environment on which the BCVTB is built, which introduces an additional socket-based transaction layer into the communication between the simulators, thus increasing the overheads due to the co-simulation (Nouidui and Wetter, 2014).

Secondly, the finding shows that the computation time of the EMS feature increased significantly faster than that of Dymola with a decreasing timestep. There may be two reasons for this:

- **Model complexity:** Compared to MATELab's FMU model in EnergyPlus, the complexity of MATELab's EMS model in EnergyPlus was higher due to the implementation of the control strategy for the blind automation system. As a result, EnergyPlus might have required more iterations in the system modelling because the results of the previous timestep were far from the final result of the next timestep (DOE, 2018d).
- **Simulation settings:** Simulation settings play an important role for the time needed to complete a simulation run in EnergyPlus (Hong, Buhl and Haves, 2008). The only simulation setting that differed between the EMS and the FMU model was that sub-hourly output reports had to be generated during the runs in the EMS model, which might have increased the computation time as EnergyPlus had to write the output to a file.

7.5.2 Effect of timestep changes on predicted blind positions

Figure 7.17 compares the mean CV-RMSE indices of the EMS feature and Dymola calculated based on the measured and predicted indoor temperature data for each timestep. It shows for the EMS feature that the smaller the timestep, the larger the mean CV-RMSE index. The mean CV-RMSE index increased by 11.3 % from a CV-RMSE index of 0.55 at a timestep of 3600 s to a CV-RMSE index of 0.62 at a timestep of 720 s. For Dymola, on the other hand, the smaller the timestep, the smaller the CV-RMSE index, which increased by 8.5 % from a CV-RMSE index of 0.64 at a timestep of 1800 s to a CV-RMSE index of 0.59 a timestep of 600, 360 and 300 s.

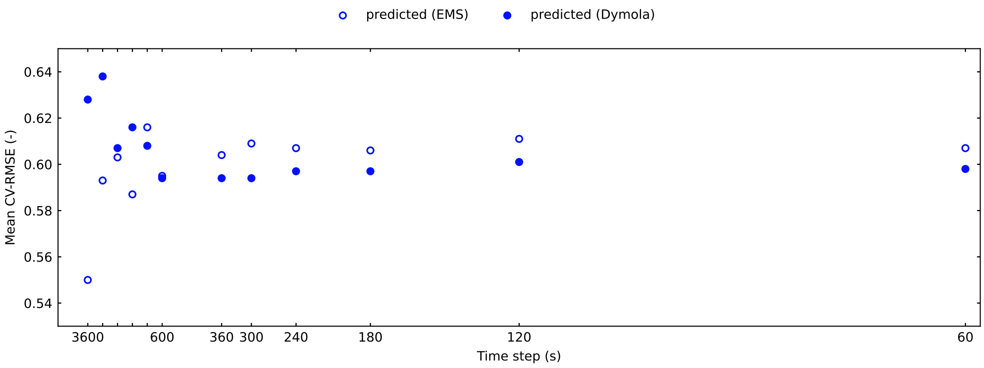
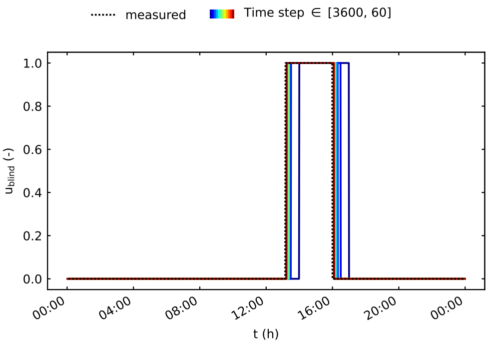


Figure 7.17: Comparison of mean CV-RMSE indices per timestep.

Although the overall effect of the timestep on the accuracy appears to be minor, this result indicates that Dymola improved the accuracy of its predictions as the timestep got smaller, while the EMS feature did not. A possible explanation for this result is that the effect of the time lagging of the coupling data was less noticeable with smaller timesteps. This can also be seen in Figure 7.18, which shows the positions of the blinds predicted by Dymola per timestep for two representative days. The dark blue line represents the control actions at a timestep of 3600 s, and the redder the lines become, the smaller the timesteps.

The figure highlights that the predicted blind positions in Dymola approached the measured blind positions the smaller the timestep got.

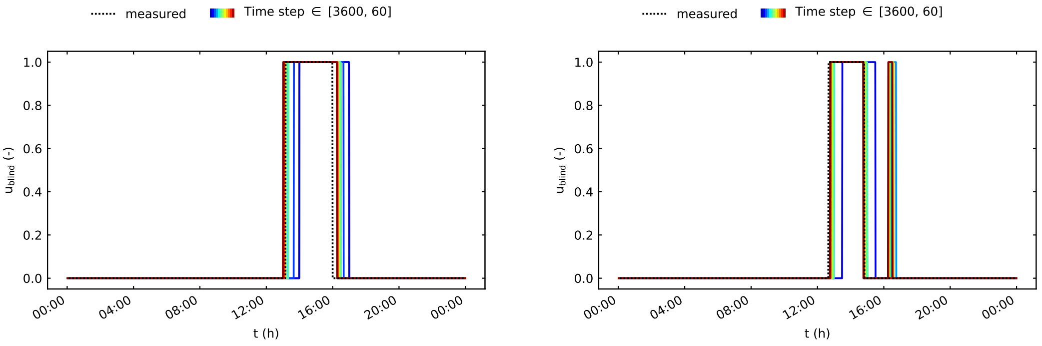


(a) 11 August.

(b) 12 August.

Figure 7.18: Blind positions predicted by Dymola per timestep for two representative days (dark blue: timestep of 3600 s, dark red: timestep of 60 s).

But this was not always the case for the EMS feature, as shown in Figure 7.19. While the predicted blind positions on 11 August approached the measured blind positions (Figure 7.19a), the interpolation error discussed above seemed to persist for some timesteps on 12 August (Figure 7.19b). Another reason for this, however, that emerged in this part of the study could be the use of the trend variables in the EMS feature to model the time delay of the control strategy. The trend variables stored the history of the solar irradiance to change the position of the blinds when it was greater than 250 W/m^2 for more than 900 s – but only for a multiple of the timestep. Since timesteps were not always evenly divisible by the time delay of 900 s, the time delay could only be approximated for some timesteps. For example, for a timestep of 600 s, the number of timesteps logged could be either 600 or 1200 s, but not 900 s. By contrast, for a timestep of 60 s, 15 timesteps could be logged, allowing the time delay to be predicted with greater accuracy.



(a) 11 August.

(b) 12 August.

Figure 7.19: Blind positions predicted by EMS feature for two representative days (dark blue: timestep of 3600 s, dark red: timestep of 60 s).

This highlights difficulties in modelling control strategies with time delays in the EMS feature, which can be modelled more straightforwardly in Dymola. A possible workaround for other modellers in the EMS feature could be to adjust the timestep according to the time delay of the control strategy. Nevertheless, the interpolation error discussed earlier must also be taken into account, because even if the originally selected timestep of 300 s was evenly divisible by the time delay of 900 s, the simulation in the EMS feature resulted in errors in the predictions of the control strategy. Therefore, the interpolation error appears to be a numerical artefact in EnergyPlus of which one should be aware and which is an important issue for future research.

7.6 Conclusion

This research was undertaken to assess the accuracy of the proposed modelling approach for predicting the performance of control strategies for adaptive building envelopes. The results of the validation show that the validated model of MATELab accurately captured the building envelope controls and properties with median CV-RMSE indices of 0.56 % for Dymola in the co-simulation and 0.57 % for the EMS feature in the mono-simulation. This underlines the capability of both models to accurately reflect the variability in the measured data.

While this result indicates that the modelling approach can generally be used to predict the behaviour of adaptive building envelopes, it also shows that EnergyPlus, with the support of the EMS feature, is equally capable of predicting the control actions of MATELab's blind automation system compared to Dymola. However, due to its integration into the EnergyPlus tool structure, the EMS feature has a number of limitations that other modellers should be aware of. For example, trend variables in the EMS feature used to model time delays of control strategy only store the history of sensor variables for a multiple of the timestep. This makes it less suitable for implementing control strategies with time delays. Compared to the EMS feature, Dymola offers much more flexibility in modelling control strategies for adaptive building envelopes, and the time lagging of the coupling data in the co-simulation was not decisive for the model output.

However, the evidence of the validation study also suggests that the control strategy is only one part of an adaptive building envelope model and that the variables related to the control strategy are not important for the model outcome. It is therefore equally critical for the verification and validation process to accurately create the weather file and the other model components and to carefully select the timestep. Another conclusion from the validation study is that due to the successful validation of the control algorithm for MATELab's blind automation system, it can be assumed that the control algorithm is transferable to other building envelopes. However, as the validation has only tested the model over its domain of applicability (i.e. the RBC algorithm), further testing is required, e.g. through comparative testing, to create a truth standard for other control algorithms.

8 Test of functionality of modelling approach through a case study

In this chapter, a test was carried out to assess the suitability of the proposed modelling approach for completing the types of tasks that end users need to be able to complete with it, i.e. to help design to tune the operation of adaptive building envelopes, using a multiple-case study. It starts with a description of the case study methodology and of the case study buildings and control strategies. The chapter then discusses the key findings that emerged from quantifying the thermal performance of each case predicted by the modelling approach. Finally, the findings are summarised and the suitability of the proposed modelling approach is assessed.

8.1 Rationale for case study design

An objective of this research was to analyse the applicability of the modelling approach under conditions likely to be encountered in real design projects questioning (i) how useful the modelling approach is for evaluating the thermal performance of design alternatives for adaptive building envelopes, and (ii) how suitable the modelling approach is for completing the types of tasks that end users need to be able to complete with it. To provide an in-depth description of how the proposed modelling approach works in its specific context, a case study design was considered a useful methodological approach for finding answers to the research problem (Fellows and Liu, 2015). A case study design was preferred because case study research, which investigates phenomena or issues in their real-life context, is highly relevant to a project-driven industry like the built environment (Proverbs and Gameson, 2008). Although the simulation of a case study is not the same as the reality, it is ‘a method (...) to model the operation of "real-world" processes, systems or events’ (J. Davis, Eisenhardt and Bingham, 2007, p. 481).

8.2 Case study methodology: design and case selection

Fundamental aspects of case study research have been discussed by Merriam (1998), Stake (2006) and Yin (2014). While Merriam (1998) and Stake (2006) suggest using only qualitative methodologies in a case study, Yin advocates using both qualitative and quantitative methodologies (Yazan, 2015). This part of the study consequently followed Yin’s approach as it was part of a mixed-methods study.

8.2.1 Case study research design

A case study consists of a detailed examination of one or more cases, and when determining how to conduct case study research, it is important to consider the number of cases to be examined. Case study research designs can use either a single- or a multiple-case design. Each of these designs uses a different number of cases, i.e. the ‘[objects] of the case study identified as the entity of interest or unit of analysis’ (Harrison et al., 2017). Compared to a single-case design, a multiple-case design uses multiple cases to allow for cross-case analysis and comparison to investigate a specific phenomenon in different settings (Runeson et al., 2012). Furthermore, a multiple-case design can adopt either a holistic or embedded design. Each of these designs uses a different number of units of analysis, the subunits that are the subject of the analysis (Grünbaum, 2007). When cases are inherently complex, an embedded design is more appropriate due to its focus on complex details (i.e. subunits) in the case (C. Meyer, 2001).

In this part of the study, an embedded multiple-case study design was preferred over a single-case study design because a single-case design can be vulnerable in terms of case selection (Yin, 2014). For this reason, a multiple-case study design can be used for theory building, yielding a ‘more robust, generalizable, and testable theory’ (Eisenhardt and Graebner, 2007, p. 27). However, a question that needs to be encountered in multiple-case research is the number of cases needed for the study, which generally depends on the degree of certainty of results the researcher wishes to accomplish (Shakir, 2002). Even a *two-case* case study may have substantial benefits as ‘analytic conclusions independently arising from two cases (are) more powerful than those coming from a single case’ (Yin, 2014, p. 64). When theory is straightforward and research demands no excessive degree of certainty, Yin (2014) suggests using two to three cases to ensure validity. As a result, this part of the study adopted a two-case research design, regarding each investigated building a case.

The units of analysis were the control strategies for adaptive building envelopes within each building, enabling this research to compare (i) individual control strategies within each building (intra-building comparison) and (ii) each control type across different buildings (inter-building comparison), as shown in Figure 8.1.

Two distinct control strategies were analysed within each case study building to guarantee theoretical replication of control features and to draw conclusions from each control type to the building performance. The two distinct control strategies were developed with different levels of complexity to analyse the functionality of the modelling approach in terms of mono- and co-simulation. Consequently, the performance of one control strategy was predicted using the mono-simulation setup and that of the other using the co-simulation setup.

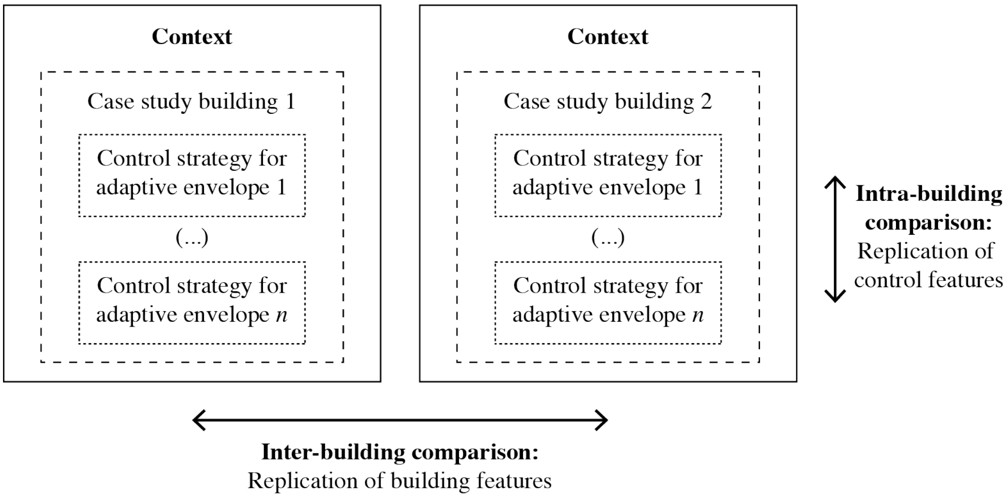


Figure 8.1: Embedded multiple-case study design.

8.2.2 Selection of the case studies

The purpose of case study research is to develop theory, which is why cases are selected theoretically rather than e.g. randomly (Runeson et al., 2012). Theoretical sampling aims at selecting cases, which ‘are particularly suitable for illuminating and extending relationships and logic among constructs’ (Eisenhardt and Graebner, 2007, p. 27).

Following Yin (2014), cases in multiple-case research should be selected in such a way that they either predict similar results (literal replication) or contrasting results but for anticipatable reasons (theoretical replication). To allow transferability of the case study findings to situations outside the original case study, replications that predict similar results were selected. Key criteria for the selection of the case study buildings were:

- typical case study buildings to represent a broader set of cases; and
- similar adaptive building envelopes to provide a basis for transferability.

The selected case study buildings were provided by BuroHappold and Arup, professional services firms. Both were open plan office developments in Central London, UK. The façades of the case study buildings had automated motorised blinds, each with two distinct control strategies as the embedded units of analysis. The control strategies were selected based on the capabilities offered by the modelling approach, which helped to exemplify the various uses of the modelling approach and illuminate the full range of variation of the set of cases.

8.2.3 Limitations of case study research

Like any other research method, case study research can lack rigour and trustworthiness (Eisenhardt and Graebner, 2007). To establish the quality of the case study research, Yin (2014) developed four tests to frame the research process, three of which were relevant to this part of the study. The three tests are listed in Table 8.1 and were applied throughout the conduct of this case study in the following way:

1. **Construct validity:** Detailed description of the case study's general methods and procedures, and carrying out of case study as part of mixed-methods research.
2. **External validity:** Selection of the multiple case studies based on the replication logic to allow transferability of findings.
3. **Reliability:** Detailed description of objectives, procedures and instruments to minimise errors and biases in the case study.

Table 8.1: Validity and reliability in case study research (Yin, 2014).

Test	Description	Case study tactic	Research phase
Construct validity	Identify correct operational measures for the concepts being studied	• Use multiple sources of evidence • Establish chain of evidence	Data collection
External validity	Define the domain to which the study's findings can be transferred	• Use replication logic in multiple-case studies	Research design
Reliability	Demonstrate that the study's operations can be repeated, with the same results	• Use case study protocol • Develop case study database	Data collection

8.3 Data collection methodology

The data collection for the case study was subdivided into three main phases: (i) pre-processing, (ii) simulation and (iii) post-processing, as can be seen from Figure 8.2. The pre-processing was concerned with the implementation of the building and controller models, and input information about the case study buildings was taken from the following sources:

1. documentary information including project reports, design notes and energy building models; and
2. personal communication with project engineers to augment and corroborate documentary information.

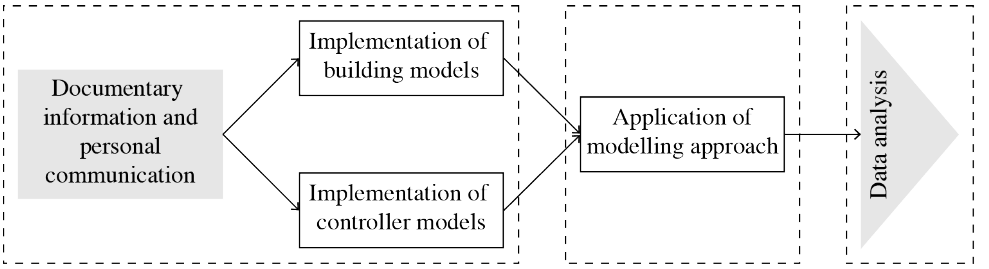


Figure 8.2: Steps involved in data collection of multiple-case study.

8.3.1 Pre-processing

The pre-processing included the development and structuring of the integrated model. The first step was to implement the building models in EnergyPlus, and the second step was to set up the models for the blind controllers in EnergyPlus and Dymola.

8.3.1.1 Building models in EnergyPlus

The building models were first implemented in EnergyPlus. The geometry inputs of the building models were created using Euclid (Software, 2017), an extension to SketchUp (Trimble, 2016) to read and write EnergyPlus geometry in its native IDF format. Detailed input information of the case study buildings is presented in Table 8.2. When referring to a specific case study building, a code that is formed by the letter B (which stands for building) and a number is applied.

The case study buildings were modelled with all floors in EnergyPlus. Since the largest part of the area of each floor was open plan offices and the other usages, such as toilets, tea kitchens and circulation areas, only accounted for a very small proportion, each floor was lumped into one zone. This was done for modelling reasons and was also considered sufficient to obtain an estimate of the total building load and to evaluate design alternatives. If there were several identical zones, zone multipliers were used to reduce the number of zones processed.

The building envelopes were modelled together with the case study buildings in EnergyPlus, and building envelope parameters are shown in Table 8.3.

8.3.1.2 Controller models

The next step was to set up the blind controller models in EnergyPlus to actuate (i) the positions of the blinds and (ii) the slat angles of the blinds. Two distinct control strategies were modelled analyse the functionality of the proposed modelling approach in performing mono- and co-simulations and to exemplify its various uses:

1. a single-input RBC strategy using the mono-simulation setup; and
2. a multi-input RBC strategy using the co-simulation setup.

When referring to a specific control strategy, a code that is formed by the letter C (which stands for control) and a number is applied.

C01 – Single-input RBC strategy

The control strategy C01 was a single-input RBC strategy that was modelled in EnergyPlus alone in order to test the functionality of the mono-simulation setup of the modelling

Table 8.2: Input information of case study buildings.

