Building performance simulation of Advanced Building Envelope (ABE): towards a python-based open-source library to support co-simulation for design and operations

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Abstract

Advancements in materials and technologies have led to the development of Advanced Building Envelope (ABEs), which enhance building performance for multiple aspects. However, assessing their performance using state-of-the-art Building Performance Simulation (BPS) tools poses significant challenges due to the absence of specific models, difficulties in integrating advanced controls, and simulating performance across multiple physical domains.

EnergyPlus has introduced the Energy Management System (EMS) and integrated Python capabilities, enabling the co-simulation of Python-based models and control strategies developed by users. The purpose of the paper is to showcase a scalable co-simulation approach, aimed at defining an open-source python-based library of ABEs, that can be interfaced with BPS tools, so to support the evaluation and optimization design of ABEs. The approach is herewith presented by co-simulating with EnergyPlus, evaluating the performance of two highly complex ABEs (1) Micro-Fluidic Triple Glazing (MFTG) and (2) flexible Double Skin Façade (DSF).

Highlights

- A generic multi-scale co-simulation method combines Python-based ABEs sub-models and EnergyPlus thermal zones for building-level analysis.
- The communication method provides scalability for potential sub-models in the ABEs library.
- Two case studies demonstrate applications in a MFTG System and a flexible DSF.

Introduction

ABEs constitute innovative building envelopes capable of reversibly adjusting their thermo-optical properties in response to fluctuating boundary conditions, such as weather and occupant preferences (Loonen et al. 2013). By leveraging advanced materials, components, and integrated control strategies, ABEs aim to achieve multiple objectives, including substantial energy savings and elevated comfort levels, while potentially generating power (Tällberg et al. 2019). A further step in this research focuses on more complex envelope systems, named Advanced Fenestration Systems (AFS), which enhance building performance by addressing a wide range of functionalities (Favoino et al. 2022).

Several ABEs are under development and evaluation by researchers, showcasing diverse approaches to enhance building performance(F. Favoino, L. Giovannini, and R.C.G.M. Loonen 2017; Ibrahim et al. 2014). Despite significant efforts to accurately simulate advanced facades, existing tools still face challenges for ABEs, especially AFSs which have much more complicated optical and airflow behavior (De Michele et al. 2018).

Existing models for innovative building envelopes are often oversimplified, neglecting complex multi-physical interactions and limiting performance assessments (Loonen et al. 2017). Moreover, while certain ABEs, such as DSF and Phase Change Material (PCM) wall, can be simulated using simplified methods in EMS (Gennaro et al. 2023; Goia, Chaudhary, and Fantucci 2018), numerous advanced technologies, such as flexible DSF, PCM in transparent building envelope still surpass the capabilities of state-of-the-art BPS tools corresponding to its complex thermo-optical performance (Taveres-Cachat et al. 2021).

To fully predict the performance of various kinds of ABEs at the building level, co-simulation can be used to build the connection between facade models and BPS tools (Taveres-Cachat et al. 2021), but very few examples exist in the literature. There are two main approaches to perform co-simulation. The first one is a middleware-based approach that uses a standardized API framework to manage the intra time-step information exchange between different models: (i) FMU/FMI is a standardized, modular format for exchanging dynamic simulating models between different environments. In Modelica, an object-oriented, equation-based language for complex physical systems modeling, FMUs are imported and connected to other Modelica components. Co-simulation is achieved by exchanging data between the FMUs and Modelica models at specified time steps, allowing diverse simulation tools to work together seamlessly (Wetter et al. 2014). (ii) Spawn of EnergyPlus is an under-development co-simulation project that marries the equation-based Modelica language with EnergyPlus. Modelica components are linked with EnergyPlus sub-models and routed through a coupling mechanism. This integration provides detailed building performance with the flexibility of Modelica and the accuracy of EnergyPlus (Elarga et al. 2023). (iii) In PyFMU, users create Python-based FMUs that define custom building components or control strategies, and PyFMU links these FMUs to OpenStudio models exchanging data between FMUs and OpenStudio models (Legaard et al. 2021).

