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Ten questions concerning co-simulation for performance prediction of advanced building envelopes

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ABSTRACT

Advanced building envelopes (ABEs) are innovative integrated systems that aim to increase the sustainability of buildings by providing flexible and efficient energy management solutions while safeguarding healthy and comfortable indoor environments. These building envelopes operate at the cross-section of architecture, engineering and data science, often involving transient multi-physical parameters and advanced material properties. The development of ABEs has increasingly relied on building performance simulation (BPS) tools to improve the understanding and management of their complex interrelationships. However, this complexity has sometimes shown to constitute barriers for their real-world implementation, in part caused by the limitations of monolithic legacy BPS tools. One of the most promising alternatives to overcoming these difficulties has been to use co-simulation. Co-simulation allows modelers to use multiple sub-models and link them to enable simultaneous data exchange during simulation runtime. This approach provides added possibilities for implementing advanced control strategies, integrating innovative data-driven inputs, and creating collaborative interdisciplinary and evolutive workflows for building envelopes at different stages and scales in projects.

This article provides a critical overview of the possibilities that co-simulation approaches offer to improve performance assessments of advanced building envelopes. This article also presents current barriers to co-simulation and discusses critical elements to overcome them. Ongoing trends in BPS and information and communication technologies are highlighted, emphasizing how they transform the field and create new opportunities for modelers working in research and industry.

1. Introduction

In order to minimize its contribution to climate change, the building sector is targeting increasingly stringent carbon emission reduction measures throughout the entire life cycle of buildings [1–4]. These policy developments place new demands on building design – and in particular building envelope design. They require going beyond the simplistic passive principles of the *"energy conservation approach"* [5] and actively exploit current technological developments in building materials and systems. As a result, significant research and innovation efforts have been deployed to develop novel building envelope systems and new design blueprints that could allow balancing these targets with the complex requirements of buildings. However, the transition from traditional building envelope designs to ones integrating innovative technologies is not seamless. Part of the reason for this is that most of the simulation tools used to evaluate envelope performance are legacy software [6,7]. This means that they originate from a time when the requirements for building envelopes and their properties were much different from today's [8]. As a result, modelers face several challenges to accurately and reliably assess the performance of new envelope technologies in legacy building performance simulation (BPS) tools. A promising approach to overcoming these limitations is to use more progressive simulation methods such as co-simulation.

This paper aims to share the critical insights of experts in building simulation on how co-simulation can be used to improve the performance prediction of innovative building envelopes. The material compiled in this work is a balanced blend of highlights from articles available in the literature, personal experiences, and a shared vision of future frameworks for co-simulation. The ten questions answered here

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Acronyms

ABE	Advanced building envelope
AF	Adaptive Facade
API	Application programming interface
BPS	Building performance simulation
EMS	Energy management system
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
ICT	Information and communication technology
MPC	Model predictive control
ODE	Ordinary differential equation
PDE	Partial differential equation

are chosen to lead the reader through a critical reflection on the challenges of using BPS for complex envelope systems, and the reasons why co-simulation may provide an interesting alternative. Readers unfamiliar with co-simulation will be warned of the many traps and difficulties that come with this approach, while experienced users may recognize challenges they have themselves faced. Readers will also find helpful recommendations based on the fit-for-purpose method to limit some of the potential issues in co-simulation and ensure that the approach developed is most relevant for the intended investigation. The added value of co-simulation for building envelope design, despite its challenges, is emphasized by highlighting its potential contribution in a bigger picture where it is integrated from design to commissioning as a dynamic layer in a larger project workflow. The reader will also find up-to-date information about the latest developments that support the uptake of co-simulation in its many forms in the field of building envelopes. Finally, it is worth mentioning that most of the challenges, opportunities and limitations of using co-simulation approaches to study and develop ABEs are also relevant for different building systems. For this reason, the answers to the ten questions proposed in this paper highlight topics and research priorities that could extend to the field of building simulation in general.

2. Ten questions concerning co-simulation for performance prediction of advanced building envelopes

2.1. Question 1: What are advanced building envelopes?

Advanced Building Envelopes (ABEs) are integrated envelope systems and technologies that can ensure high building performance across a wide range of physical domains (Fig. 1). ABEs aim to successfully balance competing performance aspects using a combination of advanced material properties, advanced components, and advanced integrated control strategies; or by having designs based on advanced design methodologies.

Designing such building envelopes, first requires shifting the focus from one-size-fits-all solutions to case-specific ones that aim at delivering a context-oriented, synergic and efficient envelope design. This is possible thanks to a series of developments in the capabilities of design and simulation tools (supporting, for example, free-form façades and geometrically complex shading elements [9–12]) and an improved ability to manage intricate interactions between different scales (material, building [13], or urban scale [14]) considering different physical domains [15]. These tools are also compatible with optimization, allowing to improve further the design and operation of innovative envelope technologies [7]. Overall, this approach is powerful in that it transforms a traditionally rigid building envelope design into a performance-oriented flexible design process that enables new functions, new behaviors, and new performance goals supported by the integration of innovative technologies.

Depending on the setting and the type of integrated technology, advanced building envelopes are also sometimes known as Responsive [5,16] or Adaptive building elements [17]. Alternatively, they may also be referred to in the literature as kinetic, smart, switchable, or multi-functional envelopes.

ABEs can assume different appearances and can be realized with different systems (Fig. 2). The main types of technologies used to design ABEs are: i) building-integrated solar energy conversion systems [18] (solar thermal, photovoltaic and hybrid systems); ii) decentralized integrated HVAC elements [19]; iii) components based on materials or systems capable of actively and selectively managing the energy and mass transfer through building envelopes, by reversibly modulating their thermo-optical properties and operating strategies according to transient boundary conditions and performance requirements [20], also