Parameter	Condition in each case study building	
	Case study building B01	Case study building B02
General description		
Building type	Office	Office
Typical floor layout	Open plan office accommodation	Open plan office accommodation
Location	Barbican, London (UK)	Spitalfields, London (UK)
Coordinates	N51°31′5.351″ W0°5′57.242″	N51°31′9.680″ W0°4′44.936″
Weather file	London Gatwick DSY2	London Gatwick DSY2
Geometry		
Number of floors	11	47
Building footprint	45.7 m × 54.7 m (square)	66.0 m × 47.2 m (L-shaped)
Floor area	26 340 m^2	76 462 m^2
Opaque structures		
External wall	Type: Aluminium rainscreen system U-value: 0.19 W/m^2	Type: Rainscreen façade system U-value: 0.27 W/m^2
External roof	Type: Inverted membrane roofing system U-value: 0.19 W/m^2	Type: Concrete deck roof U-value: 0.31 W/m^2
External floor	Type: Solid concrete floor U-value: 0.34 W/m^2	Type: Solid concrete floor U-value: 0.26 W/m^2
Transparent structures		
Glazing	Type: DSF (outer: single-glazed pane with solar control coating, inner: double-glazed pane with low-e coating) U-value: 1.10 W/m^{2}K	Type: CCF (outer: laminated low-iron glazing, inner: double-glazed unit with semi low-iron glazing and low-e coating) U-value: 0.90 W/m^{2}K
Façade depth	350 mm	220 mm
Glazing area	58.0 %	62.0 %
Shading	Automated blind, on all glazing except ground floor and stairwells	Automated blind, on all glazing
HVAC system		
HVAC system type	Ideal air system that meets heating and cooling loads	Ideal air system that meets heating and cooling loads
Thermostat control	Dual setpoint with deadband	Dual setpoint with deadband
Thermostat setpoints	Winter: 20.0 °C; Summer: 24.0 °C	Winter: 21.0 °C; Summer: 24.0 °C
Loads		
Occupancy	Number of people: 8.00 m^2/person Activity level: 130 W/person Schedule: 07:00 - 19:00	Number of people: 3.70 m^2/person Activity level: 126 W/person Schedule: 07:00 - 19:00
Equipment	25.0 W/m^2	12.8 W/m^2
Lighting	50.0 W	13.5 W/m^2
Rates		
Infiltration rate	–0.30 h^{-1}	–0.30 h^{-1}
Ventilation rate	12.0 L/(s person) (natural and mechanical)	0.025 m^3/s (mechanical)

Table 8.3: Building envelope parameters of case study buildings.

	Case study building B01	Case study building B02
Building envelope		
Type	DSF with automated blind	CCF with automated blind
Centre-pane U-value	1.10 W/m^{2}K	0.90 W/m^{2}K
g-value	0.14 – 0.50*	0.12 – 0.52*
Visible light transmittance	0.000 % – 65.0 %*	5.00 % – 65.0 %*
Blind		
Slat width/distance	60.0 mm/50.0 mm	80.0 mm/72.0 mm
Colour	White	Light grey
Solar reflectance	58.0 %	65.0 %
Visible reflectance	57.0 %	71.0 %

* lower value: closed blinds, upper value: open blinds

approach. The control strategy of C01 is an example of a two-state Finite-State Machine, often found in real blind automation systems, and is shown in Table 8.4. The inputs of this control strategy are the direct and diffuse solar irradiance, and the outputs are the position of the blind and the slat angle of the blind.

Table 8.4: Control strategy C01 for case study buildings.

Input	$I_{\mathrm{sol,dir}}$: direct solar irradiance in W/m^2 $I_{\mathrm{sol,diff}}$: diffuse solar irradiance in W/m^2
Output	$u_{\mathrm{blind}} \in [0,1]$: position of the blind (0 = open, 1 = closed) u_{slat}: slat angle of the blind in °
Algorithm	

```
set $I_{\mathrm{sol}} = I_{\mathrm{sol,dir}} + I_{\mathrm{sol,dif}}$
if $I_{\mathrm{sol}} > 240\,\mathrm{W/m^2}$ then
  $u_{\mathrm{blind}} = 1$ and $u_{\mathrm{slat}} = 45.0°$
else
  $u_{\mathrm{blind}} = 0$
end if
```

The control strategy C01 was modelled in the `WindowProperty:ShadingControl` object in EnergyPlus by entering 240 W/m^2 as `Setpoint` and `OnIfHighSolarOnWindow` as `Shading Control Type`. The slat angles of the blinds were fixed to 45.0°.

C02 – Multi-input RBC strategy

The control strategy C02 was a multi-input RBC strategy whose modelling required the use of Dymola to test the functionality of the co-simulation setup of the modelling approach. It was based on (i) the intensity of the global solar irradiance I_{sol} to control solar heat gains and (ii) the site solar altitude γ_{sol} to prevent direct sunlight passing through the façade. The threshold values of the control strategy, an example of a multiple-state Finite-State Machine, can be seen in Table 8.5. These values were calculated so that, when the blinds were closed, the g-value limited the solar heat gains to 100 W/m^2 of floor area, based on a 4.5 m floor depth. When the sky was cloudy with a global horizontal illuminance lower than 15 000 lx, the control strategy was overridden, and the blinds were fully retracted.

Table 8.5: Control strategy C02 for case study buildings.

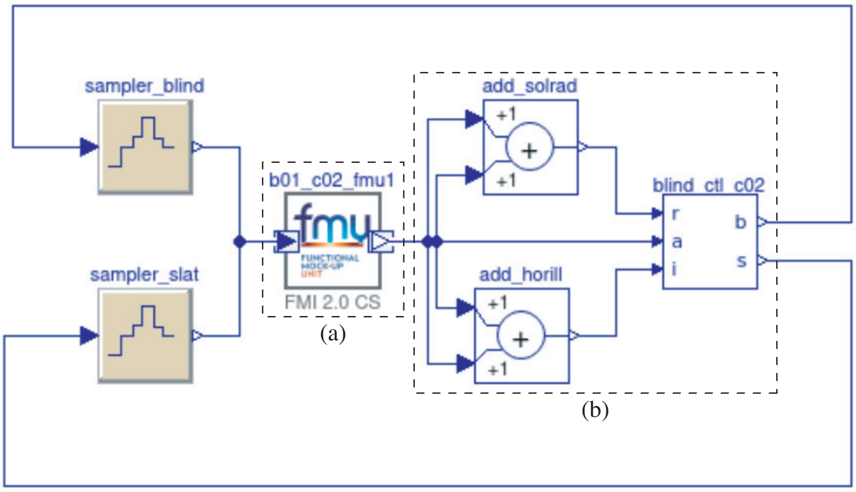
Input	$I_{\mathrm{sol,dir}}$: direct solar irradiance in W/m^2 $I_{\mathrm{sol,diff}}$: diffuse solar irradiance in W/m^2 γ_{sol}: site solar altitude in °
Output	$u_{\mathrm{blind}} \in [0, 1]$: position of the blind (0 = open, 1 = closed) u_{slat}: slat angle of the blind in °

Algorithm

```
set $I_{\mathrm{sol}} = I_{\mathrm{sol,dir}} + I_{\mathrm{sol,dif}}$
if $240\,\mathrm{W/m^2} \leq I_{\mathrm{sol}} < 530\,\mathrm{W/m^2}$ and $\gamma_{\mathrm{sol}} > 42.0°$ then
  $u_{\mathrm{blind}} = 1$ and $u_{\mathrm{slat}} = 90.0°$ (horizontal)
elif $330\,\mathrm{W/m^2} \leq I_{\mathrm{sol}} < 330\,\mathrm{W/m^2}$ and $42.0° \geq \gamma_{\mathrm{sol}} > 24.8°$ then
  $u_{\mathrm{blind}} = 1$ and $u_{\mathrm{slat}} = 60.0°$
elif $530\,\mathrm{W/m^2} \leq I_{\mathrm{sol}} < 770\,\mathrm{W/m^2}$ and $24.8° \geq \gamma_{\mathrm{sol}} > 15.3°$ then
  $u_{\mathrm{blind}} = 1$ and $u_{\mathrm{slat}} = 45.0°$
elif $770\,\mathrm{W/m^2} \leq I_{\mathrm{sol}} < 920\,\mathrm{W/m^2}$ and $15.3° \geq \gamma_{\mathrm{sol}} > 3.90°$ then
  $u_{\mathrm{blind}} = 1$ and $u_{\mathrm{slat}} = 30.0°$
elif $I_{\mathrm{sol}} \geq 920\,\mathrm{W/m^2}$ and $\gamma_{\mathrm{sol}} \leq 3.90°$ then
  $u_{\mathrm{blind}} = 1$ and $u_{\mathrm{slat}} = 0.000°$ (closed)
else
  $u_{\mathrm{blind}} = 0$ (open)
end if
```

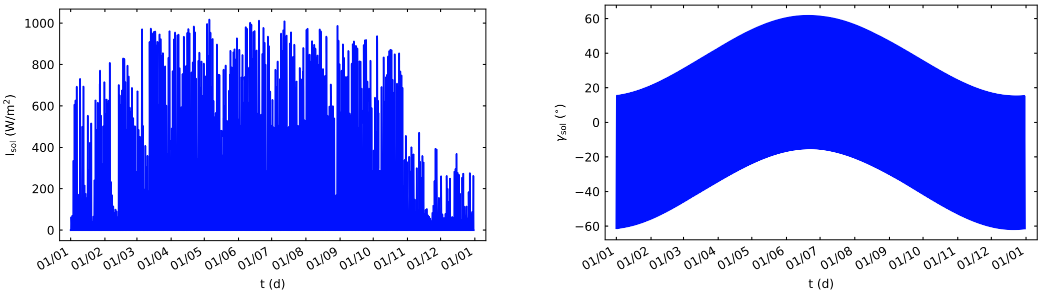
8.3.1.3 Co-simulation setup

The multi-input RBC strategy C02 required the creation of a co-simulation model in Dymola, the co-simulation coordinator, for each of the case study buildings. The EnergyPlus model with the building and building envelope components was initially encapsulated and shared using an FMU. For this purpose, the modelling approach was applied. To facilitate the execution of repetitive or technically intensive tasks in this and subsequent phases, a Python script was written that used the different modules of the modelling approach and combined them in a new script. To create the FMU from the EnergyPlus model, the `export` function of the `idf_to_fmu` class of the `cosim` package was used. The FMU was then imported into Dymola and then manually connected to exchange variables or signals with the controller model, as shown in Figure 8.3. To load the FMU automatically when Dymola was invoked from Python, the personal setup file *startup.mos* in Dymola was modified to ensure that Dymola always loaded the FMU when it was opened.



(a) Building and building envelope model (FMU)
(b) Controller model

Figure 8.3: Graphical representation of the Dymola model of case study building B01.



(a) Global solar irradiance I_{sol}. (b) Solar altitude γ_{sol}.

Figure 8.4: Weather data.

8.3.2 Simulation

The modelling approach was also applied in the simulation phase. The following functions of the `cosim` package were used to run the simulations: `cosim.simulate.monosimulate` for C01 and `cosim.simulate.cosimulate` for C02.

Simulations were run for an entire year with a timestep of 600 s. This timestep was chosen to achieve better accuracy for the simulation results and was obtained from ‘simple interpolation between "last hour’s" values and "this hour’s" values’ of the hourly weather data’ (DOE, 2018d, p. 2648). The 600-second timestep of EnergyPlus had to be equal to the sampling time of the FMU, which was achieved through a sampler that sampled the input signals and computed the output signals from the sampled input signals by a given sample period. Dymola then synchronised the FMU every simulation timestep of 600 s.

For the simulations, the DSY2 weather file of London Gatwick (CIBSE, 2014) was used. The weather data relevant for the simulation of the control strategies are shown in Figure 8.4.

8.3.3 Post-processing

For the post-processing, the predicted performances of the case study buildings with the two distinct control strategies were quantified and analysed using Python. The quantifiable performance indicators in this part of the study were (i) window heat gains and losses and (ii) indoor radiant temperatures. To automatically combine the predicted data into one dataset, Pandas was used. The data from the dataset were then statistically analysed and graphically presented and compared by using, among others, Matplotlib and Numpy.

8.4 Data analysis methodology

To better understand the phenomena under study and to propose new theoretical insights to generate new ideas and hypotheses, Yin (2014) recommends to use an analytic strategy that follows repeated cycles. These cycles consist of examining, categorising, tabulating, testing or otherwise recombining qualitative and quantitative evidence to address the research questions. Based on these analytic strategies, Yin (2014) developed five different techniques for the analysis of the cases studies. Of these five techniques, three were used in this part of the research:

- **Explanation building:** The aim of explanation building is to generate hypotheses and ideas for further studies by analysing the case study data and building an explanation about the case.
- **Time-series analysis:** The aim of time-series analysis is to elaborate trends and develop rich explanations by examining events over time using specific indicators.
- **Cross-case synthesis:** The aim of cross-case synthesis is to generate case knowledge by drawing cross-case conclusions through research syntheses and meta-analyses.

While explanation building allows for the development of causal relationships about the original topic of interest, a researcher can slowly drift away from it during the analysis if safeguards, such as a continuous examination of possible alternative explanations, are not in place. In contrast, time-series analysis can provide a solid basis for case study conclusions if it follows many complex and precise patterns and identifies trends in the data. A large number of data points, however, can make it more difficult to track changes over time within a given case. Similarly, a cross-case synthesis can enable a case study to make robust conclusions, although it relies heavily on strong and plausible arguments supported by the data (Yin, 2014).

8.5 Discussion of key findings

This part of the study set out to test the functionality of the modelling approach under conditions likely to be encountered in real design projects in terms of its usefulness and suitability. Two sets of analysis were conducted to compare (i) individual control strategies within each building (intra-building comparison) and (ii) each control type across different buildings (inter-building comparison).

8.5.1 Single-case analysis

The first set of analysis compared the thermal performances of the controller models within each case study building. This intra-building comparison allowed to draw conclusions from each control type on the performance of the single case.

8.5.1.1 Analysis of case study building B01

Simulation results suggest that the studied control strategies significantly influenced the performance of case study building B01. Initially, the performance was measured as monthly window heat gains and losses, which are the heat flow to or from a zone through an exterior window. As shown in Figure 8.5, the monthly window heat gains $Q_{\text{win,gn}}$ of C02 were on average 7.84 % lower than the monthly window heat gains of C01 (C01: 2.87×10^7 W/m^2, C02: 2.64×10^7 W/m^2). In contrast, the monthly window heat losses $Q_{\text{win,ls}}$ of C02 were on average 0.13 % higher than the monthly window heat losses of C01 (C01: -2.80×10^7 W/m^2, C02: -2.80×10^7 W/m^2), as can be compared in Table 8.6.

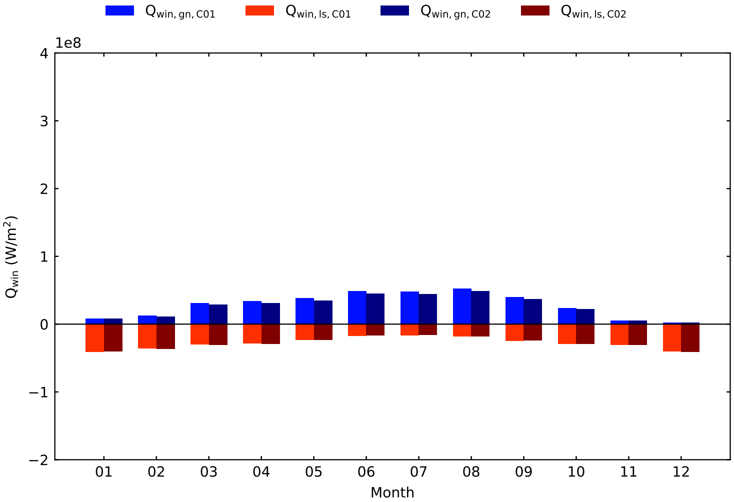


Figure 8.5: Comparison of B01 monthly mean values of $Q_{\text{win,gn}}$ and $Q_{\text{win,ls}}$.

Although the differences in the window heat gains and losses were not significant, they can be explained by the control strategies. As shown in Figures 8.6 and 8.7, blinds were

Table 8.6: Summary statistics for B01 monthly mean values of $Q_{\text{win,gn}}$ and $Q_{\text{win,ls}}$.

control strategy	Median	Standard deviation	Minimum	Maximum
$Q_{\text{win,gn}}$ (W/m^2)				
C01	2.87×10^7	1.79×10^7	2.06×10^6	5.22×10^7
C02	2.64×10^7	1.65×10^7	1.91×10^6	4.85×10^7
$Q_{\text{win,ls}}$ (W/m^2)				
C01	-2.80×10^7	8.36×10^6	-4.08×10^7	-1.64×10^7
C02	-2.80×10^7	8.56×10^6	-4.07×10^7	-1.58×10^7

less often open in C01 than in C02. The figures illustrate the blind positions per façade orientation, averaged over one hour during occupied hours for the whole year: blue (0.0) represents open blinds, i.e. $u_{\text{blind}} = 0$, and red (1.0) represents closed blinds, i.e. $u_{\text{blind}} = 1$ and $u_{\text{slat}} = 0°$. In C01, the blinds were open 96.6 % of the time, and in C02, 86.9 % of the time, which was due to the control strategies. While C01 only closed the blinds with a slat angle of 45°, C02 closed the slats of the blinds even further, depending on the amount of global solar irradiance and the site solar altitude. This may have resulted in a better barrier against heat flow through the windows in C02, as a greater percentage of the windows was closed. More heat was consequently reflected back through the windows and less heat was released into the room air. Nevertheless, it may be assumed that the solar heat warmed the blinds and this heat was immediately released into the room air, possibly resulting in an increase in indoor temperature.

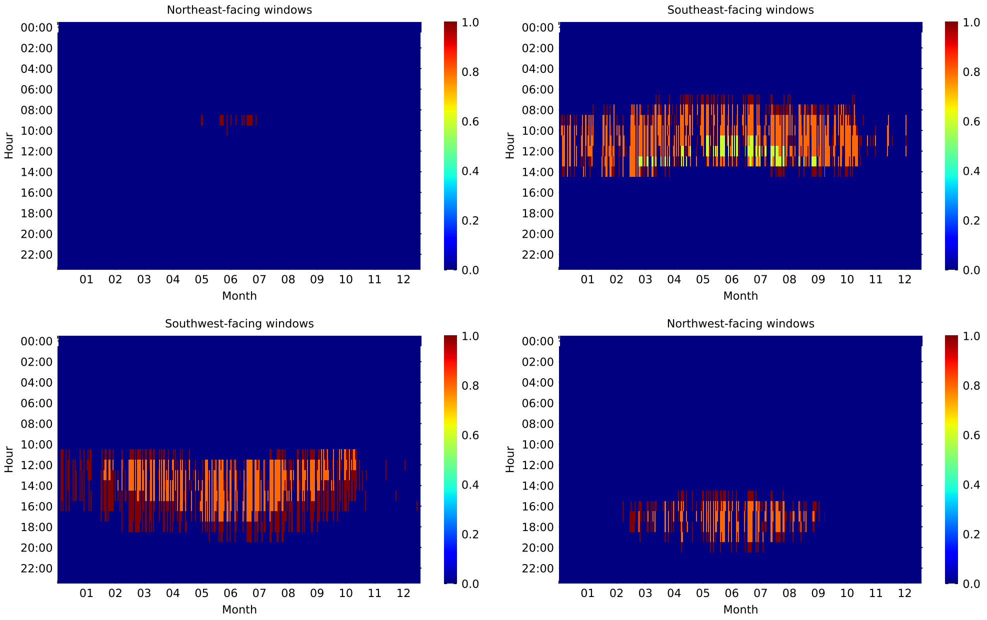


Figure 8.6: Hourly B01 blind positions per façade orientation of C01: values in the colour bar refer to 0.0 = open, 0.2 = horizontal, 0.4 = tilt 60°, 0.6 = tilt 45°, 0.8 = tilt 30° and 1.0 = closed.