https://doi.org/10.26868/25222708.2023.1628

The another approach is the BPS master-based approach, which relies on the capabilities of a BPS tools (i.e., EnergyPlus and IDA ICE) to work as a master, managing the exchange of information and the co-simulation of slave models. Since the EnergyPlus 9.3, the Python Plugin has been availabe, but version 9.6 provided the further ability to enable Plugin and API system to work together. Similarly, IDA ICE allows socket communication interaction by offering a library API function accessible with Python, MATLAB, or similar (Catto Lucchino et al. 2022). Several attempts have been made to determine the performance of the flexible DSF (Catto Lucchino et al. 2021; Gennaro et al. 2023).

Considering the challenges of evaluating novel façade technologies at the building level, we can draw lessons from HVAC co-simulation methods mentioned before. The current goal is to build and to demonstrate a generic co-simulation framework that would benefit various sub-models in our future ABEs library, and could also be useful for other researchers evaluating ABE models. Therefore, in this paper, (i) demonstrate the feasibility of a generic method to ABEs co-simulation for performance evaluation, (ii) demonstrate the mechanisim of the input/output information exchange between a Python-based library of ABEs and an BPS master-based approach for co-simulation. These objectives are pursued by considering two case studies of ABEs.

Work flow

In order to pursue the above mentioned objectives, we first demonstrate the generic co-simulation framework using two case studies, in which a shoebox room is co-simulated with a south oriented facade integrating two kinds of detailed AFS models. The communication occurs between EnergyPlus (building model) and Python, with the PythonPlugin of EnergyPlus managing the exchange of input and output data between the two software. This feature became available from version 9.3.0 and matured in version 9.6. Furthermore, the co-simulation framework could potentially utilize Radiance to perform daylighting simulations and to estimate how solar radiation transmitted through the façade is distributed onto the room interior surfaces, as demonstrated in the second case study. These were selected based on increasing complexity regarding simulation variables, physical domain interactions, controls, and other simulation:

- MFTG, which influences only internal surface temperatures, transmitted solar radiation and has an additional variable such as the outlet temperature of the water-glycol fluid from the microfluidic component, which cannot be simulated directly in the chosen BPS tool.
- Flexible DSF (Catto Lucchino et al. 2022), in which all the different ventilation operating modes of a DSF could be possible (TB, IAC, OAC, EA, SA) along with operating a cavity shading device. In this case study, all the variables connecting the indoor to the outdoor environment through the envelope are influenced (heat, including short and long-wave radiation, and mass transfer, and sound propagation). For the sake of thermal simulation, only heat and air mass transfer are considered (not pollutants). The second case study can be simulated in BPS tools with simplified models considering a single airflow path (Catto Lucchino et al. 2021; Gennaro et al. 2023).

In order to achieve the second objective, the connection between EnergyPlus as a master and the ABEs library is explored, based on the EMS python plugin (9.6). The data exchange between EnergyPlus and the library is abstracted, so that a unique representation can be used in the BPS tool to represent a generic building envelope with standard characteristics, and specific variables can be re-written in EnergyPlus (i.e., surface temperatures, solar radiation on surfaces, ventilation rates). A tentative structure of the library is designed with a layered structure starting from (i) the input/output processing layer, which could also call external software such as Radiance, (ii) the control layer, (iii) the facade system layer (where different materials and systems are joined into an equation-based engineering model, R-C network), (iv) the material level (properties of materials and the relationship between material properties and states, for example, the variation of heat capacity due to temperature in PCMs).

In Figure 1, a kind of ABEs is built based on the sub-models, which contains Material, System and Control Strategy sub-models. It uses the generic co-simulation framework to communicate with building model in EnergyPlus. EnergyPlus act as the master to manage the data exchange with Python through the PythonPlugin. Information regarding the façade boundary conditions, like external air temperature, internal air temperature, vertical incident solar radiation rate, wind speed etc., and the required modules are sent to the Python wrapper. Based on the received data, the wrapper uses the necessary modules for the multi-domain simulation of the façade (i.e., thermal model in Python or other optional modules for other physical domains) and returns data generated by the simulation for whole building calculation at next time step.