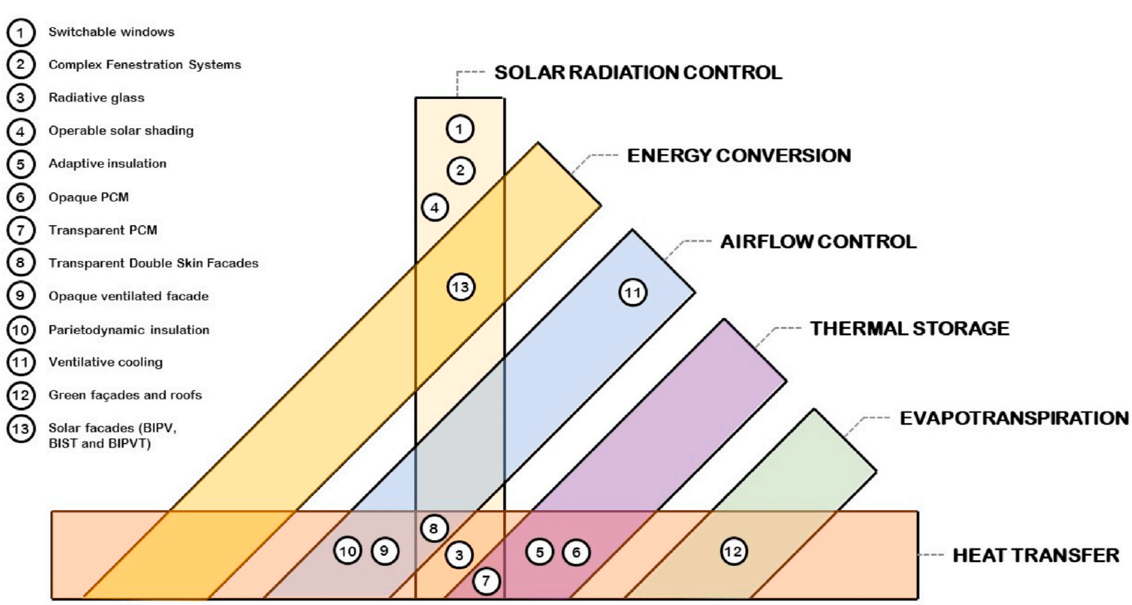

Fig. 1. Interrelated Physical domains/mechanisms influenced by advanced façade technologies (after [19]).

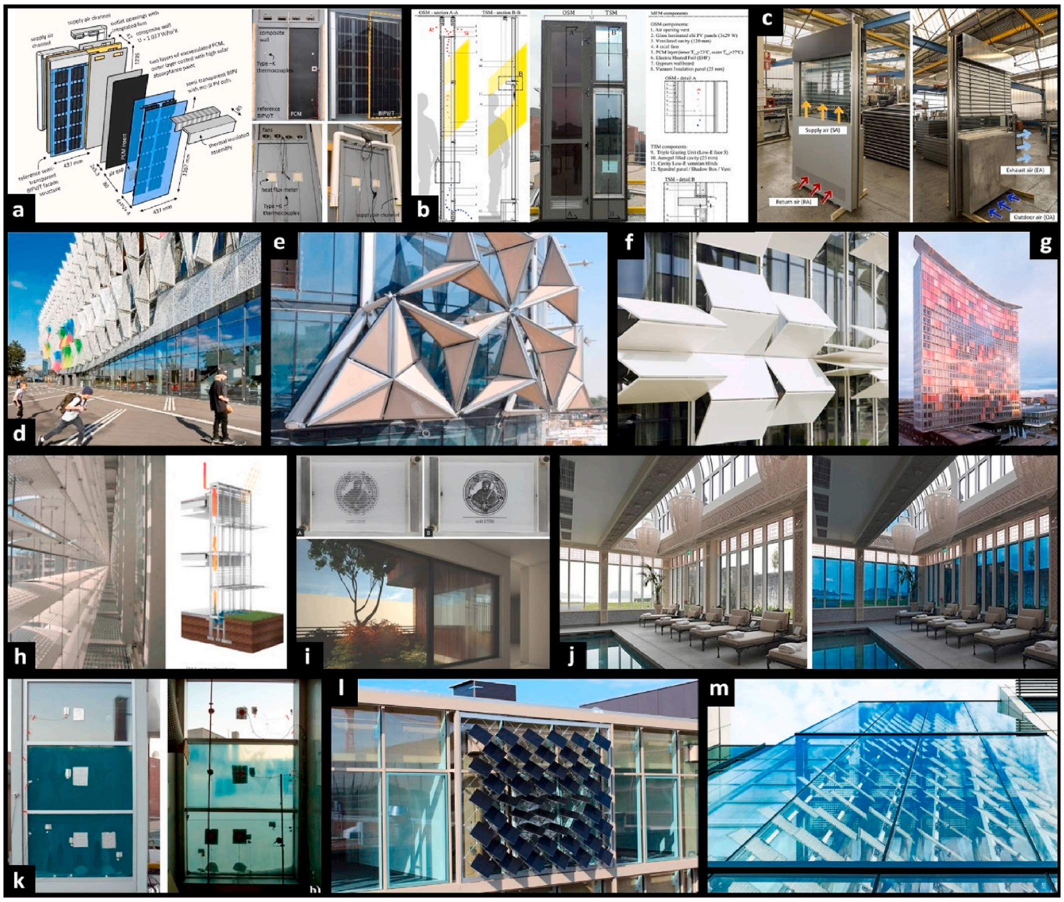

Fig. 2. *Examples of advanced building envelopes at research, prototype/demonstration, and commercial stage: multifunctional systems with integrated components such as solar (thermal) systems, HVAC units, ventilation systems, heat storage (a:* [21]*; b:* [22]*; c:* [23]*), kinetic facades (d, e:* [24]*; f:* [25]*;); double skin facades and systems with heat carrier fluids (g:* [25]*; h:* [26]*; i:* [27]*), smart glazing systems (j:* electrochromic [28]*; k:* thermochromic [29]*); solar facades with integrated dynamic, multifunctional PV and shading devices (l* [30]*; m:* [31]*).*

known as Adaptive Facades (AF).

Practical examples of ABEs may be: double skin facades or advanced integrated façades [32]; switchable glazing technologies such as electrochromic, liquid crystal, thermochromic glazing etc. [33]; operable solar shading [34–36] and complex fenestration systems [37]; wall integrated phase change materials [38]; and dynamic insulation [39] and multifunctional facades [40].

The multi-physicality of these components is illustrated in Fig. 1, where specific examples of technologies are placed according to their influence on the different domains they interact with [15]. These interactions may include more than one domain and may be static or dynamic, depending on whether the physical properties are variable and controllable. However, the intrinsic complexity of ABEs that initially sets them apart from traditional building envelopes and makes them attractive, also makes it challenging to predict their performance in BPS tools and ensure suitable design choices.

2.2. Question 2: What are the challenges of predicting the performance of advanced building envelopes?

The complex nature of ABEs calls for a holistic performance assessment in order to capture the full extent of their benefits. According to the literature, BPS plays a vital role in supporting decision making in design, product development, manufacturing, and operations of ABEs [41]. It is also crucial for verifying certification schemes and compliance with regulations [42]. However, modelling and simulating ABEs is not trivial. Simulating the operation of ABEs requires modelling phenomena that typically cannot efficiently be described in monolithic simulation software. This is because ABEs have many different prerequisites compared to a simulation-based analysis of conventional building envelopes, as discussed in Table 1.

As a result, using legacy monolithic simulation software presents several challenges. These are due to rigidities in the structure of the tools, limitations due to their intended purpose, and limited to non-existent integration options with other types of software (solving a different set of differential equations) nor with specific models (e.g. models of novel technologies developed in different tools and codes). The original issue comes from the fact that monolithic legacy tools were mainly developed to abstract the physical reality of one single domain. This means they were only built to solve the differential equations for one (or a selected few) physical domain at once (Fig. 3.a). Today, these tools continue to evolve to improve their accuracy and integrate new capabilities, which includes the addition of specific modules for the simulation of more advanced building systems. However, their large codebases render it difficult and costly to update and maintain them continuously. It is expected that in the long run, their current monolithic form will hinder them from keeping up with the pace and diversity of new material and envelope technology developments. The alternative to keep using these tools is to implement them as part of co-simulation approaches in which multiple specialized simulation engines and scripts are interconnected and exchange data (Fig. 3.b). These approaches are more suited to the modelling and simulation of complex systems and have the potential to facilitate the design and delivery of higher-performing buildings. Additionally, co-simulation could reduce redundant modelling activities (i.e. building multiple models of the same building or technology) and provide more accurate, multifaceted

Table 1
Main prerequisites for modelling ABE properties and associated requirements in terms of simulation capabilities.