The data reported in this section appear to support the assumption that the control strategies influenced the behaviour of the blinds differently. In the case studied, the more

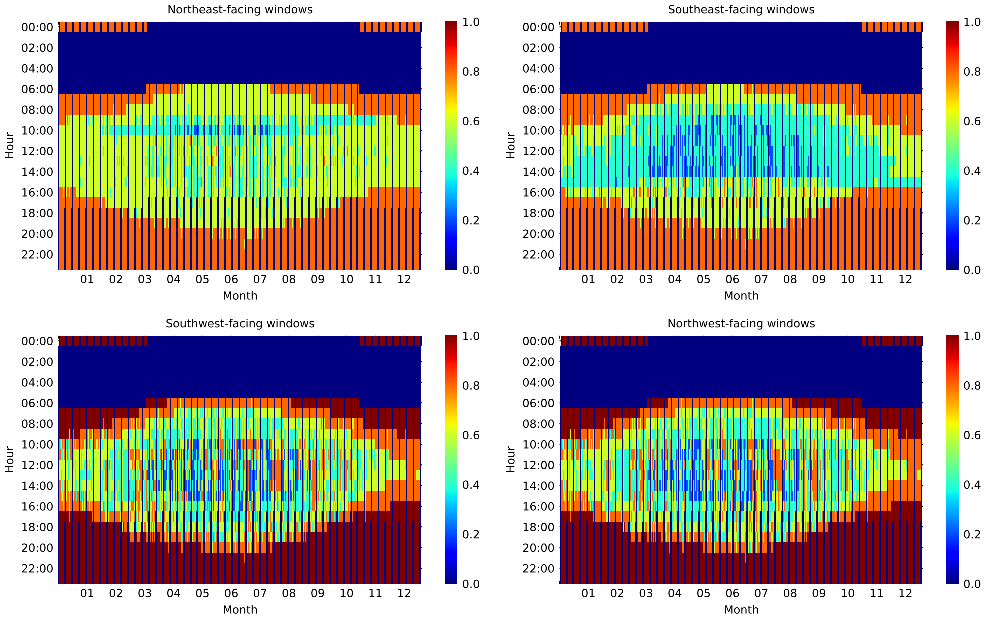


Figure 8.7: Hourly B01 blind positions per façade orientation of C02: values in the colour bar refer to 0.0 = open, 0.2 = horizontal, 0.4 = tilt 60°, 0.6 = tilt 45°, 0.8 = tilt 30° and 1.0 = closed.

complex control strategy C02 resulted in a better performance than the less complex control strategy C01, at least in terms of window heat gains and losses. However, the window heat gains and losses will also have an effect on other performance criteria, such as indoor temperature. Since a lower indoor temperature will also affect the heating and cooling demand of the case study building, the positions of the blinds will also have an indirect effect on the energy use for heating and cooling.

8.5.1.2 Analysis of case study building B02

Similar to case study building B01, simulation results suggest that the studied control strategies significantly influenced the performance of case study building B02. This is evident in the comparison of the monthly window heat gains and losses shown in Figure 8.8. It shows that the monthly window heat gains $Q_{\text{win,gn}}$ of C02 were on average 24.7 % lower than the monthly window heat gains of C01 (C01: 2.26×10^8 W/m^2, C02: 1.70×10^8 W/m^2). Similarly, the monthly window heat losses $Q_{\text{win,ls}}$ of C02 were on average 0.54 % lower than the monthly window heat losses of C01 (C01: -6.56×10^7 W/m^2, C02: -6.53×10^7 W/m^2), as can be compared in Table 8.7.

The differences in the window heat gains and losses may be again due to the control strategies studied. As shown in Figures 8.9 and 8.10, the blinds were less often open in C01 than in C02. While the blinds were open 96.9 % of the time in C01, they were open 72.3 % of the time in C02.

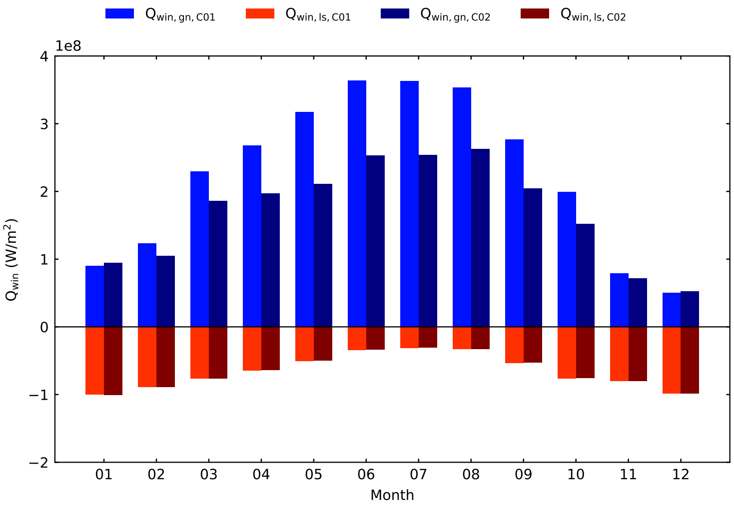


Figure 8.8: Comparison of B02 monthly mean values of $Q_{\text{win,gn}}$ and $Q_{\text{win,ls}}$.

Table 8.7: Summary statistics for B02 monthly mean values of $Q_{\text{win,gn}}$ and $Q_{\text{win,ls}}$.

control strategy	Median	Standard deviation	Minimum	Maximum
$Q_{\text{win,gn}}$ (W/m^2)				
C01	2.26×10^8	1.16×10^8	5.06×10^7	3.64×10^8
C02	1.70×10^8	7.40×10^7	5.22×10^7	2.63×10^8
$Q_{\text{win,ls}}$ (W/m^2)				
C01	-6.56×10^7	2.49×10^7	-9.99×10^7	-3.12×10^7
C02	-6.53×10^7	2.52×10^7	-1.00×10^8	-3.06×10^7

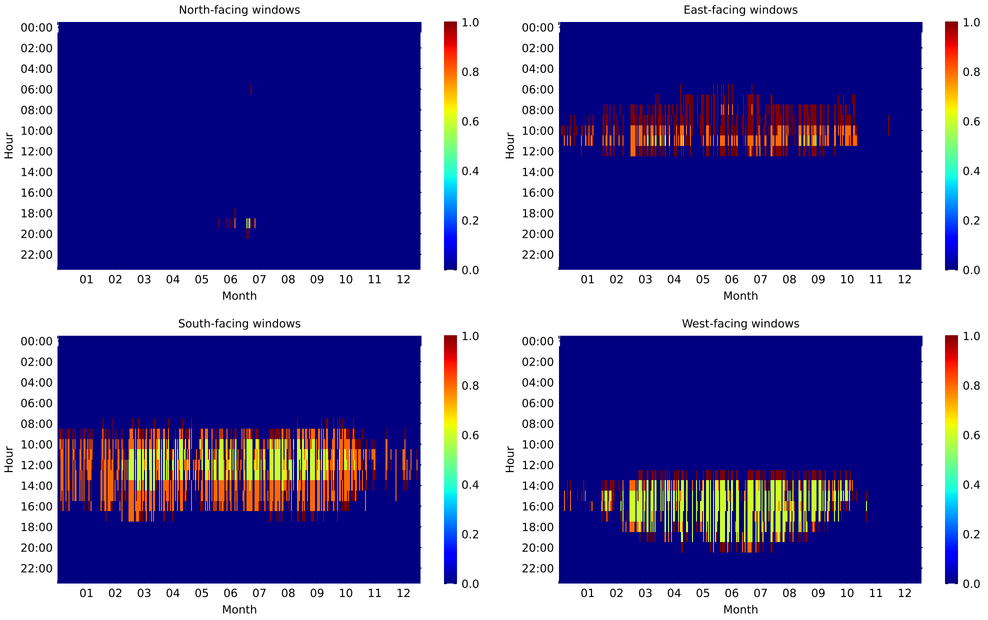


Figure 8.9: Hourly B02 blind positions per façade orientation of C01: values in the colour bar refer to 0.0 = open, 0.2 = horizontal, 0.4 = tilt 60°, 0.6 = tilt 45°, 0.8 = tilt 30° and 1.0 = closed.

What was interesting in the B02 data on monthly window heat gains was that the monthly window heat gains were generally higher than in the B01 data. Furthermore, there appeared to be a seasonal effect of the control strategies on the monthly window heat gains, as the

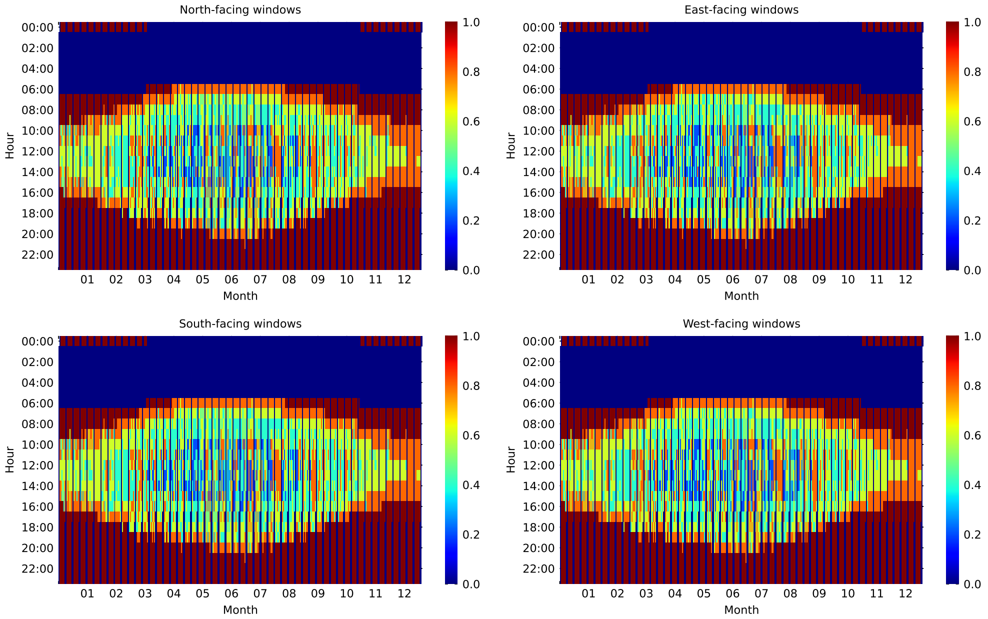


Figure 8.10: Hourly B02 blind positions per façade orientation of C02: values in the colour bar refer to 0.0 = open, 0.2 = horizontal, 0.4 = tilt 60°, 0.6 = tilt 45°, 0.8 = tilt 30° and 1.0 = closed.

differences in window heat gains occurred mainly in the summer months and less in the winter months. This may be due to the main orientations of the windows, as the orientation has a significant impact on the amount of solar irradiance, with east, south-east, south, south-west and west receiving higher amounts in the northern hemisphere in summer than north-east, north and north-west. Considering that B01 windows face mainly north-east, south-east, south-west and north-west and B02 windows face mainly north, east, west and south, B02 received higher window heat gains, particularly in the summer months. Also considering that the blinds were closed more often in C02 than in C01, it was less surprising that monthly C02 window heat gains were on average 24.7 % lower than monthly C01 window heat gains in B02. However, this also highlights that in case study building B02, the more complex control strategy C02 resulted in a better performance than the less complex control strategy C01, hence confirming findings of B01.

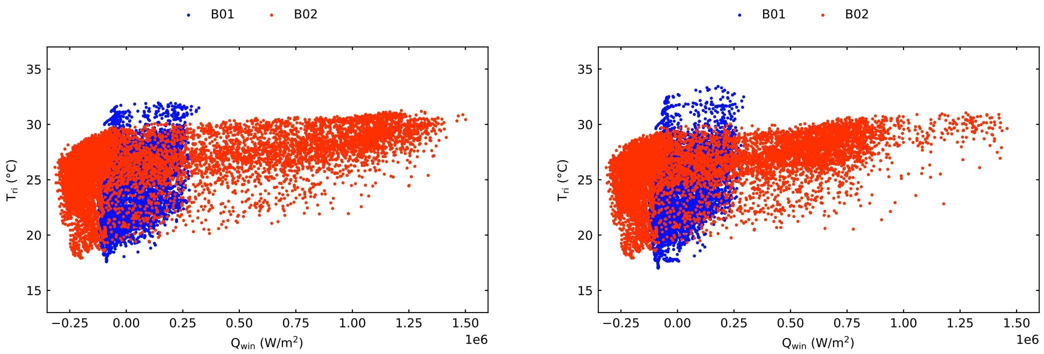
Returning to the question posed at the beginning of this part of the study, it is now possible to state that the modelling approach is useful in evaluating the performance of design alternatives for adaptive building envelopes by providing quantitative data to support decision-making. It is also possible to state that each of the blind controllers could be modelled in either (i) the mono-simulation setup of the modelling approach using the EMS scripting feature of EnergyPlus or (ii) the co-simulation setup of the modelling approach using Dymola, depending on their complexity.

8.5.2 Cross-case analysis

The second set of analysis compares the performances of each control strategy across the two case study buildings. To draw cross-case conclusions through research syntheses and meta-analyses, this inter-building comparison allowed to draw conclusions from each control type on the building performance across the case study buildings B01 and B02.

Since the findings of the first set of analysis showed that the control strategies of the blinds largely affected the window heat gains and losses, this section examines the relationship between window heat gains and losses, calculated as $Q_{\text{win}} = Q_{\text{win,gn}} + Q_{\text{win,ls}}$, and indoor radiant temperatures, another performance indicator. The indoor radiant temperature T_{ri} is a measure of the combined effects of the temperatures of surfaces within a building, i.e. the surface area multiplied by the emissivity (i.e. the thermal absorptance of the inside material layer of each surface) weighted average of the building inside surface temperatures.

Figure 8.11 shows the relationship between hourly window heat gains and hourly indoor radiant temperatures per control strategy. When visually assessing the correlations between window heat gains and indoor radiant temperatures, there were positive linear correlations in C01 and C02. This indicates that indoor radiant temperatures tended to increase as window heat gains increased.



(a) C01.

(b) C02.

Figure 8.11: Relationship between hourly mean values of Q_{win} and T_{ri}.

This was confirmed when calculating the strengths of the linear correlations r on the basis of S_{Pear} showing that the correlations were moderate in C01 (B01: $r = 0.25$, B02: $r = 0.008$) as well as in C02 (B01: $r = 0.29$ B02: $r = 0.038$). The moderate correlations between window heat gains and indoor radiant temperatures meant that as one variable increased or decreased, there was a better chance of the second variable increasing or decreasing. This suggests that indoor radiant temperatures depended on window heat gains and thus on the blind control strategies.

However, each of the control strategies had a similar effect on the indoor radiant temperatures in each case study building. For C01, mean indoor radiant temperatures of B01 were 9.43 % lower than mean window heat gains of B02 (B01: 24.0 °C, B02: 26.5 °C), as shown in Table 8.8. Similarly, for C02, mean indoor radiant temperatures of B01 were 9.13 % lower than mean window heat gains of B02 (B01: 23.9 °C, B02: 26.3 °C).

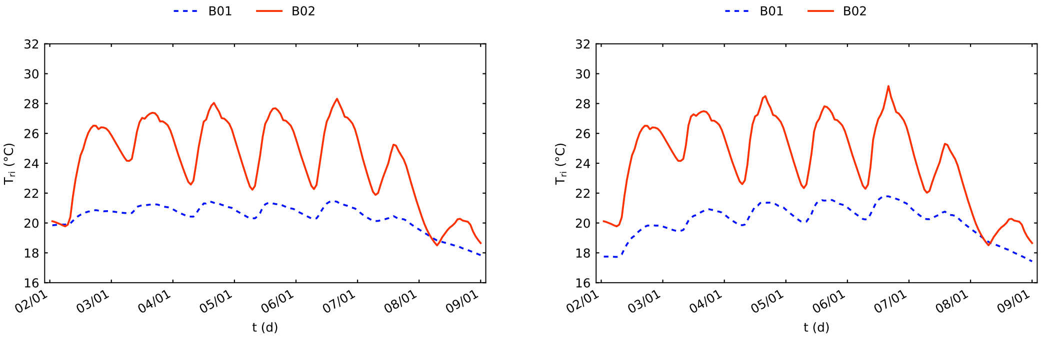
Table 8.8: Summary statistics for hourly mean values of T_{ri}.

Case study building	Median	Standard deviation	Minimum	Maximum
$T_{\mathrm{ri,C01}}$ (°C)				
B01	24.0	2.97	17.6	31.9
B02	26.5	2.45	17.9	31.3
$T_{\mathrm{ri,C02}}$ (°C)				
B01	23.9	2.86	17.0	33.4
B02	26.3	2.34	17.9	31.0

The most surprising aspect of the data is that, although the blinds in C01 were open equally often in B01 (96.9 %) and B02 (96.9 %), indoor radiant temperatures in B01 were lower than in B02. In C02, the blinds were even closed more often in B02 (72.3 %) than in B01 (86.9 %), yet the temperature performance of B01 was better. This may be due to the orientation of the external windows and walls of the case study buildings, with B01 receiving less solar irradiance than B02 due to its orientation and thus having lower indoor radiant temperatures. This suggests that whatever control strategy is chosen in B01, it may not be critical for the thermal performance of B01 and that other design parameters, such as the building orientation, may be more important.

This trend was also confirmed when the indoor radiant temperatures were examined in more detail. Figures 8.12, 8.13 and 8.14 compare the indoor radiant temperatures per control strategy for a winter, a mid-season and a summer week. These weeks were chosen because they had a high solar irradiance for the respective season, on which the control strategies depended. The figures show that B01 had lower indoor radiant temperatures than B02. For example, in C01, the mean indoor radiant temperatures in winter were 20.4 °C for B01 and 24.2 °C for B02, and in C02, 20.1 °C for B01 and 24.3 °C for B02.

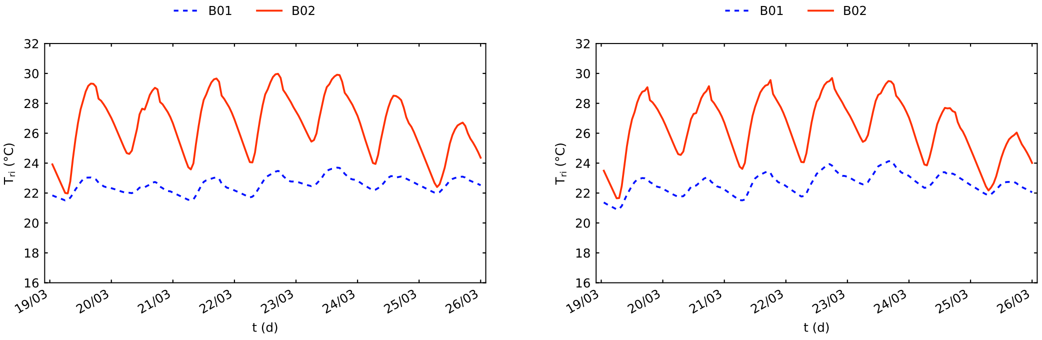
This finding is surprising as the control strategies do not seem to be the main determinant in terms of the thermal performance for the cases studied. However, as each building is very individual in its design parameters, this finding underlines the need for an accurate and representative prediction of design alternatives of adaptive building envelope controls in the design decision-making process. It also underlines that the modelling approach is capable of quantifying simulation outputs and making them comparable. As a result, the conclusions of the cross-case analysis confirms the results of the single-case analysis.



(a) C01.

(b) C02.

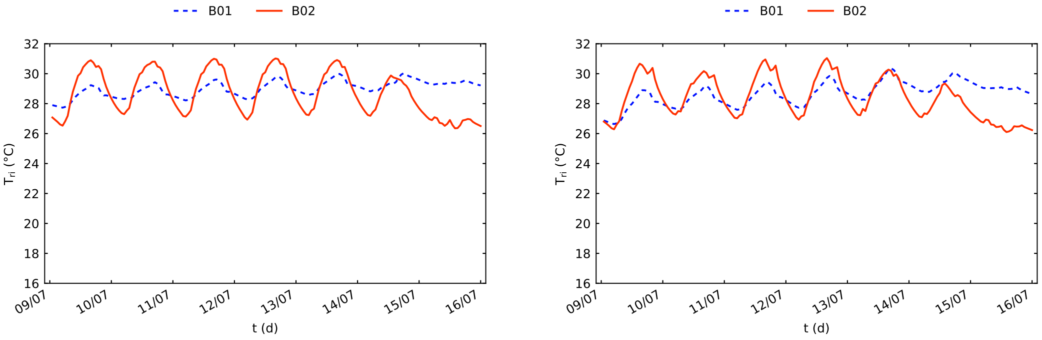
Figure 8.12: Comparison of hourly mean values of T_{ri} during winter.



(a) C01.

(b) C02.

Figure 8.13: Comparison of hourly mean values of T_{ri} during mid-season.



(a) C01.

(b) C02.

Figure 8.14: Comparison of hourly mean values of T_{ri} during summer.