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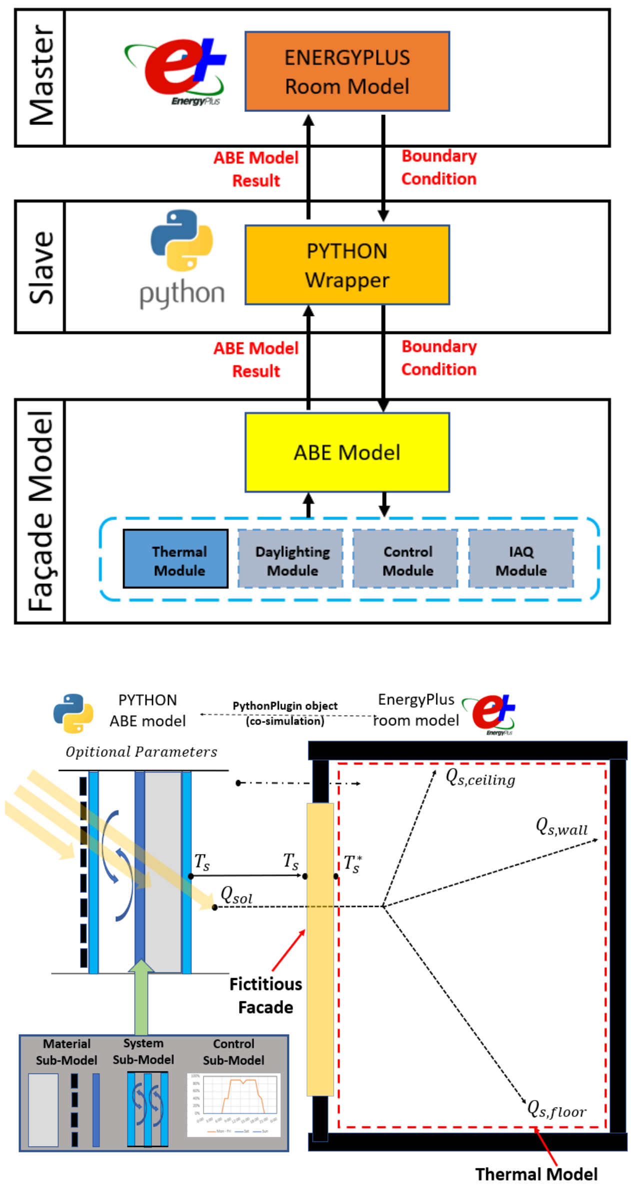

Figure 1 Scheme of the co-simulation framework

Thus, the co-simulation framework has a modular structure, where specific modules can be called according to the domain task required by the master (EnergyPlus). It is important to note that the thermal model of the façade must always be called, while all other modules are auxiliary models used according to the simulation task. For example, if the simulation domains include indoor air quality, it could be possible to incorporate a detailed model for the evolution of contaminants in the indoor room accounting for the façade configuration. Alternatively, a module related to the control strategies for operating the façade would prove particularly valuable, especially when dealing with adaptive facades.

To overwrite this information within the EnergyPlus routine, it is necessary to use some simulation workarounds. First, in EnergyPlus, the advanced façade is modeled as an opaque "fictitious façade" with high thermal conductivity and no thermal mass. This workaround is used because in EnergyPlus it is impossible to overwrite the internal surface temperature of the glazing system, as it is a state variable. However, it is possible to overwrite the external surface temperature of the opaque wall through the *OtherSideCoefficients* object. Therefore, an opaque construction with very high thermal conductivity is used so that the external surface temperature equals the internal surface temperature.