Prerequisite	Requirement in BPS
Multi-physical modelling (i.e. considering heat, moisture, light, energy, air, sound) of the interactions between the envelope, the indoor environment, and building services [43]	It requires solving the differential equations of different physical domains in a coupled way with an appropriate spatial and temporal resolution
Flexibility to **integrate models of emerging technologies** which may not be directly available in a specific BPS tool [43]	It requires the possibility to develop or integrate dedicated models of advanced technologies into whole building simulation tools to consider coupled interactions with the rest of the building
Possibility to model **time-varying facade properties** that are controlled by boundary conditions (e.g. passive adaptive building envelope technologies such as phase change [44] or thermochromic materials [45]) or an input signal (e.g. active smart glazing [46])	It requires the possibility to simulate the dynamic operation of facade adaptation across multiple physical domains in coordination with the operation of building services or using specialized control-oriented software [47]
Possibility to simulate **interactions between ABE systems and building occupants** (for dynamic and/or controllable technologies)	It requires the possibility to integrate dedicated models replicating the stochastic nature of human behavior and interaction with advanced building envelope elements [48,49]
Possibility to **integrate performance-based generative design and architectural form-finding workflows**, for example for systems with complex and kinetic geometries [50], in BPS tools	It requires the possibility to couple flexible design tools with input interfaces of BPS tools
Greater need for **sensitivity and uncertainty analysis tools** for model validation and calibration to understand the influence of ABE design parameters on relevant building performance indicators [51], or conversely, of changing scenarios on design parameters [52]	It requires integrating approaches and models for global and local sensitivity analysis in BPS tools
Possibility to use **numerical optimization tools** to explore larger solution spaces [53] based on ABE design elements or properties	It requires coupling inputs and outputs of models and simulations to external algorithms and automatize the processes for simulation launching, output collection, and data analysis

and integrated building performance evaluations.

2.3. *Question 3: What is meant by co-simulation in building performance simulation?*

Co-simulation has been defined in computer science as the combination of theory and techniques to enable the global simulation of a coupled system via the composition of multiple simulators [54]. The motivation for co-simulation is often found in the necessity of combining specialized domain-specific models that are developed in different software environments. According to Ref. [55], the advantages of co-simulation include the possibility to:

- Combine heterogeneous simulation approaches and tools that are best suited for the sub-system modeled;
- Perform rapid testing of software prototypes;
- Facilitate parallel-shared developments in distributed teams, including the option to preserve intellectual property (IP) rights;
- Enable multi-scale simulations to address the interactions between different sub-systems by modeling each of them with an appropriate level-of-detail.

In building simulation, the term co-simulation is usually used to describe approaches allowing to couple different models, each describing only one part of the governing physical relationships in the overall system (e.g. thermal models, airflow models, daylighting models etc.). Each model is run in a separate simulation tool or unit, in a way that they can exchange simulation data during runtime, and replicate the behavior of the system seen as a whole.

In this process, several decisions need to be made to establish a successful co-simulation strategy. The following considerations have an impact on the stability, accuracy, efficiency and ease of implementation, and are therefore essential when developing successful co-simulation strategies.

Coupling variables: The simulation user should decide which state variables will be exchanged during simulation runtime. It is advised that these coupling variables should represent as much as possible physical quantities as opposed to derived or abstracted data [55]. In this way, model verification and validation are easier to perform because the variables could be measured in the real world. Moreover, selecting

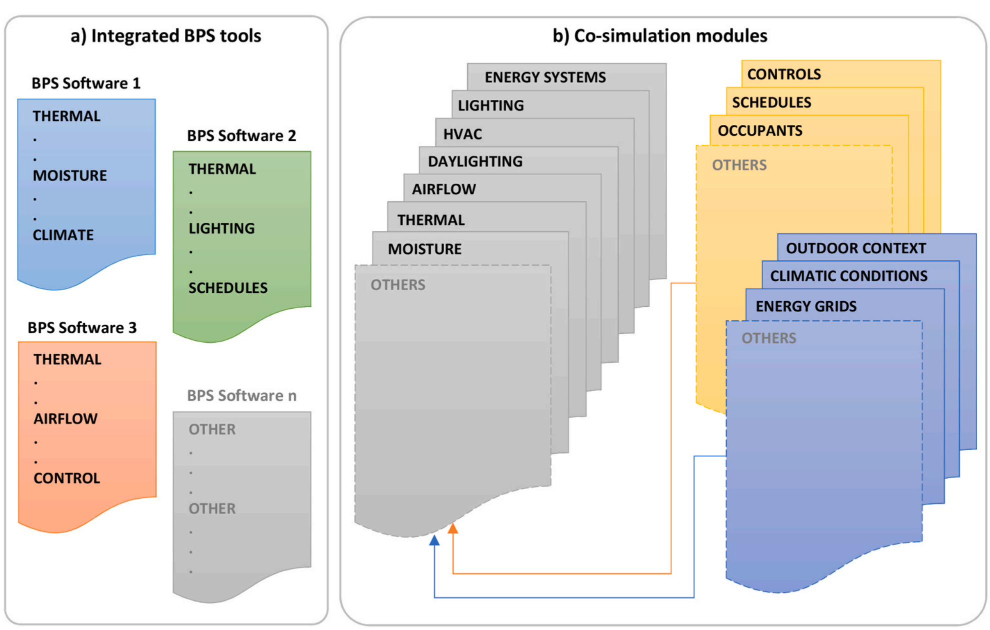

Fig. 3. Illustration of the difference between integrated BPS tools and co-simulation modules.

variables that are available in multiple domain simulators increases the modularity and opportunities for future extension.

Coupling strategies: Different methods exist for coupling multiple simulation models with one another. A first distinction can be made between sequential and bi-directional coupling strategies. In sequential coupling strategies, there is no possibility for feedback. This is, for example, the case when daylight simulations are pre-calculated, with outcomes being fed to the thermal model that is invoked afterwards [54]. Bi-directional coupling strategies, on the other hand, do allow for feedback, which is accomplished through runtime exchange of coupled data. Within this category, a further distinction can be made between strong and loose coupling. Strong coupling involves an iterative process in which solvers need to meet predefined convergence criteria before moving to the next time step. In loose coupling, on the other hand, data is exchanged after each calculation time step is completed (i.e. each model uses the results of the other model in the previous time step). The most suitable strategy depends on the level of variability in boundary conditions and the simulation time step that is chosen [56,57].