8.6 Chapter summary and potential issues for end users

The findings of this multiple-case study confirm that the modelling approach can be applied in the design of building projects likely to be encountered in real design projects. Two distinct control strategies for automated motorised blinds were tested, and it was demonstrated that they had a greater effect on the thermal performance of case study building B02 than on case study building B01. As a consequence, the findings of this part of the study support the idea that the proposed modelling approach is able to predict the control strategies in

(i) the mono-simulation setup of the modelling approach using the EMS scripting feature of EnergyPlus and (ii) the co-simulation setup of the modelling approach using Dymola. The findings also support the idea that the simulation outputs can be quantified and compared across cases to support sound decision-making in design practice.

However, the case study also set out to assess the suitability of the proposed modelling approach for completing the types of tasks that end users need to be able to complete with it, namely helping design to tune the operation of adaptive building envelopes. Potential issues users may face in terms of flexibility, accuracy and rapidness, the key areas for the development of the modelling approach identified in the interview study, when deploying the modelling approach are:

- **Flexibility:** While EnergyPlus is a commonly used tool in design practice, Dymola is not yet widely used in façade engineering. This lack of widespread use of Dymola in practice may therefore currently prevent users from taking full advantage of the modelling approach. However, this may change in the future as EnergyPlus moves towards a full co-simulation setup (Wetter, Benne et al., 2020), improving the possibilities for integrating domain-specific tools like Dymola and the knowledge about such tools.
- **Accuracy:** The accuracy of the modelling approach may be affected when used by end users for two reasons. First, the case study used the co-simulation setup to model the control strategy C02, with the blind model implemented in EnergyPlus and the controller model in Dymola. An issue users may face is that it may not always be clear to know where and how to split their all-inclusive model into sub-models and define the connections between the sub-models. Second, although programming languages like Python are becoming more common in design practice (Section 5.4.3), it may be difficult for users to use the modelling approach if they do not have sufficient programming skills. Instead of programming skills, detailed guidelines on how to use the modelling approach may help. However, these are not yet available, so users may feel left alone in setting up their co-simulation.
- **Rapidness:** The modelling approach fully automated simulations using a Python script to execute many common repetitive or technically intensive tasks. While this may have simplified and accelerated the process of e.g. generating simulation input files and reduced error rates, a process not sped up by using the modelling approach was the generation of the geometry inputs, despite being facilitated by the Euclid extension. This may not reduce the time it takes users to create a model, so issues with the modelling time may still occur.

Many of the issues discussed above are related to the identified NFRs, especially the usability of the modelling approach in design practice. As a result, further research should be done to test its usability by directly examining the modelling approach when executed by users. This may provide a realistic feedback on the behaviour of the modelling approach and thus remains the inevitable complement to other analysis techniques.

Part III

Synthesis

9 Analysis of data and discussion

This chapter presents the analysis of the findings of the industry interviews, the validation of the modelling approach and the multiple-case study reported in Chapters 5, 7 and 8, applied by implementing the data analysis methodology. The findings are related to the literature review and the contextual issues of the thermal building performance simulation of adaptive building envelopes described in Chapters 2 and 3. The discussion is structured with reference to the three gaps identified in the interview study and used to develop the modelling approach: flexibility, accuracy and rapidness. Based on the findings, several options for action and recommendations that address the major issues are also presented.

9.1 Application of data analysis strategy

The research data in this thesis were analysed according to the strategy outlined in Section 4.3.2. In line with this strategy, findings from each strand of the research were discussed in the corresponding chapters and integrated by applying the integration framework by Fetters, Curry and J.W. Creswell (2013). This enabled this research to draw inferences from the findings with regard to the research objectives.

Because findings of qualitative research are not subject to quantification (Gibson, 2017), the qualitative data (perceptions and judgements) of the industry interviews were used to clarify and supplement findings of the quantitative components of this research by adding perspectives and explanations. The validation of the findings offered greater possibilities for the development of meta-inferences (Fetters, Curry and J.W. Creswell, 2013; Venkatesh, S. Brown and Sullivan, 2016).

The relationship between the data derived from the industry-based interview study and the quantitative components of this research, as illustrated in Figure 9.1, were mostly *confirmatory*. They were therefore used for (i) convergence or corroboration of findings across different methods, (ii) elaboration or clarification of findings for one method from the other and (iii) development to inform later phases of the research based on findings of prior phases (Teddlie and Tashakkori, 2009). Data from the validation and the multiple-case study were generally *exploratory*, seeking new insights and generating ideas for future research.

9.2 Findings of data analysis

The discussion of the findings is structured with reference to the three gaps identified in the interview study and used to develop the modelling approach (Section 5.5). These gaps have been used to summarise the main achievements and areas of future research in Table 9.1 and to discuss them in detail below.

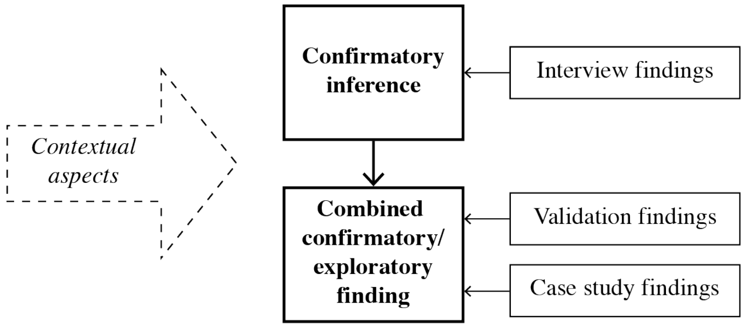


Figure 9.1: Data analysis scheme.

9.2.1 Future improvements of the proposed modelling approach

The aim of this research study was to develop an approach for the integrated modelling of control and adaptive building envelope. In the development, it was essential to consider the needs of end users so that practitioners have a tool to overcome the challenges associated with existing BPS tools in accurately representing adaptive building envelopes along with their controls. Although practitioners primarily use BPS tools for predicting the thermal performance of adaptive building envelopes, they are aware of the challenges and are therefore opening up to learning new tools and languages and becoming familiar, for example, with how to programme in order to develop their own workarounds (Section 5.4.3). As a consequence, it was not surprising that this research attracted a lot of interest from the industry. For instance, there was the opportunity to have informal discussions with industry representatives about the proposed modelling approach and receive feedback on it on various occasions (see *Publications and key presentations arising from thesis* on p. 27). Based on handwritten notes taken during these informal discussions, the most interesting findings were:

- The enhanced possibilities for modelling control strategies for adaptive building envelopes in the modelling approach were perceived as a significant benefit for the design of buildings with adaptive building envelopes.
- Dymola is only used to a limited extent in façade engineering, whereas it is regularly used in building services engineering. Regular use of Dymola in façade engineering would therefore enable the coupling of façade and building services models, thus providing opportunities for close cooperation with building services engineers and integrated planning of the two systems.
- Particularly important seemed to be the possibility of adding further analysis options to the proposed modelling approach, e.g. the possibility of assessing visual comfort. Consequently, a common question was whether it is possible to integrate tools, such as Radiance, into the modelling approach.
- It seemed important to the industry representatives to have a tool that is quick and easy to use, which confirmed the results of the interview study. Consequently, they seemed

Table 9.1: Summary of achievements and areas of future research.

Flexibility: Practitioners need more flexible tools for rapid and easy integration of bespoke models and tools.		
Requirements	Adaptation to new models	• Achievement: Extension of EnergyPlus tool structure to model controllers of multi-functional shading systems • Future research: Testing of other adaptive building envelope controllers, materials and systems in modelling approach
	Adaptation to new functionalities	• Achievement: Integration of a simulation-based optimisation in modelling approach (Borkowski, Donato et al., 2019) • Future research: Implementation of existing optimisation script in `cosim` package and integration of other design decision support methods in modelling approach
	Integration of data	• Achievement: Integration and consideration of monitored data in modelling approach • Future research: No issues for future research identified
	Applicability to every project scenario	• Achievement: Out of scope of this thesis • Future research: Testing of high and low resolution models in modelling approach
Accuracy: Practitioners need more transparency in calculation procedures and access to training and documentation for better understanding and support in using the tools.		
Requirements	Open-source code	• Achievement: Integration of EnergyPlus, the FMI Standard and Python as open-source tools and publication of the source code of `cosim` on Github • Future research: Replacement of Dymola with an open-source alternative, such as OpenModelica (OSMC, 2021)
	Training and documentation	• Achievement: Out of scope of this thesis • Future research: Creation of detailed guidelines on how to use modelling approach
	Understanding of model parameters	• Achievement: Provision of a detailed understanding of model parameters through the integration of Dymola • Future research: No issues for future research identified
Rapidness: Practitioners need tools with short modelling and simulation times for making key decisions quickly.		
Requirements	Reuse of models	• Achievement: Reuse of controller models e.g. through possibility of adding conditional clauses in Dymola (Borkowski, Donato et al., 2019) • Future research: Development of a standard systematic approach for performing co-simulations
	Modelling and simulation time	• Achievement: Automation of simulations through Python and facilitation of geometry inputs through Euclid • Future research: No issues for future research identified

to appreciate that the modelling approach is packaged as a Python script that can be invoked with a handful of simple commands.

These findings suggest that the industry perceives the modelling approach as a welcome development. They may therefore be interested in using the modelling approach in design practice in the future. However, with regard to the three gaps identified in the interview study, much remains to be done to turn the modelling approach into a practical application that creates lasting benefit for practitioners, as discussed below.

9.2.1.1 Improving flexibility

To improve the flexibility of the proposed modelling approach so that practitioners may rapidly and easily integrate bespoke models and tools, further work is needed in the following areas. To begin with, this research study accomplished to extend the EnergyPlus tool structure and couple it with Dymola through the FMI Standard, making EnergyPlus more flexible in modelling adaptive building envelopes (Chapter 6). In Chapters 7 and 8, however, the modelling approach was mainly used to model RBC strategies for multi-functional shading systems, an adaptive building envelope commonly used in today's building practices (Loonen, Favoino et al., 2016). Given that the modelling approach was capable of accurately and representatively predicting the behaviour of multi-functional shading systems, but there are many other types of control strategies and adaptive building envelopes, future studies investigating these other types would be worthwhile.

A challenge in this testing may be that the modelling approach is closely interwoven with the tool capabilities of EnergyPlus. For example, the modelling approach splits the whole-building simulation model into three component models, with the building model and the building envelope model created in EnergyPlus and the controller model created in Dymola. While this split is acceptable for adaptive building envelopes that can be modelled in EnergyPlus (Table 5.9 in the interview study), there are many adaptive building envelopes, particularly emerging ones, that cannot be modelled in EnergyPlus, some of which were identified in the interview study, such as PCM in glass. Future research should therefore investigate how to make the modelling approach more versatile with respect to emerging adaptive building envelopes and suggest ways to split the whole-building simulation model in the case of such building envelopes.

Another challenge in this testing may be the modelling of control strategies other than RBC strategies (Section 2.1.2 of the literature review). Potential tools to test other control strategies in the modelling approach may be:

Modelica IBPSA Library: As a free, open-source library developed in IBPSA Project 1, the Modelica IBPSA Library contains models for a range of controllers, such as predictors and setpoints, which can help to model other types of control strategies for adaptive building envelopes. The use of controller models from the Modelica IBPSA Library may also promote model reuse, significantly reducing modelling time.

Specialised control-oriented software: A benefit of utilising co-simulation in the modelling approach may be a higher degree of flexibility in implementing control strategies in specialised control-oriented software. For example, the MATLAB/Simulink environment and Ptolemy II allow richer semantics for expressing models than existing BPS tools (Trčka, Hensen and Wetter, 2009). An exception to this is EnergyPlus, which offers the possibility to describe control algorithms with the EMS scripting feature. Due to its integration into the EnergyPlus tool structure, however, the EMS feature has a number of limitations. For example, each EMS programme line is limited to 100 characters (DOE, 2018a), which makes it unsuitable for implementing more complex control strategies that require a sequence of different logical structures. Nevertheless, the EMS feature opens up the capabilities of EnergyPlus to implement more complex control strategies, although not to the same extent as co-simulation, as the validation study has shown (Chapter 7.6).

Python: If neither EnergyPlus nor Dymola is suitable for representing a control strategy, e.g. control strategies based on search heuristics, the use of Python may further increase the flexibility of the modelling approach. Although other programming languages such as MATLAB can be used, Python is perhaps the easiest to use because the modelling approach is already written in this language and the commands can be quickly extended to new models. For example, Python has been used in previous studies for modelling Model-Predictive Control (Arroyo et al., 2018) and control based on Reinforcement Learning (Jia et al., 2019). During the development of the modelling approach, Python was already integrated in the modelling approach to optimise the controller parameters of an adaptive building envelope (Borkowski, Donato et al., 2019). However, due to the issues mentioned in the introduction of this thesis, the optimisation could not be included in the `cosim` package and adopted in the case study. Future work will therefore need to add the optimisation script into the `cosim` package and provide further functions for design decision support.

9.2.1.2 Improving accuracy

To improve the accuracy of the proposed modelling approach, future research should concentrate on the investigation of the two following aspects. Firstly, practitioners need more transparency in the calculation procedures to better understand the modelling approach. An important capability of the modelling approach to achieve this has been the integration of open-source software, including EnergyPlus, the FMI Standard and Python. The only software that is not open-source is Dymola, which has been used primarily for its graphical frontend, which facilitates and speeds up the modelling process immensely. However, there is also an open-source alternative to Dymola, such as OpenModelica. It is recommended to replace Dymola with such an open-source alternative in the future. But attention must be paid to the limitations of these alternatives, such as only partial compatibility with models from some libraries, such as the Modelica IBPSA library.

Tool interoperability and openness in particular, as in case of Dymola, is something that sometimes goes against the intention of software developers. Autodesk, a software cooperation, for example, is trying to create its own ecosystem, partly to create a vendor lock-in. This also has advantages, because general interoperability is usually difficult to achieve even with well-defined interfaces and semantics. Since some tools are open, at least core tools like EnergyPlus, the development of an industry-standard API may be a possible path to better interoperability in the future. Integrating an interface that defines interaction between multiple software applications may be a way for users to extend existing functionality in different ways and to different degrees (Gordillo et al., 2020). An example of a good starting point is the Python API of IES VE, but this only allows users to extract model data, perform calculations on them and write them to another programme like Microsoft Excel or Word (Integrated Environmental Solutions, 2018). To develop an API for control and adaptive building envelope simulation, it is necessary to provide access to the integrated models (i.e. inputs, outputs, parameters and states) while the simulation is running. In terms of interoperability, it would therefore make sense to develop the API based on an industry standard, such as the Industry Foundation Classes, a platform-neutral, open and ISO-registered file format specification, to improve consistency and usage.

Secondly, practitioners need access to training and documentation to get better support in applying the modelling approach. Since the application of software for adaptive building envelope simulation is a user-driven process, it is possible to say that any factor that affects the user also directly affects the quality and accuracy of the software, as emphasised in Section 5.4.1 in the interview study. Ensuring that users can use the modelling approach according to its intended purpose is therefore an important step towards its successful application in design practice. As a consequence, sharing and disseminating specific guidelines and knowledge about the modelling approach should be considered a key issue for future research. For the development of user guidelines, the five steps presented in Figure 9.2 may be followed. It is important that these guidelines should be as precise, complete and accurate as possible. For example, when providing information on an invocation of the modelling approach, it is important to specify not only the meaning of each variable, but also its exact type and possible side effects from the invocation.

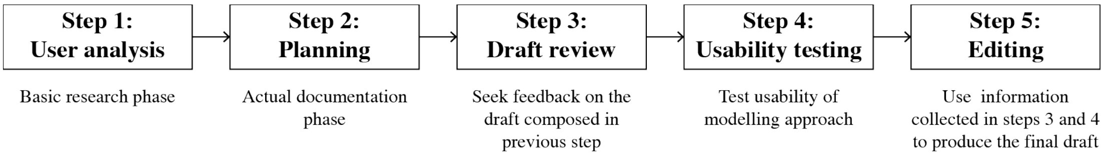


Figure 9.2: Steps in development of user guidelines for modelling approach.

9.2.1.3 Improving rapidness

To improve the rapidness of co-simulation approaches, a future study investigating the development of a standard systematic approach to co-simulation would be very interesting. However, questions have been raised about the possibilities of developing such as standard systematic approach (Taveres-Cachat, Favoino et al., 2021). This is because there is no one-size-fits-all approach to co-simulation with the end product often being case-dependent. Approaches may differ depending on the internal routines of one or the other tool used and the level of complexity required to describe the co-simulation task. This case dependency also makes it difficult to provide guidelines, so users are often left on their own to build their co-simulation model. To address these issues, this research study has attempted, although much work is still required, to develop a solution that incorporates a flexible setup for the accurate representation of adaptive building envelopes and that is nevertheless easy to use through simple Python commands (Chapter 6). But in order to facilitate the application of the modelling approach in design practice, much effort will be needed in the future to produce and disseminate guidelines and knowledge about the modelling approach, as already pointed out in the previous section.

9.2.2 Further testing of the proposed modelling approach

An important issue for future research, as already mentioned in Section 4.3.1.3, is to test the proposed modelling approach in practice to get feedback from end users. Due to time constraints, it was not possible to seek this kind of validation of the modelling approach, apart from an informal presentation and discussion with some industry representatives (Section 9.2.1). What was done in this study was to test the accuracy and functionality of the modelling approach (Chapters 7 and 8), as shown in Figure 9.3. Therefore, further tests with short and discrete tasks are needed in the future to obtain feedback from the end users who use the modelling approach on a daily basis.

However, testing the usability of tool developments is particularly difficult and is one of the most challenging areas in software development (Umar and Khan, 2011). The reason for this is that realistic feedback of the behaviour of the tool is required from the end users. One way to get this feedback is to observe the execution of the tool in practice, which in turn can help validate whether it can be used for its intended purpose and in a way that meets the needs of the end users (U.S. Department of Health and Human Services (HHS), 2006), and identify potential malfunctions.

Typical evaluation methods in software testing are summarised by HHS (2006), according to which evaluation methods often employ user-centred design methods. Possible methods for improving the usability of the modelling approach are, according to the guidelines:

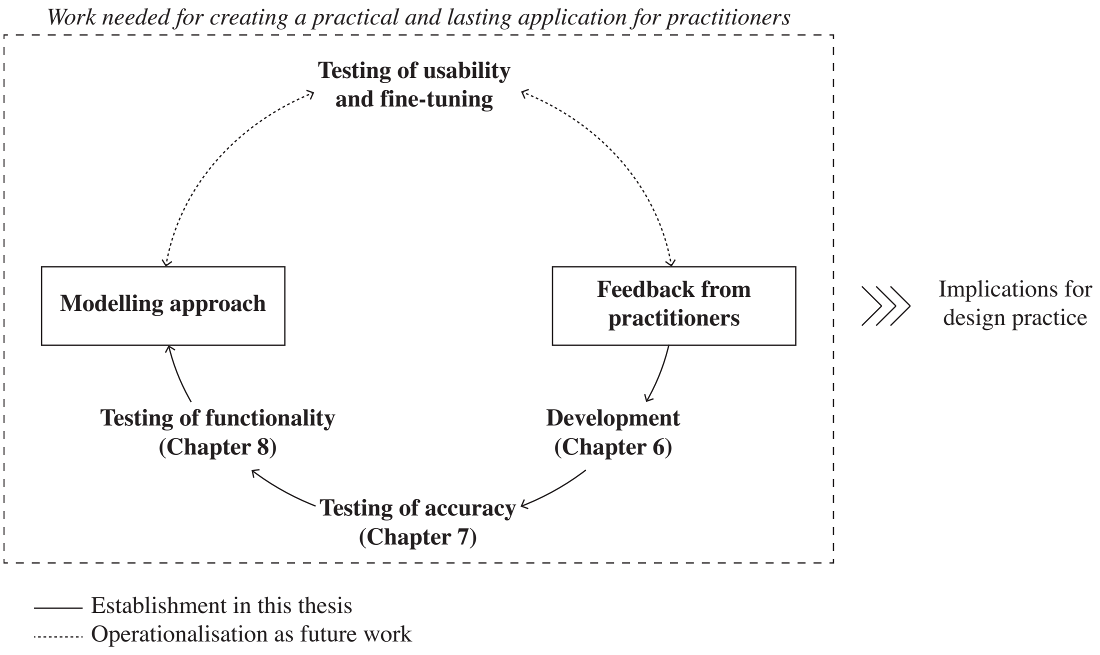


Figure 9.3: Overview of the thesis' contributions to knowledge: a modelling approach for control strategies for adaptive building envelopes.