Furthermore, if the façade is a transparent one, by using an opaque surface, the solar heat gain resulting from the transparent surface is being ignored. To solve this issue, the incident solar radiation on the internal surfaces of the zone is provided using the *SolarIncidentInside* object of EnergyPlus. Two methods can be used to split solar radiation on the internal surfaces: the first refers to the solar distribution algorithm of EnergyPlus, which splits the radiation on walls proportionally to their surface area and is used as default by the framework if Radiance is not used. However, if Radiance is used, as performed before (Gennaro et al. 2023), a more accurate solar distribution on internal surfaces can be conducted: the ratio between each incident solar radiation on internal surfaces and total transmitted solar radiation is derived from the Radiance outcomes. Here, as the objective is to focus on the co-simulation framework rather than the most accurate result, the static solar transmittance value, rather than radiance, is used to determine the amount of solar radiation on internal surfaces, estimated in the ABEs sub-model library.

For some ABEs which includes air flows that has an impact on indoor ventilation terms, the heat loss/gain caused by this air flow acts as an instantaneous convective load on the EnergyPlus zone (with a positive or negative sign depending on whether it is a heat gain or loss) through the *OtherEquipment* object.

The modification of façade-related variables is accomplished by changing the schedule values specific to each variable inside EnergyPlus. Therefore, the PythonPlugin can overwrite the schedule values based on the simulation outcomes of the modules managed by the Python wrapper. The interaction between the EnergyPlus simulation and the Python-based ABE model occurs at every predetermined time step. During each time step, the plugin sends boundary condition to the ABE model and then updates the schedule values, which are derived from the ABE model based on the previous time step's boundary condition, for this time step's whole building computation within EnergyPlus. As a result, there is a time lag between the results of the ABE model and those simulated in EnergyPlus. For example, the ABE inside surface temperature at this time step is the result based on the previous time step's boundary condition. To minimize this phenomenon, a debugging process was done by comparing the result of the external input surface temperature and the simulated internal surface temperature of the test ABEs at the time step through changing the duration of the time step. The simulations with 10-min and 5-min intervals nearly have no time lag, Figure 2 shows several important results. In order to achieve precise evaluations, the co-simulation framework chooses 5min time interval.

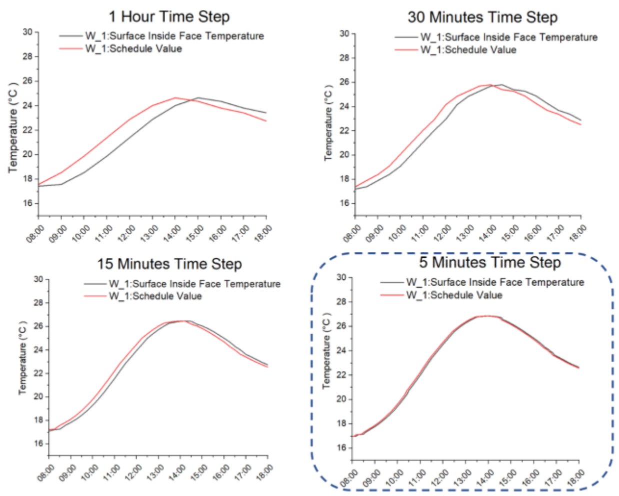

Figure 2 Time lag at different time step

To comprehensively assess ABEs at the building level, A simplified thermal zone model according to the BEST TEST Case600 (Robert H. Henninger and Michael J. Witte 2004)was considered as a representative test building, depicted in Figure 3. The model features a geometry of 8m (length) * 6m (width) * 2.7m (height), low thermal mass, and highly insulated in the external envelope except the south wall. Two opaque ABE units, each measuring 3m (length) x 2m (width), are placed on the south wall with negligible thickness and high thermal conductivity (1000 W/(m·K)) to ensure the inside surface temperature matches the inside surface temperature results derived from the ABEs Python model. The solar radiation transmitted through the transparent model is calculated within the Python script and uniformly distributed across the total surface area (150m²) before being passed to each envelope surface, excluding the south wall, within EnergyPlus. The test building is situated in Torino, Italy under 2020 weather conditions. The ventilation/infiltration flow rate is set at 0.5 ACH (air changes per hour). Additionally, an ideal heating system is implemented with a constant heating setpoint of 20°C, while no cooling system is utilized in the MFTG case and a constant cooling setpoint of 26°C for the DSF case.