Coupling techniques: *One-to-one coupling* refers to dedicated implementations that connect two simulators. Examples of this type of coupling include TRNSYS type 155 which links the TRNSYS environment to Matlab, the built-in connection between ESP-r and Radiance for coupled building energy and daylighting simulations [58], or the coupling between TRNSYS and ESP-r that was developed to enable modeling of novel integrated energy systems [59]. Co-simulation approaches based on *middleware* are much more flexible and modular, as they couple any number of simulation programs, instead of two simulators directly. The task of the middleware is to orchestrate the simulation process, manage data exchange between the simulators and facilitate post-processing. Notable examples of middleware for co-simulation include BCVTB [60] or RabbitMQ [61,62]. The third technique for co-simulation is to use a so-called *standard interface approach*. This technique allows for direct coupling with any software tool that has the same interface implemented. The functional mock-up interface (FMI) is a widely used standard for coupling software with many applications in the BPS domain.

Coupling frequency: Different coupling frequencies can be chosen depending on the type of simulation task performed. Research has shown that the coupling frequency can significantly affect the stability and accuracy of the co-simulation. This frequency should, therefore, be carefully chosen. For building energy systems, this often means that the coupling frequency should match the thermal time constant of the system investigated [63]. It should also be mentioned that the data exchange can either take place at every time step of the simulation or in a multi-rate approach with either fixed or variable time steps. Multi-rate approaches are often used when coupling CFD with BES in which the mismatch in simulation time between the two solvers favors asynchronously calling each of them.

All the considerations mentioned above must be simultaneously addressed when developing co-simulation strategies. This is especially the case for systems that exhibit complex behavior or that are exposed to highly variable boundary conditions. In this context, ABEs are a textbook example of systems that benefit from co-simulation. The reason for this is that ABEs are characterized by several performance requirements in different physical domains. Co-simulation involving multiple BPS tools also plays a vital role in providing a more accurate characterization of the integrated performance of ABEs, given that these systems do not have fixed designs or operation strategies and are defined on a case-by-case basis.

2.4. Question 4: How can co-simulation improve performance prediction of advanced building envelopes in multiple domains?

The main advantage of using co-simulation in the design phase of an ABE is that it allows tailoring each part of a model (or sub-model) to the current information available, the level of abstraction required, and to the desired output from each physical domain. Another asset of this approach is that the information exchanged between the models is both more precise and more relevant to the purpose of the simulation. Commonly used co-simulation approaches for multi-domain evaluations of ABEs are, for example, the coupling of detailed daylighting simulations with thermal simulation engines. This approach can provide more accurate estimates of the amount of light (or heat) entering a zone and result in a deeper understanding of how the building envelope interacts with solar radiation through its design. The outputted information can be immediately reused to calculate the dynamic HVAC loads or to evaluate indoor comfort parameters with a much higher level of accuracy and all within the same simulation run. This results in a direct and holistic estimation of the impact of any design modification in the system.

Co-simulation approaches also provide several other advantages for facade design compared to their traditional counterparts. First, they can be used to create dynamically evolving workflows with interlinked models that actively interact and update as new information arises during the project, as well as include sensitivity and uncertainty analysis [64]. This is a critical added value, as it avoids having multiple - and sometimes redundant - models using potentially suboptimal descriptions of non-trivial behaviors. Second, the plug and play properties provide the flexibility to use models that describe multiple physical phenomena with variable levels of detail, as well as models with different code structures or programming languages.

Ultimately, the additional information obtained through co-simulation about the behavior of ABEs is valuable for improving the design of the systems, conducting what-if analysis, and generally provides more in-depth insights about the dynamics of the envelope and its interaction with the rest of the building or occupants. All these elements not only improve the performance of ABEs in their design, but they also allow predicting their performance and quantifying their benefits more accurately. However, the use of co-simulation is not limited to the design phase of ABEs and plays an extensive role in modelling control-response behaviors.

2.5. Question 5: How can co-simulation improve the operation of advanced building envelopes?

Advanced building envelopes, particularly adaptive facades, are often characterized by their ability to tune their properties or change their performance targets following a triggering event. These triggers can originate from different sources such as natural (climatic) mechanisms, user-issued requirements, or from varyingly complex rule-based controls [16]. Successfully simulating the operation of an ABE is therefore often contingent on modelling detailed control sequences and different types of triggers based on the simultaneous analysis of the multi-physical behavior of the ABE system and its response.

In co-simulation, the modelling of a triggering event for a system can be developed in a dedicated tool and then linked to the separate simulation engines involved. Additionally, because the different tools can exchange information at different time steps, control sequences can be dynamically created and fed in during the same simulation loop. This means that a control response for an ABE can be defined during the simulation run, based on the simultaneous evaluation of (i) a triggering event (for example, based on boundary conditions), (ii) the current state of the building given by the solver of the transport and energy conservation equations, and (iii) a pre-set control algorithm. This allows for a much wider variety and complexity of control options compared to the relatively simple rule-based controls that legacy BPS tools offer. In fact, both the modelling of the triggering event and the response can be described with a higher degree of freedom in co-simulation [65].

The added flexibility given by combining performance simulation engines with dedicated algorithms that replicate triggering events is furthermore alluring for two reasons. First, it allows obtaining a more accurate performance evaluation of a distinct solution using a specific control action. Second, it enhances the possibility to focus the study on the control action itself, which is something that current building simulation tools do not fully support. Another clear advantage of co-simulation approaches is that they also allow considering occupant behavior and occupant related triggers, where the interactions between the envelope and the occupants can be modeled using many different methodologies [66]. Co-simulation approaches are also the only possibility to evaluate trade-offs in multi-domain controls that combine different sources of information for the control logic. For example, they are useful in scenarios where energy performance requirements must interplay with user requirements and indoor environmental quality performance.

Finally, co-simulation can be used in parallel to hardware-in-the-loop simulations with actual controller components in real-time simulations using the techniques and tools discussed in section 2.9. This approach is particularly relevant for ABEs since many of these systems are characterized by dynamic behaviors. Hence, there are obvious benefits to actively tuning their responses to real-time triggers. These responses can be based on different control strategies, where threshold values or rule-based algorithms are the simplest ones, and the most complex ones are based on a real-time search of the ABE's best performance through model predictive control (MPC) [47,67,68]. In MPC, a model (often a reduced-order model or a data-driven model) of the system is used to continuously search for the optimal operating state of a system considering real-time boundary conditions (or other real-time inputs). MPC is a relatively common control strategy in many processes and industries, but just recently appeared in the built environment (e.g. Ref. [69]). Only a few studies and applications are available when it comes to ABEs (e.g. Refs. [46,47]). Because of the intrinsic complexity and multi-domain characteristics of many ABEs, MPC is, in theory, ideal to ensure the most significant improvement in the operation of advanced building envelopes. However, there is still a long way to go before such advanced control methods become standard solutions for ABEs. Nonetheless, this application of co-simulation will, without doubt, constitute a hot topic in research and developments in this field in the coming years. It is expected to impact methods and techniques for control-oriented model construction, algorithms for optimization, and platforms for dataflow integration.