- **Baseline usability testing:** Evaluation of the modelling approach by testing it with representative users by having them try to complete typical tasks while observers watch, listen and take notes. The aim of this baseline usability testing is to identify any usability problems.
- **Focus groups or interviews:** In order to establish user goals, focus groups or interviews can be used to learn about users' experiences or expectations.
- **Satisfaction surveys:** A structured questionnaire completed by users that aims e.g. to find out whether the modelling approach meets users' requirements, to identify areas for improvement and to gain ideas for future improvements.

The qualitative and quantitative data from the usability tests may then be used to recommend improvements, implement recommendations and retest the modelling approach to measure the effectiveness of the changes.

9.3 Implications of findings for use of future tool developments in design practice

The data analysis indicated that the modelling approach still needs to undergo many improvements, especially usability testing, to make it a practical application that creates lasting benefits for practitioners. However, once the modelling approach – or other future tool developments – is such a practical application, it can be used in design practice, for example, to:

- represent control strategies for adaptive building envelopes;

- accurately predict the thermal performance of adaptive building envelopes; and
- integrate different physical domains (e.g. visual) and occupant interactions.

Practitioners and companies play a key role in driving the application of future tool developments. They thus have the opportunity, even if indirectly, to give adaptive building envelopes a realistic chance of being introduced to the market and contributing to climate goals. The following discusses how practitioners and companies can promote this process of driving the application of future tool developments.

On the one hand, practitioners are of central importance as they decide which BPS tool to use for a particular simulation and which building envelope – adaptive or not – to use. The interview study demonstrated that the practitioners involved in the interviews (as representatives of the population) have in-depth knowledge in the areas of physics and controls of adaptive building envelopes, e.g. being aware of the consequences if an adaptive building envelope cannot be modelled properly. They also have extensive skills in modelling and scripting, e.g. by developing and applying various workarounds to overcome the challenges associated with existing BPS tools. With this expertise, they have not only contributed to this research study to specify the requirements for future tool developments, but also demonstrated that their knowledge and skills strive for continuous improvement in design practice, especially in adaptive building envelope simulation. However, there are still some areas where practitioners may improve their knowledge and skills so that they are even better able to use future tool developments. Areas for improvement include:

- **Knowledge of various BPS tools:** The literature review showed that BPS tools have different capabilities to represent control strategies for adaptive building envelopes (Section 3.2.1). However, the interview study showed that less than half of the interviewees select the BPS tool according to the use case. This highlights that practitioners may need to learn more BPS tools in order to apply the most appropriate tool for the use case.
- **Knowledge of programming and scripting languages:** The interview study revealed that more and more practitioners in façade engineering are extending traditional building performance analysis by applying sophisticated analysis to support design decisions, such as optimisation, SA and UA (Sections 5.4.3 and 5.4.5). To take advantage of these design opportunities brought by the introduction of adaptive building envelopes, proficiency in programming with e.g. Python and MATLAB and scripting with e.g. Grasshopper is required.
- **Knowledge of domain-specific tools:** Combining domain-specific tools that are best suited for the modelled subsystem with an appropriate level of detail is a key motivation for an integrated simulation (i.e. co-simulation). However, in order to use different

tools that support individual domains, practitioners need knowledge of such tools ot the opportunity to collaborate with someone with such knowledge.

On the other hand, companies are crucial in applying future tool developments as they can commit to adapt to industry and market changes and be open to new ideas and technology to ultimately be innovative and keep the company profitable. The promotion of innovation can be supported by the following measures:

- **Encouragement of staff:** Encouraging staff to learn new skills and develop through training programmes may help practitioners to keep up with rapid change in building performance simulation and take on new challenges. This, in turn, may help motivate practitioners to try new tools and methods to improve the design decision-making process of adaptive building envelopes.
- **Industry-university collaborations:** Effective knowledge and technology transfer, e.g. between modellers, designers, software developers and researchers, may demonstrate the benefits of using future tool developments and contribute to wider dissemination. This, in turn, may improve the possibilities for modelling adaptive building envelopes in design practice and thus lead to wider uptake in future buildings.
- **Knowledge sharing:** The joint development of models, solvers and interfaces by software developers, design firms and other organisations may be helpful in facilitating the reuse of future tool developments based on co-simulation, thus accelerating the development of more advanced solutions and libraries. This may help to avoid redundant efforts and significantly reduce investment costs for future developments.

10 Conclusion

This chapter presents the conclusions of the research on the basis of the analysis of the main findings discussed in the previous chapter. Implications of the thesis' findings for different stakeholders and issues that were beyond the scope of the study design and methodology are also discussed. Finally, this chapter highlights contributions to knowledge in the field of adaptive building envelope simulation and proposes dissemination activities.

10.1 Conclusions of research

The purpose of the present study was to identify requirements for future tool developments for the simulation of adaptive building envelopes and to determine the contribution of future tool developments for an accurate prediction of their thermal performance.

With respect to the specific objectives of the research, the findings of this study support the conclusion that future tool developments based on mono- or co-simulation approaches have the potential to accurately and representatively predict the thermal performance of adaptive building envelopes. However, due to the challenges associated with both approaches to accurately represent control and adaptive building envelope, significant efforts are still required in research and industry to improve the integrated modelling of the interacting components and technologies used in adaptive building envelopes.

Specifically, the following conclusions for the thermal building performance simulation of control strategies for adaptive building envelopes can be drawn from this study:

- Requirements for future tool developments with a specific focus on adaptive building envelope simulation have been identified. The requirements have been partially addressed in this research by, for example, investigating the accuracy attribute through the validation study. However, further work is needed to fully address the requirements, especially the usability attribute, as discussed in Section 9.2.2.
- Existing BPS tools, most of which adopt the mono-simulation approach, are suitable for the thermal performance simulation of adaptive building envelopes. However, the application of BPS tools is recommended to depend on whether their capabilities are sufficient to represent the complexity of the adaptive building envelope to be simulated. When using existing BPS tools, it is consequently recommended that practitioners work with a suite of tools and select the most suitable tool for their use case.
- Co-simulation showed no clear benefits in terms of accuracy over mono-simulation, if an appropriate timestep was selected. Yet, co-simulation may be more flexible in terms of control integration, thus allowing for a more representative modelling of adaptive building envelopes and contributing to potential accuracy improvements.

10.2 Limitations of research

The present research had numerous contextual and methodological limitations that highlight the need for further research on thermal building performance simulation of control strategies for adaptive building envelopes. These limitations are outlined below for each aspect of the research. Notwithstanding these limitations, the research offers some important insights into a key emergent area, where more research is needed to make adaptive building envelopes common practice in building design and operation.

The scope of the research was limited in three respects, which are discussed below: (i) the research design, (ii) the data collection and (iii) the data analysis.

10.2.1 Research design

The aim of this research was to gather timely and specific information on the building performance simulation of control strategies for adaptive building envelopes. Little information was widely available due to novelty; also, the research subject was dynamic in nature with ongoing developments and regular updates of the tools. This posed a challenge on the selection of the research design, which sought to ensure the maintenance of the relevance of the study findings in the ongoing developments in industry and research.

Due to the emergent and dynamic nature of the research subject, a mixed-methods research design was adopted that included both qualitative and quantitative methods and combined them into a single approach. While a mixed-methods research design creates a more complete picture of the phenomenon under study, it balances the weakness in each method to leverage the strengths of both. Nevertheless, the mixed-methods research design was subject to at least two limitations:

- This study used a sequential design, where a dimension of the phenomenon being investigated was used to inform one or more strategies drawn from a different method. It was therefore implemented over several phases, which required a considerable amount of time and resources for the data collection.
- In the present study, the data from the different methods were used to investigate a single phenomenon under study and to interpret them together in a meaningful way through the integration framework by Fetters, Curry and J.W. Creswell (2013). Although the method was fully researched and understood, the complexity of integrating the findings of the separate strands was found to be difficult, which may have resulted in the method not achieving its full potential or increased bias.

Despite the limitations, the mixed-methods research design adopted in this research generated a better understanding of the mechanisms underlying the integrated modelling of control and adaptive building envelope, as shown in Chapter 9.

10.2.2 Data collection

This study collected data through the use of different research strategies and methods, each of which had its limitations. To acknowledge these limitations, they are described below for each part of the study.

10.2.2.1 Limitations of interview study

The findings in the interview study were subject to at least two limitations. First, a major limitation of the industry interviews was the sample size, which was determined by the small theoretical population size of 22. While the interviews achieved a point at which no new insights, themes and issues were identified, a larger sample size might have captured all subtle or conceptual issues. Second, the industry interviews could have also been limited by self-selection bias of the 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 issues reported by participants with the literature.

10.2.2.2 Limitations of validation study

The transferability of the findings of the validation study is subject to certain limitations. Firstly, empirical validation only tests ‘whether the simulation model’s output behaviour has the accuracy required for the model’s intended purpose over the domain of the model’s intended applicability’ (Sargent, 2013, p. 18). The modelling approach consequently validated the behaviour of the test scenario only for its intended application. Secondly, empirical validation should never be used as the only validation method due to measurement uncertainty and experimental complexity (Cattarin et al., 2018). There is therefore abundant room for further progress in fully determining the accuracy of the modelling approach, e.g. by undertaking inter-model comparisons with more BPS tools. Thirdly, the validation study has only examined a RBC strategy for the test scenario’s blind automation system. Given that there are many other types of control strategies and adaptive building envelopes, future research should investigate other types of control strategies and adaptive building envelopes to validate the modelling approach over the complete domain of its intended applicability.

10.2.2.3 Limitations of multiple-case study

The most important limitation of the multiple-case study lies in the fact that it was a small, UK-based study with a limited sample size of case studies and units of analysis. Quantitative results that indicate the thermal building performance of the case study buildings may therefore be understood as indicative. Also, the case study was limited by modelling uncertainties that arose due to assumptions in the models of the case study buildings. As these assumptions had potentially affected the accuracies of the models, the same assumptions were adopted for both case study buildings:

- **Input data assumptions:** Input information of the case study buildings were mainly extracted from project reports, design notes and existing energy building models. While most of the information needed was found in these sources, assumptions had to be made about material properties, occupancy schedules and HVAC system configurations in accordance with CIBSE and ASHRAE standards.
- **Façade modelling assumptions:** EnergyPlus offers no direct way to accurately describe the transient heat and mass transfer phenomena that occur in the complex three-dimensional geometry models of the case study buildings' DSFs (B01) and CCFs (B02). In modelling these two façade systems, the multiple-case study followed the best practice guidelines published by the EU project *BESTFAÇADE*. These guidelines recommend to model such façade systems with a double-glazed unit as the inner glass layer and a single-glazed unit as the outer glass layer (Waldner et al., 2007).

10.2.3 Data analysis

The key challenge during the data analysis stage was the integration of data from quantitative and qualitative strands, a common issue in mixed-methods research (Bergman, 2008). While the traditional usage of integration refers to checking the validity of an interpretation by bridging the qualitative-quantitative divide and combining data produced by various methods, this research followed a different form of integration. The use of quantitative and qualitative methods to investigate the integrated modelling of control and adaptive building envelope was compared from different viewpoints (i.e. industry, validation, real-world applicability), which provided different pictures of the phenomenon under study. Brought together, these different pictures yielded a fuller and more complete picture of the research subject.

10.3 Contributions to knowledge

This research has shed light on the various areas worth investigating to address the integrated modelling of control and adaptive building envelope and has provided an important opportunity to advance the understanding of modelling systems and controls with a fast, dynamic response. In achieving the main research aim, the study has made the following original contributions to knowledge in the field:

- The interview study has for the first time explored in detail methods, tools and workarounds used in current design practice to predict the thermal performance of projects with adaptive building envelopes, taking into account the end user perspective. It thus provides additional evidence with respect to real-world challenges of applying BPS tools in practice and the requirements for future tool developments tailored to the needs of end users.
- The information gathered in the interview study on workarounds and challenges associated with the capabilities of current BPS tools, as well as feedback regarding practical improvements for future tool developments, helped to establish a greater understanding of major research needs and gaps on the one hand. On the other hand, the information might not yet fully exist due to novelty in the key emergent area on adaptive building envelope simulation. The findings of the interview 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.
- To establish a link between component models to accurately represent the whole-building simulation of the thermal performance of adaptive building envelope and control, a solution for their integrated modelling was developed. The development was guided by the FRs and NFRs identified in the literature review and the interview study, with the aim of meeting the needs of the end users, i.e. the practitioners. Further research is, however, needed to observe the execution of the modelling approach in design practice through usability testing.
- The validation study has gone some way towards enhancing the understanding of the verification and validation of co-simulation setups for predicting the thermal performance of adaptive building envelopes by applying the workflow proposed in Chapter 7. Although the workflow has only been tested on one test scenario and should therefore be tested on more scenarios in the future, it provides an exciting opportunity to increase confidence in the predictions of adaptive building envelope models coupled in co-simulation setups.
- The empirical findings of the validation study extend the knowledge on the accuracy of integrated modelling approaches used to predict the thermal performance of adaptive building envelopes. While the result suggests that co-simulation setups can generally be used to verify and validate the behaviour of adaptive building envelopes, it also shows that EnergyPlus, with the support of the EMS feature, in a mono-simulation setup is equally capable of predicting the control actions of the test scenario's blind automation system. Compared to the EMS feature, however, Dymola used in a co-simulation

setup offers much more flexibility in modelling control strategies for adaptive building envelopes.

- Most studies on adaptive building envelope simulation test their modelling approaches using simple case study buildings, like Lopes Alves Homem (2016), who used Case 600 of the Building Energy Simulation Test diagnostic method (ASHRAE, 2014a). However, to assess whether the modelling approach developed in this research is applicable under real-world conditions, it seemed useful to test it using real case study buildings. In this way, it was possible to investigate whether the modelling approach is beneficial for predicting the thermal performance of the dynamic behaviour of adaptive building envelopes in practice.
- While the modelling approach is useful for design practice as it enables practitioners to accurately represent the dynamic behaviour of adaptive building envelopes, it may also be an important instrument for other fields, such as R&D aimed at bringing innovative adaptive building envelope technologies from initial concept to market. This is because BPS tools used as virtual laboratories can add complementary value to exploratory R&D projects, alongside actual experiments, by enabling what-if investigations and whole-building insights.

10.4 Dissemination activities

The main findings of this research have been discussed through the publication of peer-reviewed articles in journals in addition to peer-reviewed articles in proceedings (see *Publications and key presentations arising from thesis* on p. 27). Further publications arising from the thesis, such as the test of the coupling frequency in the validation study (Section 7.5) and the multiple-case study (Chapter 8), are in preparation.

As the modelling approach seeks to turn into a practical application that creates a lasting benefit for practitioners, dissemination of findings beyond academic publications was an important issue that was considered from the very beginning of the research. Consequently, the findings were presented on a number of opportunities:

- As a reflection of the collaborative nature of the research, dissemination activities have taken place throughout the research in the form of continuous feedback, and key findings from the research have been presented at invited talks and meetings with the industry.
- In recognition of the significant role of industry professionals in the interview phase of the research, the main findings were shared in the form of a summary with the industry professionals who participated in the interviews.

Furthermore, the code of the proposed modelling approach, packaged and stored in a Python package called `cosim`, has been published on Github (Borkowski, 2021).

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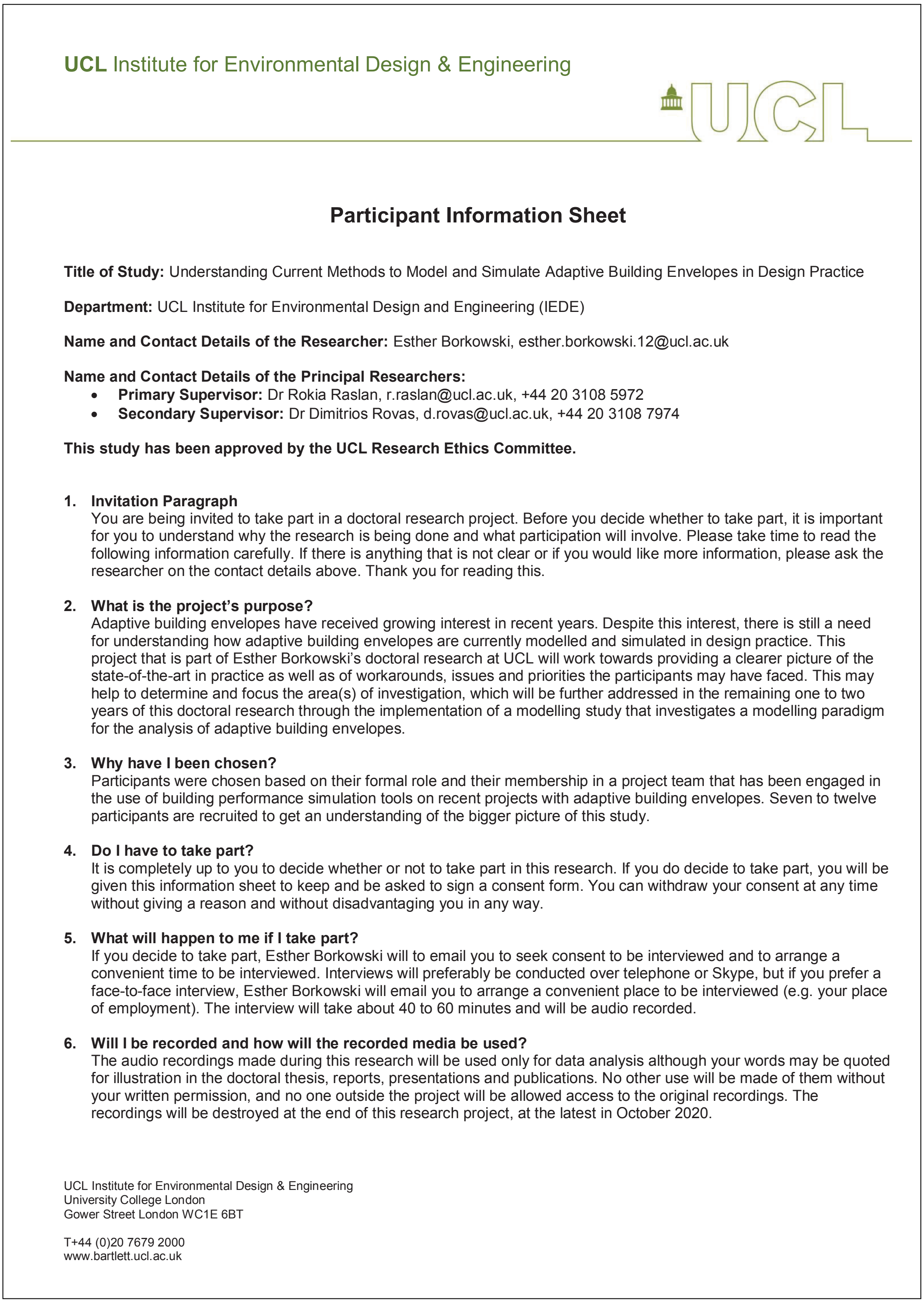
Appendices

A Industry interviews

A.1 Participant information sheet



UCL Institute for Environmental Design & Engineering

Participant Information Sheet

Title of Study: Understanding Current Methods to Model and Simulate Adaptive Building Envelopes in Design Practice

Department: UCL Institute for Environmental Design and Engineering (IEDE)

Name and Contact Details of the Researcher: Esther Borkowski, esther.borkowski.12@ucl.ac.uk

Name and Contact Details of the Principal Researchers:
- **Primary Supervisor:** Dr Rokia Raslan, r.raslan@ucl.ac.uk, +44 20 3108 5972
- **Secondary Supervisor:** Dr Dimitrios Rovas, d.rovas@ucl.ac.uk, +44 20 3108 7974

This study has been approved by the UCL Research Ethics Committee.

1. **Invitation Paragraph**
   You are being invited to take part in a doctoral research project. Before you decide whether to take part, it is important for you to understand why the research is being done and what participation will involve. Please take time to read the following information carefully. If there is anything that is not clear or if you would like more information, please ask the researcher on the contact details above. Thank you for reading this.