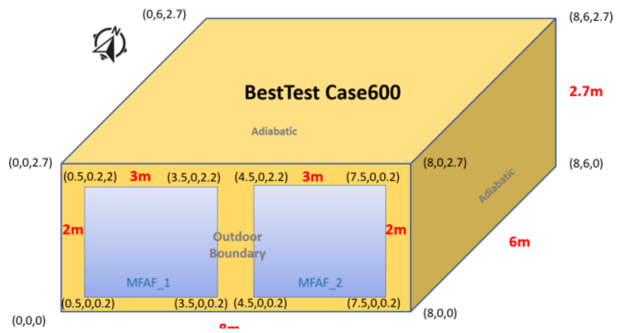

Figure 3: Test building model.

Results

MFTG

Micro-Fluid Glazing (MFG) is a glazing component characterized by an array of micro-channels containing flowing liquid, which can be integrated as a layer within an Insulated Glazing Unit (IGU) (Heiz et al. 2017). By modulating the inlet fluid temperature and flow rate, MFG can alter the outlet water temperature (T_out) and the internal surface temperature (T_int).

A numerical MFTG Thermal model has been developed according to the scheme illustrated in Figure 4. In the horizontal direction, the thermal network is established by partitioning each of the three glazing layers into three nodes (two surfaces and the central point of the glazing), considering the heat balance for each node. In the vertical direction, the network is divided into 10 nodes, and the temperature increase in the micro-fluid layer is accounted for by using the middle point temperature of the micro-fluid layer at the previous position as the initial temperature for the subsequent position, followed by a horizontal iteration. The variables are defined as follows: T_{ae} (°C) and T_{ai} (°C) represent the outdoor and indoor temperatures, respectively; I_{inc} (W/m^2) denotes the vertical incident solar radiation rate; $S_i(m)$ indicates the glass thickness of the i layer; h_{ae} $(W/(m^2 \cdot K))$ and h_{ai} $(W/(m^2 \cdot K))$ correspond to the outside and inside surface convective heat transfer coefficients, respectively; h_{rk} $(W/(m^2 \cdot K))$ and h_{ck} $(W/(m^2 \cdot K))$ represent the radiative and convective heat transfer coefficients of the k cavity; λ_i $(W/m \cdot K)$ and α_i represent the thermal conductivity and thermal absorptance of the i glass layer; and C_{gi} $(J/(kg \cdot K)$ signifies the thermal capacity of the i glass layer. The important parameters are shown in Table1.

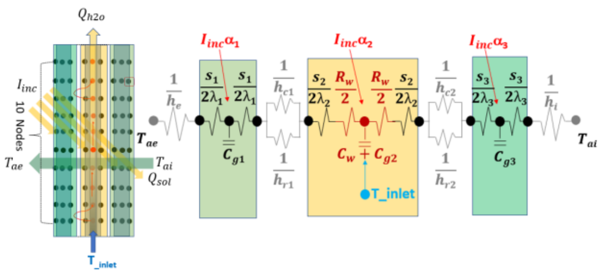

Figure 4: MFTG numerical model scheme.

Table1 MFTG System Parameters

Layer	Thickness (m)	Emi-ssivity	Boundary Condition
Glazing1	0.0048	0.038	$h_{ae} = 7.7W/(m^2 \cdot K)$
MFTG Channal	0.00485	0.837	$h_{fluid} = 863W/(m^2 \cdot K)$
	0.00375	0.837	
Glazing3	0.0048	0.038	$h_{ai} = 3.1W/(m^2 \cdot K)$

To validate the numerical model, an experiment was performed at the Department of Energy (DENERG) at Politecnico di Torino (Manuela Baracani et al. 2022). From Figure 5, the MFTG is a 44 mm TGU, with an MFTG layer as the central panel, two air cavities of 14 mm, and two glazing layers with low-e coating. The MFTG layers are connected to a hydraulic system, which enables the fluid flow within the layers.