Overall, co-simulation approaches have the potential to solve several of the challenges that modelers face when using monolithic software. Additionally, they offer sophisticated possibilities for optimal and real-time dynamic control of ABEs. However, they are still in no way a silver bullet. In practice, there are still several barriers that prevent the widespread use of co-simulation approaches for ABEs and limit its implementation to studies carried out by experts with intimate knowledge of simulation engines.

2.6. Question 6: What are the current barriers and challenges to co-simulation of advanced building envelopes?

The main barriers to co-simulation approaches stem from two tightly interrelated issues, namely a standardization gap and a knowledge gap.

Standardization gap

The standardization gap points to the lack of systematic and homogeneous interfaces for data exchange between different software tools or simulation engines. This gap ends up manifesting itself at several different levels in co-simulation approaches, affecting not only the data being exchanged but also how the exchange happens, with many negative ramifications.

The issue initially stems from the fact that legacy BPS tools have been developed independently, each one with a different organizational structure. Because the engines were also intended to be monolithic, their coding structure did not anticipate the possibility to exchange data with one another. This makes them neither flexible nor modular. Only very recently have releases of BPS software started to address this by offering more access to the solvers, including the possibility to feed in or extract data during runtime. However, despite recently increased integration between BPS tools and generic programming languages, substantial difficulties for co-simulation due to an absence of standardization persist.

Standardization issues in co-simulation mainly concern the nature of the data, the information it contains, and the way data is extracted and provided to the different simulation tools and scripts. The solvers used in different BPS software may differ greatly, and the accessibility of data may also vary. This means that, for example, a data point (let that be a variable, an input or an output) that is accessible in one tool may not necessarily be accessible in another tool. This issue is deeply rooted in the fact that BPS tools have different levels of detail in their sub-routines and do not process inputs the same way.

Another consequence of the lack of standardization concerns the limited number of reusable methodologies for carrying out co-simulation. Combining different simulation engines is still a complex task with no generic one-size-fits-all approaches, and the end product is often tailor-made for the application and the BPS tools used. This issue is only made worse by the fact that there is not yet an established culture to promote sharing of models. This often results in a duplication of efforts in research.

Finally, the lack of standards hinders the establishment of a shared benchmarking procedure for co-simulation approaches. While conventional BPS tools undergo validation and comparison based on reference simulation cases (e.g. when it comes to thermal behavior, using the BESTEST cases), the nature of co-simulation makes it difficult to have a comprehensive set of standard applications. In respect to this topic, it is expected that single engines can be validated for individual domains using existing standards. However, co-simulation approaches should instead rely primarily on a verification process [70] - i.e. to test and confirm that the algorithms and numerical methods implemented are correctly executed when integrated into a single dataflow structure.

Knowledge gap

The knowledge gap is tightly related to the standardization gap. Today, co-simulation is mostly reserved for a somewhat limited group of experienced BPS users due to the lack of easily accessible and shared documentation. Successful execution of co-simulation requires robust knowledge of the physico-mathematical models and algorithms implemented in BPS tools, as well as programming skills. Additionally, a deep understanding of possible workarounds and "backdoors" to overcome the rigidity of the current simulation tools is also a prerequisite for today's implementation of co-simulation approaches.

Currently, there is limited widely available know-how to tackle the technical challenges of correctly defining data exchange parameters in co-simulation. Data exchange protocols in co-simulation depend on three elements: the timing of the exchange (i.e. inter or intra time step), the frequency of the exchange, and the nature of the data exchanged. All of these aspects are to be set up with care to ensure that the different numerical solvers implemented in the linked engines are stable, that they converge, and that they lead to meaningful numerical solutions. This is particularly true for strong coupling approaches where systems of ODE or PDE need to be resolved numerically and simultaneously in different engines - which can prove to be a delicate procedure. However, other desynchronized or loosely coupled strategies are less impacted by these challenges. Hence, it is often advised to investigate whether a strong coupling strategy can be modified to an equivalent, more loosely connected approach without leading to a major loss in accuracy or significance of the outputs. The reason why these challenges persist is that the practical implementations to overcome them are almost always case-dependent (i.e. the standardization gap). They might differ based on the internal routine of one or another simulation engine but almost always depend on the tool used as well as the level of complexity necessary to describe the ABE co-simulation task. As a result, creating guidelines is a laborious task and users are often left on their own to set-up their co-simulation approaches. Another aspect that can be considered part of the knowledge gap relates to the fact that the value proposition of using co-simulation is sometimes unclear. While the use of simulation-based design is becoming more widespread, the use of advanced dedicated workflows is still reserved for high profile projects. In these projects, the requirement to provide a fully holistic characterization of the ABE is a cornerstone of the design process. Consequently, the value and the reasons to use co-simulation may not always be known to all the stakeholders in a less ambitious project. There is still limited knowledge transfer between modellers, designers, consultants, developers, contractors, and policymakers that could highlight the benefits of using co-simulation or of developing multi-factorial performance assessments. Overcoming this would support a more general adoption of integrated simulation approaches as well as it would support a greater uptake of efficient building envelope solutions. This may also allow overcoming barriers to ABEs due to a lack of widely accepted performance metrics to communicate their benefits.

With time and as co-simulation receives more attention, it is expected that the purely technical issue relating to IT languages, programs and routines to exchange data will be resolved in the coming years. However, the more substantial challenges of co-simulation which stem from a lack of standardization and knowledge require a larger effort from expert BPS users to share and disseminate specific guidelines and knowledge about co-simulation. This includes recommendations about how to approach co-simulation tasks and how to select the suitable tools and engines.

2.7. *Question 7: Which important elements should one take into consideration before selecting a co-simulation approach and a suitable set of software tools?*

The decision whether to use a co-simulation approach when modelling an ABE is a complex choice the modeler should make primarily based on the purpose of the simulation and their knowledge and skills. It is important to remember that co-simulation often requires significant efforts before any meaningful result can be extracted due to the discussed lack of standardization. In research and development, the time and effort required to develop new simulation approaches is often accepted as part of the task. However, this may not always be the case in professional practices where the stakes are different. In most cases, it is worth verifying whether something that may seem to require a completely new co-simulation workflow might be solved with some minor trade-offs using functions or documented workarounds in conventional BPS tools.

The first recommendation to successfully using co-simulation is to follow a fit-for-purpose approach [71,72]. The fit-for-purpose method supports starting any modelling task with the development of a software agnostic conceptual model with a comprehensive analysis of the goal of the simulation. The point is to ensure that each model used has the right inputs, and provides the correct outputs, with a minimum modelling and computational effort. Then, special care should be given to the selection of the basic simulation environment(s) that will make up the multi-domain representation (e.g. the thermal energy simulation, the optical behavior, the fluid dynamics, etc.). These decisions should be based on the experience of the modelers since it may require them to have intricate knowledge of the different software and models implemented. In particular, it is recommended that one carefully considers the modularity of the algorithms used and the accessibility of the different variables in the physical-mathematical models.