2. **What is the project's purpose?**
   Adaptive building envelopes have received growing interest in recent years. Despite this interest, there is still a need for understanding how adaptive building envelopes are currently modelled and simulated in design practice. This project that is part of Esther Borkowski's doctoral research at UCL will work towards providing a clearer picture of the state-of-the-art in practice as well as of workarounds, issues and priorities the participants may have faced. This may help to determine and focus the area(s) of investigation, which will be further addressed in the remaining one to two years of this doctoral research through the implementation of a modelling study that investigates a modelling paradigm for the analysis of adaptive building envelopes.

3. **Why have I been chosen?**
   Participants were chosen based on their formal role and their membership in a project team that has been engaged in the use of building performance simulation tools on recent projects with adaptive building envelopes. Seven to twelve participants are recruited to get an understanding of the bigger picture of this study.

4. **Do I have to take part?**
   It is completely up to you to decide whether or not to take part in this research. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. You can withdraw your consent at any time without giving a reason and without disadvantaging you in any way.

5. **What will happen to me if I take part?**
   If you decide to take part, Esther Borkowski will to email you to seek consent to be interviewed and to arrange a convenient time to be interviewed. Interviews will preferably be conducted over telephone or Skype, but if you prefer a face-to-face interview, Esther Borkowski will email you to arrange a convenient place to be interviewed (e.g. your place of employment). The interview will take about 40 to 60 minutes and will be audio recorded.

6. **Will I be recorded and how will the recorded media be used?**
   The audio recordings made during this research will be used only for data analysis although your words may be quoted for illustration in the doctoral thesis, reports, presentations and publications. No other use will be made of them without your written permission, and no one outside the project will be allowed access to the original recordings. The recordings will be destroyed at the end of this research project, at the latest in October 2020.

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7. **What are the possible disadvantages and risks of taking part?**
There are no disadvantages and risks to participants, which arise during the research, except the time needed for completing the interview.

8. **What are the possible benefits of taking part?**
Whilst there are no immediate benefits for those people participating in this research project, it is hoped that this work will contribute towards understanding how adaptive building envelopes are currently modelled and simulated in design practice. Participants can be informed of the major results of this project if they are interested.

9. **What if something goes wrong?**
If you are concerned about any part of this research or your participation, please contact the Supervisors and/or the Director of Ethics at the UCL Bartlett School of Environment, Energy and Resources (BSEER):
   - **Primary Supervisor:** Dr Rokia Raslan, r.raslan@ucl.ac.uk, +44 20 3108 5972
   - **Secondary Supervisor:** Dr Dimitrios Rovas, d.rovas@ucl.ac.uk, +44 20 3108 7974
   - **BSEER Director of Ethics:** Michelle Shipworth, m.shipworth@ucl.ac.uk, +44 20 3108 5991

10. **Will my taking part in this project be kept confidential?**
All the information we collect about you during the course of the research will be kept strictly confidential and will only be shared with the research team (Esther Borkowski, Dr Rokia Raslan, Dr Dimitrios Rovas). You or your organisation will not be able to be identified in any ensuing thesis or publications unless you have expressly given your permission to this.

11. **Limits to confidentiality**
Please note that assurances on confidentiality will be strictly adhered to unless evidence of wrongdoing or potential harm is uncovered. In such cases the University may be obliged to contact relevant statutory bodies/agencies.

12. **What will happen to the results of the research project?**
The results of this research will be pseudonymised and mainly reported in the doctoral thesis and academic papers, although it is possible that the results will also be included in reports and/or presentations. Major results will be summarised and communicated with the participants if they are interested.
Any personal data that we collect from you will be processed only for the purposes outlined in this information sheet and only so long as required for this research project. They will be stored on Esther Borkowski's UCL Filestore@UCL central file storage and will only be used by Esther Borkowski and the Supervisors. Your pseudonymised interview data will be stored separately from your personal data on an encrypted laptop and an encrypted USB external hard disk as backup solution. Personal data, audio files, field notes and transcripts will be destroyed at the end of this research project, at the latest in October 2020.

13. **Data Protection Privacy Notice**

Notice:
The data controller for this project will be University College London (UCL). The UCL Data Protection Office provides oversight of UCL activities involving the processing of personal data and can be contacted at data-protection@ucl.ac.uk. UCL's Data Protection Officer can also be contacted at data-protection@ucl.ac.uk.

Further information on how UCL uses participant information can be found here:

www.ucl.ac.uk/legal-services/privacy/participants-health-and-care-research-privacy-notice

Your personal data will be used for the purposes outlined in this notice. The categories of personal data used will be as follows:

Name
Company name
Position
Email address

The legal basis that would be used to process your personal data will be performance of a task in the public interest.

Your personal data will be processed so long as required for this research project. If we are able to anonymise or pseudonymise the personal data you provide, we will undertake this and will endeavour to minimise the processing of personal data wherever possible.

You have certain rights under data protection legislation in relation to the personal information that we hold about you. These rights apply only in particular circumstances and are subject to certain exemptions such as public interest (for example the prevention of crime). They include:

- The right to access your personal information;
- The right to rectification of your personal information;
- The right to erasure of your personal data;
- The right to restrict or object to the processing of your personal data;
- The right to object to the use of your data for direct marketing purposes;
- The right to data portability;
- Where the justification for processing is based on your consent, the right to withdraw such consent at any time; and
- The right to complain to the Information Commissioner's Office (ICO) about the use of your personal data.

If you are concerned about how your personal data is being processed, or if you would like to contact us about your rights, please contact UCL in the first instance at data-protection@ucl.ac.uk.

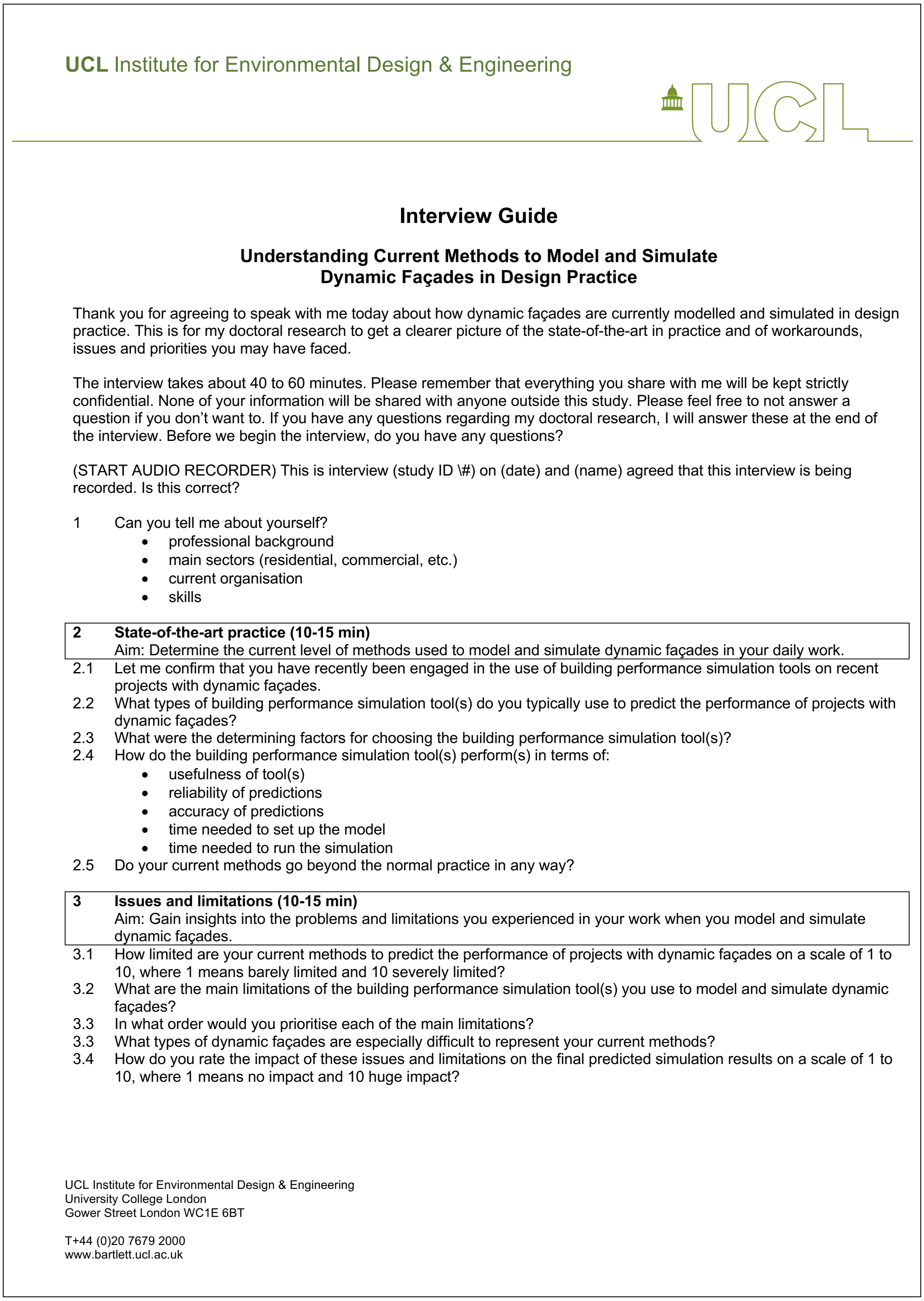
If you remain unsatisfied, you may wish to contact the ICO. Contact details, and further details of data subject rights, are available on the ICO website at: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

14. Who is organising and funding the research?
Esther Borkowski receives a monthly stipend from the Stiftung der Deutschen Wirtschaft (sdw).

15. Contact for further information
If you have questions or want more information on the research, please contact Esther Borkowski on esther.borkowski.12@ucl.ac.uk.

You will be given a copy of the information sheet and of the consent form to keep. Thank you for reading this information sheet and for considering taking part in this research study.

A.2 Interview guide



UCL Institute for Environmental Design & Engineering

Interview Guide

Understanding Current Methods to Model and Simulate Dynamic Façades in Design Practice

Thank you for agreeing to speak with me today about how dynamic façades are currently modelled and simulated in design practice. This is for my doctoral research to get a clearer picture of the state-of-the-art in practice and of workarounds, issues and priorities you may have faced.

The interview takes about 40 to 60 minutes. Please remember that everything you share with me will be kept strictly confidential. None of your information will be shared with anyone outside this study. Please feel free to not answer a question if you don't want to. If you have any questions regarding my doctoral research, I will answer these at the end of the interview. Before we begin the interview, do you have any questions?

(START AUDIO RECORDER) This is interview (study ID \#) on (date) and (name) agreed that this interview is being recorded. Is this correct?

1 Can you tell me about yourself?
- professional background
- main sectors (residential, commercial, etc.)
- current organisation
- skills

2 State-of-the-art practice (10-15 min)
Aim: Determine the current level of methods used to model and simulate dynamic façades in your daily work.

2.1 Let me confirm that you have recently been engaged in the use of building performance simulation tools on recent projects with dynamic façades.
2.2 What types of building performance simulation tool(s) do you typically use to predict the performance of projects with dynamic façades?
2.3 What were the determining factors for choosing the building performance simulation tool(s)?
2.4 How do the building performance simulation tool(s) perform(s) in terms of:
- usefulness of tool(s)
- reliability of predictions
- accuracy of predictions
- time needed to set up the model
- time needed to run the simulation

2.5 Do your current methods go beyond the normal practice in any way?

3 Issues and limitations (10-15 min)
Aim: Gain insights into the problems and limitations you experienced in your work when you model and simulate dynamic façades.

3.1 How limited are your current methods to predict the performance of projects with dynamic façades on a scale of 1 to 10, where 1 means barely limited and 10 severely limited?
3.2 What are the main limitations of the building performance simulation tool(s) you use to model and simulate dynamic façades?
3.3 In what order would you prioritise each of the main limitations?
3.3 What types of dynamic façades are especially difficult to represent your current methods?
3.4 How do you rate the impact of these issues and limitations on the final predicted simulation results on a scale of 1 to 10, where 1 means no impact and 10 huge impact?

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4 Workarounds (10-15 min)
Aim: Learn about methods for overcoming the issues and limitations in the process of modelling and simulating dynamic façades.

4.1 What do you think is a workaround to overcome the issues and limitations we just discussed?
4.2 What type(s) of workarounds do you apply in your organisation to overcome the issues and limitations we just discussed?
4.3 At what development stage are these workarounds on a scale of 1 to 10, where 1 means only internally tested and 10 fully employable to ongoing projects?
4.4 How do the workarounds perform in terms of:

- usefulness of workarounds(s)
- reliability of predictions
- accuracy of predictions
- time needed to set up the model
- time needed to run the simulation

4.5 What were the reasons why you or your organisation opted for exactly this workaround(s) and no other?

5 Future practice (10-15 min)
Aim: Find out how future methods to model and simulate dynamic façades may look like.

5.1 What do you think are innovative methods for modelling and simulating dynamic façades in the future, let's say in 10 to 15 years?
5.2 Do you have any innovative methods for modelling and simulating dynamic façades planned in the future?
5.3 How to you expect these innovative methods perform in terms of:

- usefulness of future methods
- reliability of predictions
- accuracy of predictions
- time needed to set up the model
- time needed to run the simulation

5.4 Do you know of any innovative methods planned by other organisations working on dynamic façades?
5.5 Are you aware of Modelica? Have you already tested it yourself or do you know an organisation that already tested it?

6 Are there any other comments you would like to make?

A.3 Steps undertaken in interview methodology

Step 1: Audiotape interview and make field notes with emphasis on the interviewers' impressions of the interaction during the interview.
Step 2: Review field notes immediately after the interview and expand initial impressions of the interaction with more considered comments and perceptions.
Step 3: Listen to audio recordings and amend and revise field notes to ensure they provide an accurate and descriptive reflection of the interaction.
Step 4: Write gisted transcriptions based on field notes.
Step 5: Listen to all data repeatedly to achieve immersion and specify central themes of the research.
Step 6: Derive codes from the recordings that appear to capture crucial thoughts or concepts and make notes of first impressions, thoughts and initial analysis.
Step 7: Identify labels for emergent codes that are reflective of more than one key thought and come directly from the recordings by using NVivo's *new node* function. A node is a collection of references about a specific theme in NVivo.
Step 8: Create a detailed codebook of key themes deduced from the key research focuses specified in Step 6 (deductive) and from reviewing field notes and gisted transcripts and listening to audio recordings (inductive).
Step 9: Define each category and subcategory and test and refine codebook. Structure nodes or create new nodes in NVivo based on the codebook.
Step 10: Code all interviews following the codebook by applying the nodes created in NVivo. This step was facilitated by the fact that all interviews followed the same pre-specified topics.
Step 11: Refine nodes and group similar nodes together to form organised categories created with the assistance of NVivo's *tree node* option (N. Davis and B. Meyer, 2009) and apply to all recordings.
Step 12: Prepare for reporting the findings, and identify exemplars for each code and theme from the data.

Figure A.1: Process of interview data management, coding and categorising.

A.4 Interview transcripts

A.4.1 P01 interview transcript

The participant's work focuses mainly on commissioning, indoor environments and sustainability. The work concentrates not only on thermal building simulations but also on understanding energy transports in façades. Also, the work of the participant covers all the areas behind a façade that are affected by the external environment or the façade by looking at daylighting and ventilation design.

A.4.1.1 Current practice

The predominant BPS tool in the participant's organisation is IES VE that is mostly used for calculating thermal and energy building performance. The IES VE model is also exported to a software used for compliance in the country, where the organisation is located, and to DIVA to make daylight calculations.

The main reasons why IES VE has been chosen in the organisation include the following:

- The IES VE model can be exported to Revit, a BIM software used by many architects.
- IES VE has a user-friendly graphical interface.
- Control strategies in IES VE are more realistic than in BSim, the BPS tool used in the organisation before the introduction of IES VE.
- Other offices of the organisation in other countries also rely on IES VE, which facilitates, e.g., model exchange and collaboration.

The participant rates the usefulness of IES VE as good once users get to know all the different input possibilities. The accuracy of IES VE depends entirely on the user, who needs to understand the calculation procedures behind IES VE to be able to assess if the predictions of IES VE are correct or not. The participant criticises that lots of users rely merely on the software guidelines without taking responsibilities for their calculations and assumptions. Concerning the modelling time, the participant notes that IES VE is quite time-consuming, which is why the organisation uses the same IES VE model for other applications as well, such as daylight, heat loss, cooling demand and ventilation simulations. Having all the models in one tool also reduces the risk of error and the costs in the participant's view.

The participant believes that the way of how IES VE is employed in the participant's team (i.e. use of different applications) goes beyond standard practice in the industry. The participant admits, however, that the way of how IES VE is generally used in the organisation complies with industry standards.

A.4.1.2 Issues and limitations

When asked to rate the extent of the limitations of IES VE on a scale of 1 to 10, where 1 means barely limited and 10 severely limited, the participant answered 3. Although IES VE has a few issues, it is absolutely what the organisation needs. One of the main limitations of IES VE is that there are only a few ways of correctly model solar shading. Other limitations of IES VE in the participant's opinion are:

- Custom control strategies cannot be modelled in IES VE. Often, the actual controller of a building cannot be implemented in the IES VE model including PI, PID and predictive controllers.
- Material properties are predefined in IES VE. As a result, custom material properties, such as phase change material within glass or dynamic U-values for insulation, cannot be modelled in IES VE.

However, the participant notes that these kinds of technologies are rarely used in building projects at present. But since models for such dynamic façade are not implemented in current software, professionals cannot officially proof the benefits of such technologies and support their use in the building sector.

The impact of these limitations on the predicted simulation results varies according to the type of dynamic façade between 0 and 10 on a scale of 1 to 10, where 1 means no impact and 10 huge impact. If there is no model available in IES VE, as in case of phase change material within glass, the impact on the predictions is 10. If there is an available and representative model, the impact on the predictions varies between 0 and 5 depending on whether the user understands the physics behind the technology and the tool's calculation procedures correctly. The participant highlights again that the predictions of a BPS tool depend entirely on the user, who must be capable of using a specific tool and its calculation procedures correctly.

A.4.1.3 Workarounds

While IES VE does not support co-simulation as variables cannot be manipulated during simulation run time, Python scripts can be used with IES VE to manipulate input data and to post-process the simulation results to find the optimal solution. Apart from Python scripts, the participant believes that parallel simulation is a potential workaround to overcome the issues and limitations discussed above. What is meant by parallel simulation is that the same model is simulated several times either in IES VE or a combination of different tools, each time with other input data. The results of these simulations are then combined, e.g., in an Excel spreadsheet to see the effects of the technology to be simulated. The organisation opted for this and not another workaround because it wanted to have reliable output data that can serve as a basis for the comparison with the results of the parallel simulation. Two potential technologies that can be simulated through parallel simulation are:

- Low emissivity coating that is either on the inside or the outside of glass. Through parallel simulation, the coating can be either switched on or off.
- Phase change material within glass can be modelled through parallel simulation by adding a thermal energy storage material to one model to cope with the benefits of the phase change material.

Since parallel simulation solves software issues, it is useful for tasks that cannot be modelled in BPS tools. Although parallel simulation is applied to ongoing projects in the organisation, the participant questions the reliability of this workaround, which is not verified. As a result, parallel simulation is entirely dependent on the knowledge and the capabilities of the user. The participant also notes that the time of setting up a parallel simulation is even more time-consuming than a stand-alone simulation.

A.4.1.4 Future practice

The participant says that models for dynamic façades are already implemented in BPS tools to some extent. But the technologies that are part of such façades (i.e. adaptable material technologies) are not yet supported in current tools and need to be integrated with more detail in the future. There is also a need to have adequate models for control strategies to operate the dynamic behaviour of such façades. The participant believes that control strategies for dynamic façades become more relevant in the future due to pressing building regulations. As regulations become stricter in terms of energy and daylighting, the design of, e.g., solar shading becomes more critical.

The participant is unsure if the methods to model dynamic façades are about to change in the future since the building sector is conservative in the field of such façades. Nevertheless, the participant expects the usefulness, the reliability and accuracy as well as the modelling and computation time to be similar to today while the scope of analysis expands. The focus probably moves more into stochastic and optimisation modelling so that practitioners have a greater understanding of sensitivities of each parameter implemented into a model. Besides stochastic modelling, the participant believes that other companies try to improve the interaction between different tools.