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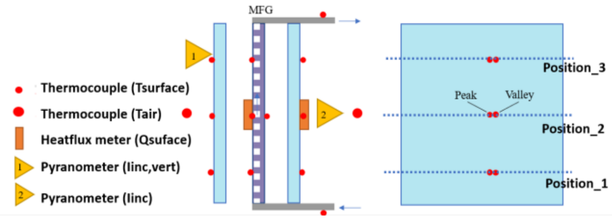


Figure 5: MFTG Experiment.

The mockup was tested under several flowrates. In this paper, we conducted the validation using only the 9.3L/h flow rate. As the long running of the system, the color of the micro-fluid channels will change from clean to dark yellow, which will affect absorptance. Therefore, we changed the absorptance from 0.274 to 0.32 to fully express the aging. The validation indicators employed the internal surface temperature T_{int} (°C) at the top position (position 3). The simulated results are compared to the experimental data and are presented in Figure 6, indicating a good agreement. For the internal layer surface temperature, the Adjusted R-Square value is 0.967, including a maximum deviation of -4.04°C during the night and a maximum deviation of 4.09°C during daytime.

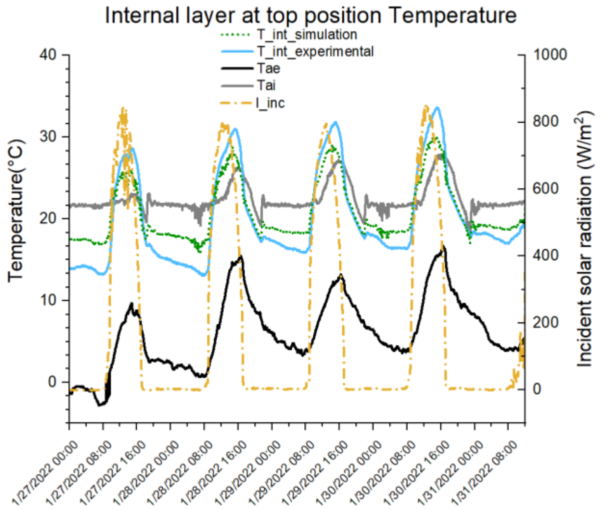


Figure 6: MFTG Numerical Model Validation.

Subsequently, a co-simulation is conducted at the building level using the generic co-simulation framework previously described. The co-simulation scheme for MFTG is depicted in Figure 7. At present, the primary focus is on assessing the impact of various control strategies and inlet temperatures on the indoor thermal environment. The investigation of indoor optical aspects and the utilization of heated water will be addressed in future research. But, to check the reliability of the amount of the Solar radiation transmitted into the room, a comparative single glazing model with the same Solar Radiation Transmittance (0.4) was simulated. Figure 8 shows a very small difference per window area, which verifies the reliability of solar radiation part. The various working conditions selected for analysis are presented in Table 1 and the working modes based on incident solar radiation I_{inc} (W/m^2) and fluid velocity F_v (m/s) are presented in Table 2.