Additionally, as much as possible, one should consider using sequential simulations rather than ones that require the synchronized solving of differential equations. This is to increase the robustness of the coupled simulation environments and avoid stability or convergence issues, due to using different time steps in the simulation engines, for example. Co-simulation can still be difficult even for experienced modellers, however recent developments in BPS have been trying to facilitate the process. This can be seen through native integration of other modules or by allowing external code to be called directly within simulation engines to create more advanced modelling and simulation workflows.

2.8. *Question 8: How can co-simulation be integrated into multi-disciplinary design workflows of advanced building envelopes?*

BPS and, in particular, building energy modelling (BEM) software process many inputs and outputs relating to geometric design, material properties, energy use and more. Some performance simulation tools are already compatible with architectural software and derive inputs from building information models (BIM) through industry foundation class (IFC) imports. This connection allows developing performance-based design approaches for ABEs with immediate 3D visual feedback. However, in a perspective of co-simulation, this information can be further integrated into a multi-domain workflow spanning the entire development of an ABE (Fig. 4). In such workflows, information processed through co-simulation can be directly linked to, for example, cost or GHG emission from materials and building operations [73]. In such workflows, it is also possible to consider peak loads and equipment sizing calculations when ABE systems are tightly integrated with HVAC services, hence detailing the calculation to fully assess the potentials given by the holistic approach in the design of the building envelope and building service.

Platforms supporting multi-domain integration and dynamic data exchange between disciplines are a key extension of co-simulation workflows. These can, for example, allow visualizing effects of variable inputs on multi-disciplinary key performance indicators. Considering that co-simulation also provides the option to protect the IP of separate parts of the model, private actors can contribute through co-simulation to drive innovation and expand the application of their products. This prospect is also an important step to integrating new technologies directly into projects with the option to assess their benefits in the same simulation loop. For building envelope design, this approach is most powerful, as envelopes also define the architectural expression of the building and impact many stakeholders.

The inclusion of an interconnected building simulation layer in digital twins is also a way to ensure proper commissioning and follow-up on actual building performance results during operation. As previously discussed, co-simulation schemes can support parallel hardware-in-the-loop simulations, which provides the possibility to troubleshoot any deviations between expected and actual operations as well as resolve issues that may otherwise go undetected [74,75].

Currently, there are two paths to integrating building performance simulation into larger BIM workflows. The first one is to use BIM-based simulation tools that can directly reuse building data created by architects and different parties through standard data schemes such as industry foundation class (IFC) and green building extensible markup language format files (gbXML) [76]. The second path is to use BIM to BEM translators, for example, based on the ModelicaBIM library [77] and object-oriented physical modelling (OOPM) [78], or in the ModelicaBEM framework [79]. A complete overview of the current possibilities to implement BIM in BPS tools is provided in Refs. [80,81].

Finally, new open-source data management platforms such as the Speckle server [82] are emerging and challenging traditional workflows of building design in the industry. Speckle is a platform for automation and interoperability that connects different modelling tools from the architecture, engineering and construction industry. It is built to allow multiple users to visualize specific data across disciplines of simulation. Moreover, Speckle lives in the cloud and allows users to manage who has access to projects, coordinate and collaborate by streaming project data between people and extend the platform to create custom third-party applications and workflows. Currently, Speckle connects to the BIM modelling software Revit, to the Rhinoceros and Grasshopper environments as well as Dynamo and others.

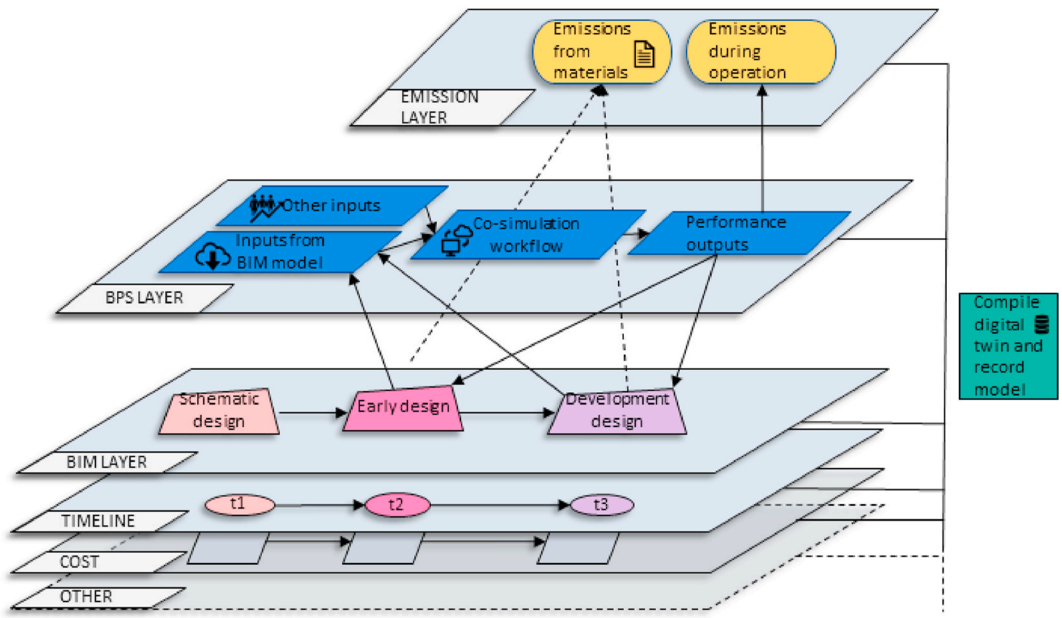

Fig. 4. Example of a multi-layer workflow integrating a co-simulation layer.

2.9. *Question 9: Which recent developments in BPS provide added possibilities for co-simulation of ABEs?*

BPS tools have benefited from many advancements in the past decade. For co-simulation, these changes pertain to two main categories: the integration of co-simulation options within existing software and the development of new tools with added flexibility for co-simulation. In the latter category, we distinguish tools and platforms that are more engineering-oriented and those that are more architecture-oriented. We also note that while these changes affect building performance simulation capabilities in general, they can be particularly interesting to improve the performance of ABEs themselves and the quality of the performance prediction.

Developments within existing whole building performance simulation tools

Several recent developments in software include inbuilt connections in simulation tool interfaces to different specialized engines. These are, for example, the integration of the backwards ray-tracing algorithm Radiance or the possibility to use computational fluid dynamic calculations with OpenFOAM [83]. BPS tools are also increasingly integrating inbuilt connections to the LBNL software Window [84] and THERM [85]. The possibility to directly couple BPS tools to Matlab-based block diagram environments, such as Simulink, also provides options for multi-domain simulations, model-based design, and optimization.