A.4.2 P02 interview transcript

A.4.2.1 Current practice

In terms of the current level of methods used to model and simulate dynamic façades in design practice, the participant highlights that BPS tools are mainly used in the organisation to support design and to create high-performance spaces. Typical work includes daylight, glare and visual comfort analyses with Radiance, thermal comfort and energy performance analyses with mainly IES VE and EnergyPlus and fluid analysis with CFD tools, such as OpenFOAM. To run parametric analyses, Grasshopper, Ladybug, Honeybee and Dragonfly are used. If an existing software does not what is needed for a specific project, in-house coders write their own software in Python, MATLAB or other languages.

A current trend the participant sees in building simulations is that professionals start diving to complex analysis without necessarily needing to. This is why the participant tries to understand what tool the project team wants to use for a particular project depending on the required level of detail of the modelling task. If, for instance, the project team wants first advice or needs to know the sensitivity of design parameters to different design options, Excel with benchmark data is employed. If a high level of detail is required or a client is considering, e.g., different glass specifications, Radiance with physically accurate material definitions is used.

The participant believes that the performance of the simulation tools used in the organisation highly depends on the user. There is a risk that an inexperienced user can produce inappropriate outputs although the tool is well validated. The setup and simulation run time of a model also depends on the user, who has to understand and correctly implement the level of detail required for a certain modelling task.

A.4.2.2 Issues and limitations

Especially the issues and limitations of IES VE and EnergyPlus have been discussed in the interview since they are the predominant BPS tools in the organisation.

IES VE is the standard tool within the organisation used for compliance and if a project team is sure that IES VE algorithms and routines are reasonable for a specific project. The participant points out that IES VE has no models for certain dynamic façades. An example of a dynamic façade without a representative model in IES VE is CCFs with dynamic shading. This is why in one of the organisation's projects the shading in a CCF has been replaced with electrochromic glazing to allow the shading coefficient to change according to a multiple step function based on the incident solar radiation. A typical control logic for blinds in IES VE is a single step function (ON/OFF), which can be easily implemented in IES VE just as well as other simple control syntaxes.

The participant rates the extent of the limitations of IES VE as 7 (fairly limited) on a scale of 1 to10, where 1 means barely limited and 10 severely limited. The participant believes that people in the field of building simulations got already used to the fact that they need to take what is available, appropriate it and make it as close enough to answer a question as possible. Therefore, it is even more critical to check and test the functions of a software, which is, however, difficult in IES VE as it is a bit like a black box that hides many things from the user. This can be risky for practitioners in the participant's view as they have to trust that the software engineers have gotten the models right while still having the responsibility for sensible inputs and outputs. As a result, practitioners should instead understand the software than putting the responsibility on the software developers.

This means for software developers, in the participant's opinion, that they should make software transparent and applicable to every project scenario that their users are going to encounter while keeping some level of general behaviour in the tool. This is the main reason why the participant likes EnergyPlus, where it is possible to understand the calculations the tool performs at every time step. In the organisation, EnergyPlus is employed when the functionality of IES VE is not sufficient for specific project needs and when more control of the modelling is desired. Even if used only at the previous employer, the EMS feature is particularly interesting for the participant. This is because users can start to write their own code, which offers great flexibility to customise control logic. The EMS feature, however, can be daunting if users have not the mentality of running, e.g., IF-statements. Because the EMS feature opens up the functionality of EnergyPlus, the participant rates the extent of the limitations of EnergyPlus as 3.

Although both IES VE and EnergyPlus have limitations, the participant does not rate the impact of the limitations on the predicted simulation results as large (on a scale of 1 (no impact) to 10 (huge impact); IES VE: 5; EnergyPlus: 4). The reasoning for this rating is that there are also many other aspects in a model that have a significant impact on the predictions of these tools.

A.4.2.3 Workarounds

From a process point of view, the participant sees a workaround as an alternative functionality within a tool. This alternative requires a whole bunch of testing to check if the model behaves appropriately. Typical outputs for such a check are transmitted solar gains, conduction gains through the façade and heating and cooling loads within the perimeter space. Ultimately, if the model does not behave as expected, the outputs can be post-processed, usually in Excel, and adjusted by hand. This is, however, the last option in a process as it introduces human error and is less repeatable. Two examples of alternative approaches within the participant's organisation are:

- Since IES VE and EnergyPlus provide only zone-averaged temperature values, time step data from one of these tools are brought into Honeybee to move from zone to subzone level. By using Honeybee's view factor tool, a more spatial understanding of temperature distributions and, therefore, comfort variation through the space can be created.
- To get a more accurate idea of wind conditions, the organisation tends to attain long-term historical wind data, which are processed in MATLAB and Ladybug. Windroses and other wind-related data are visualised in Grasshopper.

These workarounds become part of ongoing projects if they are identified as a more appropriate methodology to get a certain answer or output. The validation of the workarounds is conducted in terms of quality assurance of inputs and outputs and a four-eyes-principle with a senior specialist. This makes the alternative approaches in the participant's opinion reliable.

A.4.2.4 Future practice

The participant thinks that there is a big focus on post-construction energy and carbon building performance assessment in the future, which eventually helps to close the performance gap. Because of this increasing awareness of building performance, the simulation of dynamic façades is dragged along in the process. To better simulate these façades, user behaviour and building automation for dynamic façades need to be better understood and predicted in a model in terms of simulation algorithms or controls that allow for a better understanding of how these systems work in reality.

The participant is unsure if this development leads either to new models for dynamic façades in existing tools or to suites of tools that capture the different interactions of occupants, BMS, sensors, actuators and so forth. However, the participant is quite sure that the current trend of Grasshopper and visual plug and play tools might shape how specific building systems are simulated in the future. The participant also thinks that the trend of sharing, e.g., Grasshopper models with the rest of the industry is valuable and can uplift the entire industry skill set.

In the participant's organisation, some new simulation methodologies and procedures and some new ways to resolve modelling issues are developed. The participant thinks that future methods are not used by practitioners if they take too long to run or to set up because of the economics of business. New tools have to be simple and accessible so that users understand how to use them. Similar to BPS tools, the accuracy and reliability of new methods come down to users, who need a high skill level. This could be particularly true for Modelica, which the participant considers as an excellent complementary tool in the future, even though the participant has no personal experience with it yet. The participant believes that it would be helpful if future tools could include an error range in their predictions to show what goes wrong in a model.

A.4.3 P03 interview transcript

The participant used already most of the common BPS tools, including EnergyPlus, IES VE, Ecotect, DAYSIM, Radiance and Grasshopper, to design all kinds of buildings.

A.4.3.1 Current practice

The BPS tool used in the participant's current organisation depends on the type and complexity of the project and the type of simulation needed to be run. IES VE is used for most of the projects since it is user-friendly and validated. Grasshopper and EnergyPlus are used when a project is more complex or needs to be assessed in the early design stages. Further considerations in the tool selection process are that the project team must:

- have a good benchmark of the quality of the output;
- know that the predictions are reliable; and
- get the results quickly (i.e. short model setup and simulation run time).

Comparing the usefulness of IES VE and EnergyPlus, the participant highlights that IES VE is much more user-friendly than EnergyPlus while also being reliable. The usefulness of EnergyPlus depends on whether it is used with or without a graphical user interface, such as OpenStudio or DesignBuilder. In the participant's view, orientation towards the user is key when developing software used for building performance simulations. The use of simulation engines, such as EnergyPlus, might be ok for research environments, but when it comes to work environments, a graphical user interface and the possibility to quickly set up a model and get results in a presentable format is crucial.

The participant says that in 90 percent of the time, the simulation methods used in the organisation do not go beyond standard practice in the industry. The reason for this is that in early design stages, the chances are high that practitioners try innovative technologies even though the risk of error in the predicted results is high. However, in late design stages, practitioners often go for the more traditional technologies and, hence, more reliable simulation methods.

A.4.3.2 Issues and limitations

The participant rates the limitations of BPS tools on average as slightly limited (6 on a scale of 1 to 10, where 1 means barely limited and 10 severely limited). This depends, however, always on the client, the project and the person working on the project.

The main limitation of current tools to simulate the building performance is that adaptive façade behaviour cannot be modelled. While models in IES VE are fixed and cannot be extended by the user, it is possible in Grasshopper to assess the dynamic behaviour of the envelope and also to test different design configurations, which provides the user with different type of feedback. Some examples of dynamic façades that are difficult to model in BPS tools are:

- adaptable behaviour of glass (i.e. variable g-value);
- blinds and shades controlled by, e.g., solar radiation; and
- phase change materials.

When asked to rate the impact of these issues and limitations on the final predicted simulation results on a scale of 1 to 10, where 1 means no impact and 10 huge impact, the participant responded 3-4 for more typical façades, like blinds, and 5-6 for dynamic façades.

A.4.3.3 Workarounds

Since more and more practitioners can script and code, i.e., in Grasshopper or other scripting languages, most of them create their own workaround to overcome the issues and limitations discussed before. In the participant's organisation is a specialised team, which develops bespoke scripts if asked to do so. Ideally, these scripts are written in such a way that they can be reused in other projects to minimise time and cost expenditure. The scripts are mainly linked with more complicated tools like EnergyPlus and Radiance as it is almost impossible to connect a script to IES VE.

The participant is not sure why the organisation chose exactly this workaround but guesses that this was because it seems to be a promising solution to solve the limitations of BPS tools. The participant rates the scripting workaround as follows:

- **Usefulness:** The participant personally likes scripting methods due to the opportunities they open up. However, a project is always a trade-off between client needs and flexibility. This is why the participant believes that a project team can get a lot of more benefits if it has the opportunity to use scripting methods early in the design stage, where the client and the project team are happier to accept changes.
- **Reliability and accuracy:** The reliability of the scripting workaround employed in the organisation is risky because one needs to rely on the capabilities of the developer of the script, and the predictions of such a script are not always as expected. The participant notes, however, that it is possible to validate this workaround by applying it to different projects and comparing the results with each other.
- **Modelling time:** It takes quite a lot of time to script a workaround.

A.4.3.4 Future practice

Key considerations in the development of innovative methods to simulate dynamic façades in the future are according to the participant:

- enhanced user-friendliness;
- reduced modelling and computation time; and
- quick way to get results.

It is the participant's hope that practitioners would see such an innovative analysis method for the building envelope not as a waste of time but as common practice. The participant compares innovative methods for dynamic façades to finite element analyses of thermal bridges, which has not been widely used ten years ago but is now common practice. Nowadays, 90 percent of the practitioners can use one tool or another to do a finite element analysis and get reasonable results.

The participant believes that, rather than seeing new tools, existing BPS tools develop further in the future, similar to the developments noticed in Grasshopper add-ons like DIVA and Ladybug in recent years. However, the participant could also imagine that tools specialised in building envelope analysis develop in the future.

The participant has not used Modelica so far and knows of nobody within the organisation working with it.

A.4.4 P04 interview transcript

A.4.4.1 Current practice

The BPS tool mainly used for the modelling and computation of dynamic façades in the participant's organisation is IDA ICE, developed by EQUA in Sweden. In the past, the participant also employed other tools including EnergyPlus, TRNSYS, BSIM2000 and IES VE. However, since many other companies close to the organisation work with IDA ICE, the decision to use this tool was logical. The participant has the impression that the software developers of IDA ICE focus more on the building physics side of things than other software:

- appropriate calculation procedures as in the case of the window model that is based on ISO 15099, an international standard for detailed calculation methods for window and door systems;
- transparency in a way that users can (i) track and export every parameter IDA ICE uses in its calculation procedures (compared to EnergyPlus, in which the type of outputs users can see is predefined) and (ii) unhide and, hence, understand codes and algorithms the tool uses; and
- flexibility, which becomes clear from the fact that users can programme and add their own building systems and content in IDA ICE.

These advantages of IDA ICE are key for the participant believing that it is essential to be aware of the calculation methods in whatever tool. If the capabilities of IDA ICE are not sufficient for a certain project, the organisation develops its own scripts in Grasshopper, Excel or other tools.

Although the advanced level of IDA ICE might be difficult for beginners, its engineering approach is beneficial for the participant. Also, the reliability of IDA ICE is excellent as it is based on valid standards and users can do reliability checks by extracting every calculation parameter they want. Because IDA ICE has no fixed time step but determines the best time step on its own, the simulation time and accuracy is improved compared to EnergyPlus in the view of the participant. However, the run time of a simulation always depends on the level of detail of the model.

A.4.4.2 Issues and limitations

The participant rates the extent of the limitations of IDA ICE as 3 on a scale of 1 to10, where 1 means barely limited and 10 severely limited. The reasoning behind this rating is that IDA ICE is highly programmable. The participant highlights that the more programmable a tool, the more models it can support. Types of façades that can be easily implemented in IDA ICE include double skin façades, blinds and phase change materials. Complex control strategies can also be modelled in IDA ICE. If a model for a specific dynamic façade is not available, users should start looking for another tool; Just as the participant did in the case of a negatively sloping wall, for which the participant had to use EnergyPlus instead of IDA ICE.

However, the participant also notes that the limitations of every tool depend on the project and the user. A general problem the participant currently sees in building simulation software is that software developers want to make their software approachable to a broad range of people, but most of the people do not understand the calculation procedures in the software. As a result, people do not know how to correctly use whatever software, which can bring lots of damage.

Nevertheless, the participant is generally satisfied with the capabilities of existing software, especially IDA ICE. If a tool cannot model a certain dynamic façade type, such as a CCF, the impact on the final predicted simulation result can be of limited value (7 on a scale of 1 to 10, where 1 means no impact and 10 huge impact).

A.4.4.3 Workarounds

To overcome the limitations of BPS tools in modelling and simulating dynamic façades, the participant firstly tries another or a combination of other tools. If there is no way to solve the issue, the participant uses Grasshopper or scripting methods. In a few projects, the participant also asked the software developers of a particular tool to develop a new model, which they happily did.

Although some of the workarounds may affect the quality of the work, any of these workarounds are usually applied to ongoing projects. The project team usually does a feasibility check to be able to rely on the workaround. The participant also highlights that extensive experience and knowledge of the physics help in trusting a specific workaround.

A.4.4.4 Future practice

The participant believes that tools like Grasshopper, in which the user can link different engines, develop further in the future. This is why co-simulation is also a fascinating approach in the future. The participant points out, however, that a problem with co-simulation, Grasshopper and other more flexible tools is that there are not validated compared to EnergyPlus or IES VE. Although validation of such software packages is possible through comparative testing, comparative tests carried out in the participant's organisation showed that the predicted results of various tools concerning the performance of dynamic façades varied by more than 10 percent. Another challenge of more flexible tools and approaches the participant mentions is the question of who is taking responsibility for the correctness of the predicted results of Grasshopper and similar software.

In general, the participant thinks that future tools should be flexible to create all different types of models, have a good user manual to understand the physics behind a tool entirely, be transparent to look out for every parameter during the simulation process and be open-source. To do this, software does not necessarily require a fancy interface.

In terms of Modelica, the participant says to be aware of Modelica, but not to know anyone, who already tested or worked with it. The participant notes, however, that building envelope, system and control models of IDA ICE are written in the NMF or Modelica language.

A.4.5 P05 interview transcript

A.4.5.1 Current practice

The participant uses mainly IES VE for energy and compliance modelling and Radiance or IES VE for daylight modelling (i.e. spatial daylight autonomy and sun exposure calculations). Scripted in-house tools to carry out, e.g., solar radiation analyses also exist in the organisation. In the past, the participant used Ecotect and Sefaira for environmental analyses and DIALux for lighting calculations.

Even though the participant says not to have been fortunate enough to model very complicated dynamic façades other than blinds, one of the main challenges the participant's organisation encounters when it comes to dynamic façades is the accuracy of predictions. Generally, however, the participant believes that the accuracy of predictions depends on the tool, the analysis, the question that needs to be answered and the building characteristics (i.e. thermal properties, openings for natural ventilation). The participant tends to rely more on pure calculation engines like EnergyPlus, Radiance and in-house tools than on other tools like IES VE due to their transparency, which enables users to understand calculations procedures and assumptions. By contrast, the participant thinks that IES VE is a bit of a black box; yet trusting it since it is an industry standard.

The participant rates the modelling time of all of the available software as very time-consuming. The painful part for the participant is to get the geometry into the model. But the participant notes that the purpose of BPS tools is not the geometry but the analysis.

A.4.5.2 Issues and limitations

There are a few façade types that can be easily implemented in BPS tools. In current tools is, for instance, a straightforward way of modelling shading according to the participant. The participant would also feel confident in modelling blind control in tools available on the market although there could be a need for post-processing the results through interpolation.

By contrast, it is challenging to simulate façades with thermal resistors, bimetals and variable permeability surfaces in the current tools. The participant also believes that the predictions of a CCF in existing tools would not be accurate. In such a case the participant would discuss with a façade specialist the adjustments needed to create a model that is representative of the actual conditions. When discussing control strategies for dynamic façades, the participant said to feel limited in modelling façades, which are adaptive in terms of control, such as adaptive thermal properties as in phase change material. In case a façade control cannot be modelled, the final predicted simulation results can be profoundly affected. When asked to rate the impact of these issues and limitations on the final predicted simulation results on a scale of 1 to 10, where 1 means no impact and 10 huge impact, the participant responded 7.

A.4.5.3 Workarounds

A typical workaround for the participant is to post-process the predicted results through interpolation. As an example, the participant chose the following approach to model a simple ON/OFF blind automatically controlled by daylight illuminance:

- model all different situations of the blind;
- simulate all of the situations independently of each other; and
- manually interpolate the results in an Excel spreadsheet.

Although the participant admits that there might be software packages that can simulate such a blind automatically, the participant thinks that practitioners will hardly find a tool that provides them with the results ready.

Another workaround used in the organisation, but not by the participant is scripting methods including Python, a beta version of IES VE and Grasshopper. Some of the in-house solutions have been developed because there is a lack of early design stage as well as thermal comfort and environmental analysis tools.

A third potential workaround in the participant's view is to make reasonable assumptions if something cannot be adequately modelled. In the participant's opinion, a large part of engineering work is to make reasonable assumptions and adjustments. Before applying a workaround, the participant would always check inputs, plot results to examine interrelations of variables and run a sensitivity check first. The participant assesses predictions based on prior knowledge and experience, benchmark data and checking with senior colleagues.

In the view of the participant, workarounds do not extend the time needed to set up a model. It is rather the geometry input that uses most of the modelling time.

A.4.5.4 Future practice

The participant sees several issues that need to be improved in BPS tools:

- interoperability across applications and integration of BIM and sketching tools;
- live update links with other software of, e.g., geometry and design variables;
- open-source capabilities to enable all project members to access a model remotely and play with it, e.g., to allow architects to check design alternatives themselves quickly;
- parametric performance to be able to change parameters more quickly and intuitively; and
- capability to perform simulations of controls with dynamic patterns.

Also, the participant believes that future tools are more accurate, especially in advanced project phases. However, the higher the accuracy, the longer the modelling and computation time required for a specific model. This is why the participant highlights that the organisation misses software that has different degrees of accuracy.

The participant heard of Modelica but has no experience with it.

A.4.6 P06 interview transcript

The main focus of the participant's work is energy modelling in non-domestic buildings. This also sometimes includes natural ventilation, overheating and Building Research Establishment Environmental Assessment Method assessments and Computational Fluid Dynamics (CFD) analyses.

A.4.6.1 Current practice

The participant uses IES VE for most of the projects. For some projects in the early design stage, the organisation developed a series of tools based on Revit, Grasshopper and Rhino to optimise specific design parameters, such as U-value, g-value and light transmittance, to inform the architect of the best thermal mass, orientation, configuration and so forth and to find the optimum solution. The organisation also developed a Grasshopper script, which copies all relevant information from a Revit model to a thermal model and which runs a series of simulations with Tas in the background automatically. If changes occur in the Revit model, the script immediately captures these changes and adapts the thermal model accordingly. The participant evaluates IES VE as follows:

- **Usefulness:** Although there a mixed opinions about IES VE in the organisation and some colleagues find IES VE frustrating, not intuitive and not user-friendly, the participant finds it useful for the purpose of the analyses to be carried out. The participant also notes that the latest version of IES VE includes scripting possibilities that open up the flexibility of IES VE compared to the past, where IES VE used to be a black box.
- **Reliability and accuracy:** The participant relies on the predicted results of IES VE and compares them to actual data, if possible. In the cases, where the participant was able to compare predicted with measured data, the predictions have not been too far away from the measurements. Consequently, the participant relies on the predicted results of IES VE.
- **Time needed to set up a model and to run a simulation:** The geometry setup used to be a pain in the participant's view. However, the organisation uses now an IES VE SketchUp plug-in that allows to use the SketchUp model from the architects and import this model as a gbXML file to IES VE.

A.4.6.2 Issues and limitations

The participant rates the limitations of IES VE as very limited (5 on a scale of 1 to 10, where 1 means barely limited and 10 severely limited) when it comes to adaptability in façades. For instance, the user has no opportunity to control shading elements to move, e.g., depending on weather conditions. They are rather seen as fixed elements in the model. The participant experienced this limitation when modelling a CCF with a between-glass blind, which was eventually modelled as a double-glazed window with an internal blind. Another example in terms of limitations in IES VE is curvy façade elements and double skin façades, which could be modelled with some approximations.

When asked to rate the impact of these issues and limitations (i.e. shading device operated based on weather conditions) on the final predicted simulation results on a scale of 1 to 10, where 1 means no impact and 10 huge impact, the participant responded 8.

A.4.6.3 Workarounds

A workaround the participant would apply if a certain façade system could not be modelled in IES VE is to test and understand different configurations of similar systems and to see if there is a simplified configuration that would be representative of the not modellable façade. In such a case, the participant would use the worst case scenario to calculate the thermal building performance, which would, however, not take into consideration the benefits of the adaptable façade.

Another solution would be looking for other software that would be able to represent the façade that could not be modelled in IES VE. For instance, Grasshopper could be used to model the adaptable part of the façade. This would, however, take much time to set up the model and increase the risk of error in the model.

A.4.6.4 Future practice

Considering that many practitioners in the building sector use Revit, the participant expects the development of a plug-in for Revit to model building energy performance. The participant could, however, not imagine that there is an IES VE integration into Revit in the future as the IES VE software developers are not open towards integration with other software.

The participant believes that, in the future, software developers add new models for dynamic façades in their BPS tools, such as models for control strategies to enable practitioners to create the adaptable part of the façade. The participant also thinks that practitioners can write their own scripts in Grasshopper or similar tools in the future to create custom models addable to current tools.

The participant is not aware of anyone inside the organisation working with Modelica.

A.4.7 P07 interview transcript

The participant's work focuses mainly on commercial buildings. Thermal modelling is used to assess, among others, thermal comfort, overheating, energy performance and carbon reductions. Additional analyses, such as CFD or daylight analyses, are done if a client specifically asks for it. CFD analyses have been carried out in the participant's organisation to understand wind patterns due to building massing.

A.4.7.1 Current practice

IES VE is the main BPS tool used in the organisation. The reason why the organisation chose IES VE is that it is certified by the authorities producing plausible results that can be used in energy and sustainability strategies required for planning. In the façade design process, the organisation usually does not account for blinds since authorities expect enough daylight and restricted solar gains in a building without the use of blinds. The participant says that the organisation is mainly looking at window-to-wall ratios, U-values and solar exposure during façade design. The participant rates IES VE as follows:

- **Reliability:** The participant thinks that the predictions of IES VE are reliable.
- **Usefulness:** IES VE is becoming more complex making it difficult to handle it.
- **Simulation time:** In the participant's view, the simulation time of IES VE slowed down over the years, particularly in running the IES VE SunCast analysis, an analysis to examine the effect of sunlight and shadows on the thermal behaviour of buildings.

A.4.7.2 Issues and limitations

The participant discussed issues and limitations of in IES VE of modelling various façade types:

- **Curvy building shapes and forms:** It has been highlighted by the participant that curvy building elements are difficult to model in IES VE. Although it might be more straightforward and less time-consuming to model curvy shapes and forms in Grasshopper or another scripting method, a potential solution in IES VE is to, e.g., break a curvy wall down into several segments.
- **Blinds:** As long as users know all the parameters (e.g. g-value, transparency) that need to go into a model, all different types of blinds can be modelled in IES VE. Also, all different kinds of profiles for blind control can be assigned to blinds.
- **Varying façade properties:** The participant notes that varying façade properties (e.g. g-value, U-value) that can, for instance, be found in photochromic glazing or windows with translucent panels cannot be modelled in IES VE.

The participant rates the limitations of IES VE as 4 on a scale of 1 to 10, where 1 means barely limited and 10 severely limited. When asked to rate the impact of these issues and limitations on the final predicted simulation results on a scale of 1 to 10, where 1 means no impact and 10 huge impact, the participant responded 3-4.

A.4.7.3 Workarounds

The participant believes that for most of the limitations in IES VE, users can find an adequate workaround, such as educated assumptions based on available data sheets from product manufacturers. However, design teams need to be clear on assumptions they made in project reports, meetings and so forth.

The organisation is currently exploring possibilities of how Grasshopper or scripting methods can be applied to projects. The main reason why these methods are explored is to be up-to-date with recent developments in the industry, not because of insufficient tool capabilities.

A.4.7.4 Future practice

In the future, the participant likes to see easier and quicker modelling capabilities in IES VE and enhanced import possibilities for Revit models. The participant hopes that software developers add custom control profiles (e.g. on weather conditions or neighbouring building) for shading or other building elements and models for varying façade properties in future releases of IES VE.

The participant has not yet heard of Modelica.

A.5 Transcription keys

Table A.1 shows the keys of transcription used in this part of the study. Such a standardised system of transcription keys helps handle, compare and share language data.

Table A.1: Keys of transcription employed in study (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 indicated the emphasised syllable(s)
word-	A dash indicates a cut-off
()	Empty parentheses indicate that the transcriber was unable to get what was said
(word)	A parenthesised word indicates an uncertain word
((comment))	Double parentheses contain additional comments from the transcriber

A.6 Interview codebook

A - Current tool developments

- Current tools used
    - Tools used
    - Fields of application
        - CFD
        - Comfort
        - Daylight
        - Environmental assessment methods
        - Parametric analysis
        - Thermal and energy performance
        - Ventilation
    - Methods beyond industry standards
- Factors for tool selection
    - Accessible training and knowledge in company
    - Calculation procedures
    - Compliance
    - Exchange and interoperability
    - Flexibility
    - GUI
    - Insight and transparency
    - Modelling and computation time
    - Project requirements
- Performance of tools
    - Usefulness
        - Usability for projects
        - User-dependency
        - User-friendliness
    - Accuracy and reliability
        - Degree of dissemination in industry
        - Time step handling
        - Transparency
        - User-dependency
        - Validation
    - Modelling and computation time
        - Time requirement
        - Reasons for time requirement
        - Time-related costs

B - Issues and limitations

- Degree of limitations
- Types of limitations
  - Controllers
  - Façade systems
  - Geometry
  - Materials
  - Methods
  - Shading systems
- Impact of limitations
  - Impact on predictions
  - Implications

C - Workarounds

- Types of workarounds
  - Alternative model
  - Alternative tool
  - Assumptions
  - Parallel simulation
  - Post-processing of simulation results
  - Scripting
- Applicability to ongoing projects
- Factors for workaround selection
- Performance of workarounds
  - Usefulness
  - Accuracy and reliability
    - Four-eyes-principle
    - Knowledge and experience of user
    - Quality assurance of input and output data
    - Validation of workaround
  - Time
    - Time requirement
    - Time-related costs

D - Future tool developments

- Types of tool improvements
  - Exchange and interoperability
  - New models
    - Controllers
    - Materials and façade systems
  - New tools and methods
  - Tool capabilities
- Performance of tool improvements
  - Usefulness
    - Collaboration
    - Responsibility for predictions
    - Support
    - Tool capability
  - Accuracy and reliability
  - Modelling and computation time
  - Scope of analysis
- Experience and awareness of Modelica

A.7 Interview data analysis

Table A.2: Main tools used by participants in each field of application.

Field of application	Tool used	Interview code
Thermal and energy modelling	IES VE	P01, P02, P03, P05, P06, P07
	EnergyPlus	P02, P03, P05
	IDA ICE	P04
Daylight and visual comfort modelling	IES VE	P01, P05, P07
	Radiance	P02, P03, P05
	DIALux	P05
	Diva	P01
Scripting methods	Grasshopper with add-ons	P02, P03, P04, P05
	Python	P02, P05
	EMS scripting feature	P02
	MATLAB	P02
	In-house tools	P05

Table A.3: Factors for tool selection in participants' companies.

BPS tool	Factor for BPS tool selection
All BPS tools	• **Modelling and computation time:** BPS tools are selected project-specifically, whereby it is key that the model setup and simulation run time are short, as this leads to a fast return of outputs (P01, P02). • **Project requirements:** BPS tools are selected project-specifically, whereby it is key that tool capabilities match the project's required level of detail (P02) and provide high-quality and reliable predictions (P03).
IES VE	• **Building energy regulation compliance:** IES VE offers calculations for compliance with Part L in the UK (P01, P02, P07). • **Accessible training and knowledge in company:** IES VE has been selected due to a natural development over the years as colleagues have shared their knowledge with the growing team (P07) and due to extensive in-company training on it (P06). • **Exchange and interoperability:** IES VE provides possibilities for exchange and interoperability across IES VE applications, where the same model can be used for different analyses and calculations (P01). • **GUI:** IES VE has a user-friendly GUI (P01). • **Insight and transparency:** IES VE offers more transparent possibilities for the implementation of control strategies than other BPS tools, such as BSim (P01).
IDA ICE	• **Calculation methods:** IDA ICE provides suitable calculation methods, e.g. through the window model according to ISO 15099 (P04). • **Exchange and interoperability:** IDA ICE facilitates collaboration between companies, all of which work with IDA ICE (P04). • **Flexibility:** IDA ICE allows users to programme it and to add their own building systems (P04). • **Insight and transparency:** IDA ICE offers transparent calculation methods that allow users to understand parameters, codes and algorithms it uses (P04).

Table A.4: Usefulness, reliability and simulation time of future tool developments.

Type	Description
Usefulness	• Better exchange and interoperability would enhance communication between project team members (P05, P06). • Most of the participants expect the usefulness of future tool developments (i.e. user-friendliness, accessibility and straightforwardness for quick understanding of tool) to be similar (P02) or better (P03) compared to today. • Improvement of the usefulness of future tool developments through parametric modelling and optimisation to enable practitioners to better understand the sensitivity of each parameter implemented in a model and to empower clients to make smarter decisions (P01, P05).
Reliability	• A potential problem with co-simulation, scripting and other more flexible tools is that they are not validated compared to EnergyPlus or IES VE, which raises the question of who takes responsibility for the accuracy of the predictions (P04). • The accuracy and reliability of future tool developments depends on the users, who require a high level of qualification (P02).
Time	• A critical consideration for future tool developments is the reduction of the modelling and computation time in order to get results quickly (P03). • Even if the modelling and computation time could be reduced anyway as computers become more powerful, practitioners may not use future tool developments if they take too long, due to the economics of business (P02). • A tool with different levels of accuracy would increase the modelling and computation time in later design phases as the degree of accuracy increases (P05). • Once practitioners know the sensitivity of each parameter through parametric analyses, they can begin to neglect or detail parameters, which could change the focus or scope of analysis of building performance simulations in the future (P01).

B Overview of cosim Python package

B.1 Software requirements

To predict the performance of control strategies for adaptive building envelopes, `cosim` requires the software packages listed in Table B.1. `cosim` has been tested on Ubuntu 20.04.

Table B.1: Software packages adopted in modelling approach.

Software	Developer	Version	Release date	Release date of v1.0
EnergyPlus	NREL	v8.9.0	2018	1999
EnergyPlusToFMU	Nouidui, Lorenzetti and Wetter	v3.0.0	2020	2013
FMI Standard	MODELISAR	v2.0	2014	2010
Dymola	Dassault Systèmes	v2020x	2020	1992
Modelica	Modelica Association	v3.4	2017	2000
Python	Python Software Foundation	v3.8.5	2019	2001

B.2 Installation

`cosim` will become available on Github shortly. Once it is made available, it can be downloaded and extracted into a local directory. To access `cosim` in Python, it needs to be in a list of directories assembled from the following sources:

- the directory from which the input script is run;
- the current directory if the interpreter is being run interactively;
- a directory contained in the PYTHONPATH environment variable, if it is set; or
- an installation-dependent directory configured at the time Python is installed.

Once `cosim` is in this list of directories, it can be made available to the caller with the `import` statement: `import cosim`. To import individual objects from a module directly into the symbol table of the caller without the package prefix, the `import` statement can be alternated. For example, `from cosim.output.export import idf_to_fmu` can be used to import just the required function `idf_to_fmu` from the `export` module to the caller.

B.3 Code documentation

The following is a description of the use and functionality of `cosim`.

B.3.1 Module `simulate`

This module contains the class `simulate(output_dir, s_start=0, s_stop=31536000, s_step=600)` that can be used to run a model from (i) a mono-simulation in EnergyPlus or (ii) a co-simulation in EnergyPlus and Dymola through the FMI Standard. It uses the `__init__` constructor to allow the class to initialise the attributes of the class. The initialisation arguments of the class are:

- `output_dir`: The output directory. This parameter specifies to which directory the output and log files are moved on completion of the simulation.
- `s_start`: The start time of the simulation in s, automatically converted to EnergyPlus or Dymola syntaxes.
- `s_stop`: The stop time of the simulation in s, automatically converted to EnergyPlus or Dymola syntaxes.
- `s_step`: The time step of the simulation in s, automatically converted to EnergyPlus or Dymola syntaxes.

By default, the simulation is run for a whole year (start time: 0 s, stop time: 31 536 000 s) with a time step of 600 s. But these defaults can be changed as needed. If they are changed, it is important to bear in mind that EnergyPlus requires a simulation length of a multiple of a day, i.e.86 400 s, so simulations can only be performed on a daily basis.

The `simulate` class contains two functions: (i) `monosimulate` and (ii) `cosimulate`. The first function of the `model` class executes the previously initialised model in a mono-simulation setup:

```
cosim.model.simulate.simulate.monosimulate(eppy_path, idd_file, epw_file,
idf_file, leap_year=False)
```

The arguments of the function are:

- `eppy_path`: The path to eppy (Philip, 2019), a Python library to run EnergyPlus simulations.
- `idd_file`: The path to the IDD file (*Energy+.idd*) located in the main folder of EnergyPlus, usually a folder named *EnergyPlusV8-9-0*.
- `epw_file`: The path to the weather file in .epw format.
- `idf_file`: The path to the IDF file of the EnergyPlus model in .idf format.
- `leap_year`: An argument to indicate whether the year of the simulation is a leap year or not, as specified in the weather file.

The default value of the `leap_year` argument is `False`. If the weather file has the leap year flag set in its header, this argument can be set to true (`leap_year=True`), so an additional day is added to the `RunPeriod` object in the IDF file.

The `monosimulate` function can be called as shown in Code 6.2 and returns a eplusout.csv file to the output directory.

The second function of the `simulate` class executes the previously initialised model in a co-simulation setup:

`cosim.model.simulate.simulate.cosimulate(model_name, show_gui=False, exit_simulator=True)`

The arguments of the function are:

- `model_name`: The name of the Dymola model.
- `show_gui`: An argument to show the GUI of the simulator, i.e. Dymola.
- `exit_simulator`: An argument to avoid terminating the simulator.

The default value of the `show_gui` argument is set to `False` and the `exit_simulator` argument is set to `True`. These two arguments are useful for debugging a model as they open the GUI (`show_gui=True`) and keep the simulator open after the simulation (`exit_simulator=False`).

The `cosimulate` function simulates the co-simulation model through the `Simulator.simulate()` method of the BuildingsPy package (LBNL, 2019). It can be called as shown in Code 6.3 and returns a .mat file generated by Dymola to the output directory.

B.3.1.1 Module `export`

This module contains two classes:

- `idf_to_fmu`: This class can be used to create an FMU for co-simulation from an EnergyPlus IDF file using the FMI Standard v2.0.
- `mat_to_csv`: This class can be used to export a .mat output file from a Dymola simulation to a .csv file.

Each of the classes uses the `__init__` constructor, and the initialisation arguments of the `idf_to_fmu(eptofmu_file, idd_file, epw_file, idf_file)` class are:

- `eptofmu_file`: The path to the *EnergyPlusToFMU.py* file located in the main folder of EnergyPlusToFMU.
- `idd_file`: The path to the IDD file.
- `epw_file`: The path to the weather file in .epw format.
- `idf_file`: The path to the IDF file of the EnergyPlus model in .idf format.

The `idf_to_fmu` class contains the function `export` to create the FMU from the EnergyPlus model:

`cosim.output.export.idf_to_fmu.export()`

It can be called as shown in Source code 6.4 and returns an .fmu file.

The initialisation arguments of the `mat_to_csv(mat_file, csv_file=None)` class are:

- `mat_file`: The path to the .mat file generated by Dymola.
- `csv_file`: The path to the .csv file to be created in this class.

The default value of the argument `sim_params` is `None`. If no argument value is passed during the function call, the .csv file created in this class has the same file name and directory as the .mat file.

The `mat_to_csv` class contains the function `export` to export the .mat output file from the Dymola simulation to a .csv file:

```
cosim.output.export.mat_to_csv.export(output_vars=None)
```

The argument of the function is:

- `output_vars`: A tuple with variables to be added to the list of output variables.

The argument of this function is `None` by default. To add variables to the list of output variables, they have to be passed in the following form: `output_vars=('var1', 'var2', 'var3')`.

It can be called as shown in Source code B.1 and returns a .csv file for further use.

Source code B.1: Usage of `export` function of `mat_to_csv` class.

```
from cosim.output.export import mat_to_csv
import os

vars = ('var1', 'var2', 'var3')

if os.path.isfile('/etc/my_model.mat') == True:
mat_for_export = mat_to_csv(mat_file='/etc/my_model.mat',
↪  csv_file='/etc/my_model.csv')
mat_for_export.export(vars)
```

C Uncertainty indices for validation

Key uncertainty indices for assessing model accuracy are the NMBE and CV-RMSE indices. To better understand the magnitude of the error of NMBE and CV-RMSE indices, the MBE index is explained first. The MBE index is the average of the errors of a sample space and a good indicator of the overall behaviour of the simulated data regarding the regression line of the sample. In Equation C.1, m_i is the measured data point for each model instance i, s_i is the simulated data point for each model instance i and n is the number of measured data points.

$$\text{MBE} = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} \tag{C.1}$$

Compared to the MBE index, the NMBE index is used to scale the MBE results and to make them comparable. The NMBE index normalises the MBE index by dividing it by the mean of the measured data points ($\bar{m}$), thus giving the global difference between measured and simulated data points. In Equation C.2, p is the number of adjustable data points[1].

$$\text{NMBE} = \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n - p} \cdot 100 \quad (\%) \tag{C.2}$$

Positive values of MBE and NMBE suggest that the model under-predicts measured data, and negative values suggest that the model over-predicts measured data. The main problem with these indices is the cancellation error, where the sum of positive and negative values reduces the value of MBE or NMBE. The use of these indices alone is consequently not recommended, and a further measure of model accuracy is the CV-RMSE (ASHRAE, 2014b). This index (Equation C.3) measures the variability of the errors between measured and simulated data points, thereby giving an indication of the model's ability to fit the data (Coakley, Raftery and Keane, 2014).

$$\text{CV-RMSE} = \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n - p}} \cdot 100 \quad (\%) \tag{C.3}$$

To represent the overall goodness-of-fit, NMBE and CV-RMSE indices can be consolidated into the single statistical index δ_t. In Equation C.4, w_NMBE and $w_\text{CV-RMSE}$ are the weights of the NMBE and CV-RMSE indices. Assuming equal weights for w_NMBE and $w_\text{CV-RMSE}$ of e.g. 0.5, Equation C.4 can be reduced as shown.

---

[1] According to Robertson, Polly and Collis (2013), $p = 0$ for Equation C.1 and C.2 and $p = 1$ for Equation C.3

$$\begin{aligned}\delta_{\mathrm{t}} &= \sqrt{\frac{w_{\mathrm{NMBE}}^2 \cdot \mathrm{NMBE}^2 + w_{\mathrm{CV-RMSE}}^2 \cdot \text{CV-RMSE}^2}{w_{\mathrm{NMBE}}^2 + w_{\mathrm{CV-RMSE}}^2}} \\ &= \frac{\sqrt{2}}{2} \cdot \sqrt{\mathrm{NMBE}^2 + \text{CV-RMSE}^2}\end{aligned} \tag{C.4}$$