More specifically, the DOE simulation software EnergyPlus has, in recent years, substantially improved its ability to implement co-simulation [86]. In its 9.3 version release, the developers' of EnergyPlus have announced the introduction of a Python plug-in that can allow users to write their own scripts and connect to the EMS system. Version 9.3 also provides a new API that allows calling EnergyPlus as a library, where either a compiled C program or a Python script can be used. This API exposes functional, runtime, and data exchange capabilities in the software. Finally, one of the most significant developments tied to the EnergyPlus software is the creation of the Spawn of EnergyPlus, also referred to as Spawn or SPAOE [87,88]. Spawn does not aim to replace EnergyPlus but provides a version of the software which allows reusing modules for lighting, the building envelope, and load definition. The difference with the monolithic version of EnergyPlus is that the HVAC systems and controls are handled by the equation-based language Modelica [89,90]. Spawn can be coupled to platforms made for co-simulation and Functional Mock-up Units, both of which are described in the next paragraph. Note that for users, both Spawn and EnergyPlus work with the Open Studio interface [91], which means the interface for both software are identical and compatible with Open Studio measures.

Development of external tools and platforms supporting co-simulation

The second category of development in BPS supporting co-simulation is the emergence of tools and (co)simulation platforms that aim at facilitating co-simulation between existing tools. Currently, the only platform or middleware for co-simulation in building performance simulation is the Building Control Virtual Test Bed (BCVTB) [92]. BCVTB is a software environment that allows expert users to couple different simulation tools for distributed simulation or real-time simulation connected to a control system [93] (Fig. 5). The BCVTB connects to many whole building simulation tools, to Functional mock-up Units (FMUs), Dymola [94], and Matlab-based tools such as Simulink. Importantly, for co-simulation of multi-physical phenomena, the BCVTB connects to simulation software such as Radiance, which can allow using detailed daylighting simulations [95].

One of the most advanced approaches for co-simulation is driven by the development of the Functional Mock-up Interface (FMI) standard. Whereas co-simulation using the BCVTB is a method based on middleware (Fig. 5), the FMI is an interface standard that allows co-simulating two or more simulation programs in a co-simulation environment and, for example, to create modular workflows [96]. The core of the FMI standard is maintained by the Modelica Association project [97]. Its aim is to simplify operations related to the creation, the storage, the exchange and the use (or reuse) of system models in collaboration with other software or hardware-in-the-loop simulation and considering different applications such as cyber-physical systems [98]. The FMI standard defines the structure of the inputs and returns of Functional Mock-up Units (FMU) that different software must be packaged into to allow for co-simulation. The data exchange between the FMU is orchestrated by a master algorithm which controls data exchange between slave programs. The sub-systems are solved by their individual solvers but exchange data at discrete points in time. The approach of using the FMI standard for the performance prediction of ABEs is particularly interesting for systems that require advanced controls. The advantage of the FMI approach versus the BCVTB middleware approach

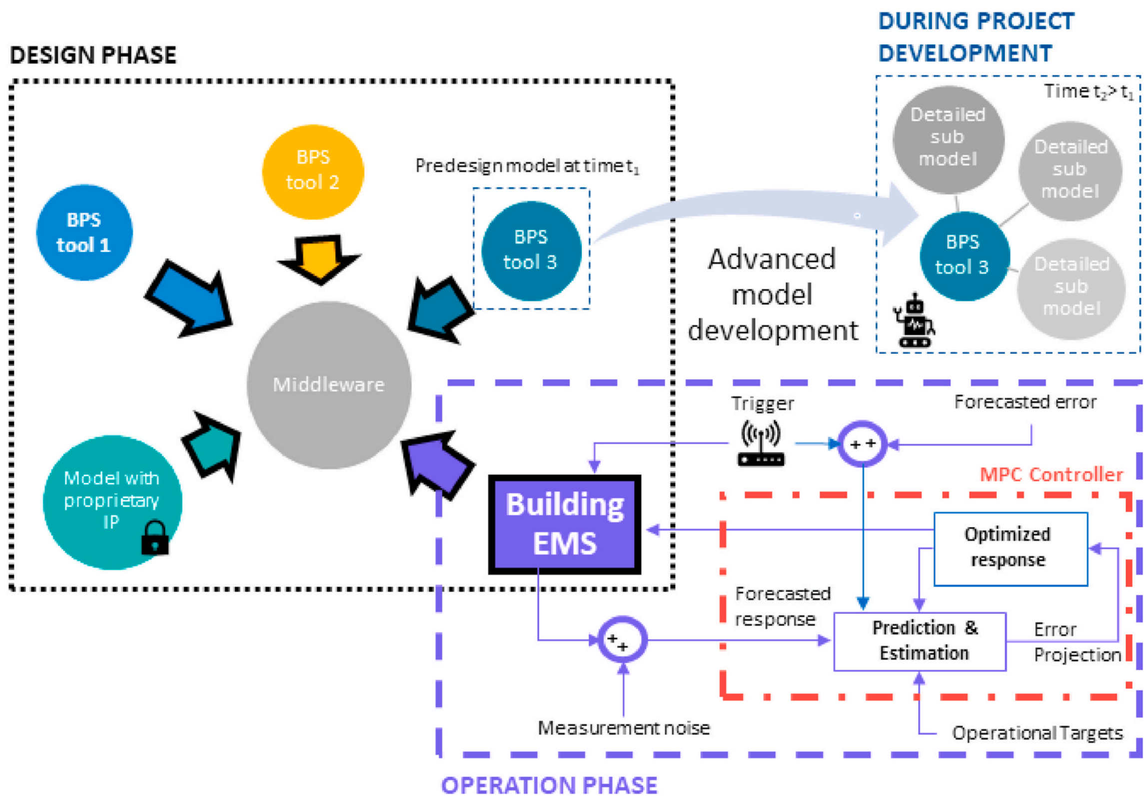

Fig. 5. Example of a co-simulation framework based on a middleware approach. The figure also illustrates the possible development of models during project time and building operation.

is that the FMI provides a more streamlined method for co-simulation. However, the FMI and the BCVTB both support hardware-in-the-loop (HIL) simulation, which is a significant added value for better control design of ABEs and can be used in parallel to co-simulation schemes.

As previously presented, the successful design of ABE solutions needs to address performance considerations at multiple spatial scales, ranging from materials, components and system assemblies to whole-building integration aspects [99]. The focus of these analyses can change over time as more information becomes available when the design process evolves. Co-simulation strategies, and especially structures, tools, and platforms enabling co-simulation should facilitate smooth transitions across these spatial scales as this can benefit from the hierarchic modeling paradigm [100]. Here, the term hierarchy refers to the use of agreed-upon input-output definitions that allow for multiple interchangeable sub-models and which encapsulate descriptions of the relevant physical interrelationships with different levels of detail relating to, e.g. fenestration systems [100] or façade-integrated HVAC systems [101]. It should be acknowledged that such multi-layered simulations reinforce the need for systematic approaches for collection, storage, sharing, and analyses of both simulation input and output data [102]. For example, a novel approach has recently been proposed by Mitterhofer et al. [103] to preserve the integrity of input data in co-simulation. To ensure consistency in simulation output and performance metrics across model resolutions and spatial scales, it is expected that explicit approaches such as the ones presented, in general terms for co-simulation, by Bleil de Souza and Tucker [104] and Mahdavi and Wolosiuk [105] will help to guarantee an error-free simulation process and to quantify the quality of the co-simulation infrastructure.

Finally, a simpler approach to co-simulation can be achieved through parametric scripting platforms such as Grasshopper in the Rhinoceros 3D modelling environment [106]. Parametric design has become an increasingly popular topic in architecture in the last decade and presents many opportunities for integrating loosely coupled co-simulation approaches. In particular, the development of The Ladybug Tools [107] - which provide interfaces to EnergyPlus (including Open Studio), Radiance, Window, Therm, and OpenFOAM - support performance-based design approaches for advanced building envelopes. Additionally, Grasshopper offers possibilities for structural engineering analysis, optimization approaches and more. The entire list of plug-ins is available at Food4Rhino [108]. The added value of coupling geometric design parameters directly to simulation software is also an important function that can help with the design of free-form facades, kinetic facades, or any type of architecturally responsive façade. The Grasshopper environment is compatible with scripts written in Python and C#, which also provides users with the freedom of writing components.

2.10. Question 10: Which recent developments in ICT provide added possibilities for co-simulation?

Many advances in ICT can be exploited to enhance the adoption and performance of co-simulation workflows. Distributed and cloud computing, are two of the developments which are expected to help leverage co-simulation the most. The option to divide the different computational tasks over more than one machine (distributed computing), and to outsource the computational tasks to external shared servers (cloud computing) are structurally compatible with co-simulation - especially when models with very different requirements in terms of computational power are combined. The application of distributed and cloud computing to co-simulation tasks can help to overcome these bottlenecks by dispatching sequential sub-routines across different resources. These computational techniques rely on the implementation of dedicated infrastructure that can allow timely communication between the distributed nodes in the computing system, or between the local machine and the computational system in the cloud. External server or distributed machines can execute a task from a list of commands, and computationally heavy tasks can be streamlined to an even higher degree by allocating these parts of the overall simulation process to machines, servers, or supercomputers with a higher computational capacity. These approaches can be found in the literature, for example, batching of daylighting simulation as executable Radiance files [109].

These developments, together with improved solutions for collecting, storing and managing data have made it possible to develop the previously discussed trends of data-driven design and model predictive control. Indeed, as the market of smart home sensors and the IoT (internet of things) grows, an unprecedented amount of data is recorded, with a remarkable level of granularity. This data covers indoor temperatures, daylighting level, relative humidity, CO_2 levels, – all of which are important indicators for comfort - as well as local weather data and sub-hourly energy use. This information can be exploited during operation to improve the performance of ABEs, both for real-time control but also for anticipated control like MPC. These approaches can use weather data or behavioral data collected with IoT devices can deliver tailored control sequences based on data analytics and machine learning. Effective implementation of MPC-based strategies for ABEs' optimal performance management will depend on a list of future development that spans from dedicated control-oriented modelling, algorithms for optimal control, and dedicated integration platforms (e.g. Ref. [110]).

Edge computing (local execution of computational tasks) can be an efficient solution to support co-simulation when combined with cloud computing, for example, to address real-time simulation targeting optimal control of ABEs. While computationally expensive optimization processes are impossible to run in real-time on controller embedded in ABEs, even if based on a simplified model representation of the ABEs, these are possible if executed in the cloud. In the long run, it is possible to imagine synergic management of ABEs where cloud computing supports identifying the optimal values for a series of performance requirements (for example in the form of heat gain, or fresh air supply). In contrast, edge computing takes care of translating such performance requirements into process variables and communicating them to different actuators in the envelope.

3. Conclusions

Advanced building envelopes (ABEs) are integrated envelope systems and technologies that ensure high-performance in multiple physical domains to efficiently balance competing aspects through advanced design, advanced material properties and components, and when appropriate, advanced control strategies. ABEs demand a holistic performance assessment in building performance simulation to capture the full extent of their benefits efficiently. This task often requires modelling details or physical phenomena that cannot efficiently be carried out in monolithic simulation software tools. Interdisciplinary approaches like co-simulation, which allows coupling different models that describe parts of the governing physical relationships in the system (e.g. thermal models, daylighting models, etc.), provide a valuable alternative.

In co-simulation, each sub-model describing the ABE is run in a separate simulation tool or unit and connected in a way that key information is exchanged during runtime to replicate the behavior of the whole system. This approach provides solid grounds for what-if analysis and robustness checks of systems as well as it supports the innovative, performance-driven design of envelope systems with non-trivial behaviors and controls. However, it is not a fool-proof process and still suffers from several barriers that relate to a lack of standardization and of widely available knowledge about how to implement it correctly. Conducting a successful co-simulation requires that users consider different elements before selecting the software that will be used. Adopting a fit-for-purpose approach will avoid overcomplicating tasks and models and improve the robustness of modelling strategies. This approach recommends selecting a tool based on the purpose of the simulation, the knowledge and skill level of the modeler, the structure and the characteristics of the information exchanged by the different simulation units, and the type of co-simulation which will be used to evaluate the performance of the whole system.

Ideally, a co-simulation scheme can become a multi-user and multi-scale modular dynamic workflow describing a building envelope, and that evolves as information becomes increasingly available in the project. This provides opportunities for the different stakeholders to exchange model data with a better understanding of design relationships and implications, without compromising the IP of the individual simulation tools. Co-simulation for predicting the behavior of ABEs is further supported by several recent trends and development in BPS tools. These range from the development of model libraries for simulation and equation-based modelling, the development of new generation computational tools for building and community energy systems, to the development of a standard interface for co-simulation. Additionally, co-simulation approaches for ABEs benefit from improved possibilities for batching simulation-runs to reduce computational overhead, the development of parametric design multi-interfaces to validated simulation tools, and the integration of optimization algorithms for single and multi-objective studies in whole building simulation tools. Finally, co-simulation for ABEs also benefits from other developments in ICT which are supporting methods based on data-driven design and can be used in coordination with parallel assessments based on model predictive control strategies thanks to advances in cloud computing, data storage, and data management.

While focusing our analysis on the specific, yet broad topic of simulation-based performance prediction of advanced building envelopes, many of the presented challenges, flaws, potentials, and possibilities are relevant for larger sets of other complex modelling and simulation tasks such as the simulation of building clusters and neighborhoods and interactions with thermal and electrical grids. The identified key-questions and the answers we provided in this paper can be used to drive both a more conscious implementation of co-simulation, as well as to stimulate research and development efforts that can enable a more robust and user-friendly implementation of multi-domain, integrated performance simulation.

Description of expertise of the authors on the topic

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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