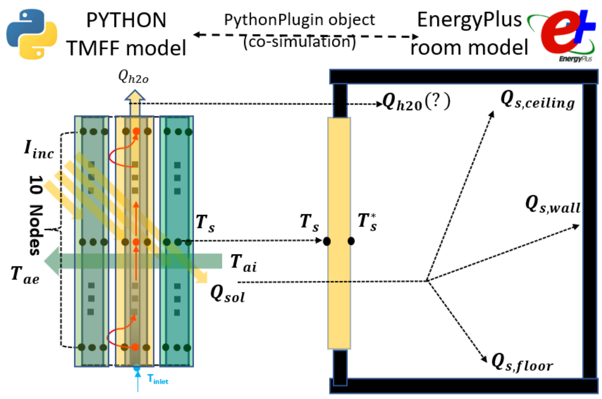


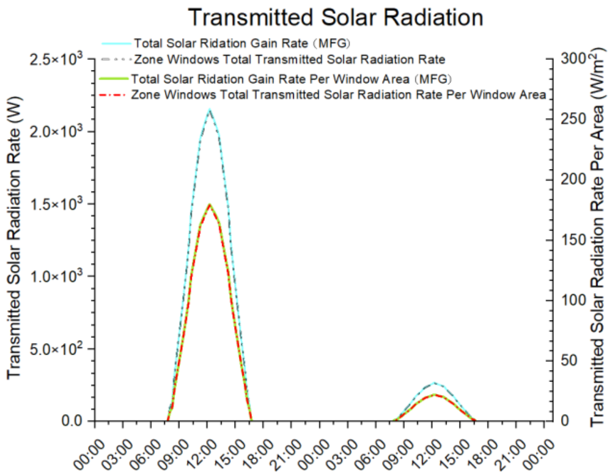
Figure 7: MFTG Co-simulation Framework

Table1 Working Condition

Name	Inlet Temperature (°C)	Working Mode
Constant_inlet10	10	Constant
Constant_inlet15	10	Constant
Dynamic_inlet10	15	Dynamic flow
Dynamic_inlet15	15	Dynamic flow
Advanced_inlet15	15	Advanced flow

Table2 Working Mode

Season	Dynamic Flow		Advanced Flow	
	I_{inc}	F_v	I_{inc}	F_v
Sum 6-8	≤50	0.00013	≤50	0.00320
	>50	0.00160	>50	0.00480
Win 1-2 11-12	≤50	0.00000	≤50	0.00000
	>50, ≤250	0.00107	>50, ≤250	0.00013
	>250	0.00160	>250	0.00062
Mid 3-5 9-10	≤50	0.00013	≤100	0.00013
	>50, ≤250	0.00107	>100, ≤300	0.00160
	>250	0.00160	>300	0.00320



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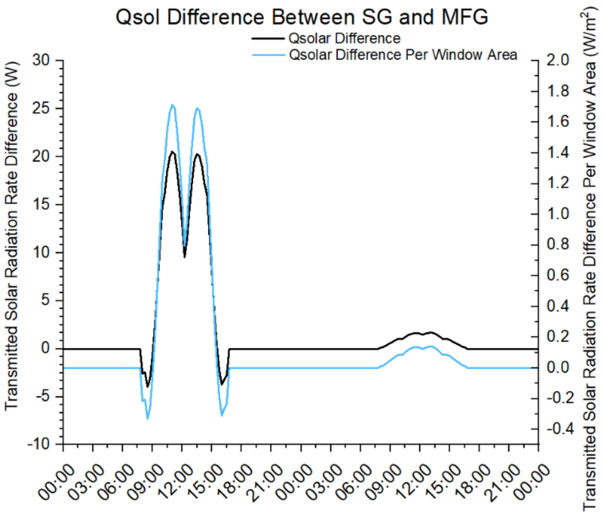

Figure 8: MFTG and Single Glazing Comparision.

Figure 9 displays the performance of MFTG under Dynamic mode with 10°C inlet temperature over three typical summer days : T_sur, T_out, and Q_harvest (harvesting energy rate per façade area). It demonstrates the flexibility of implementing various control strategies and inlet water temperatures to affect the façade surface temperature and the indoor environment for optimization design. Figure 10 illustrates the ideal heating load , the harvested energy per window area, and the overheating rate (the ratio of the time over 28°C) for the entire year of MFTG under different working mode. It is evident that MFTG possesses significant potential for solar energy harvesting, achieving up to 213.15 W/m^2.

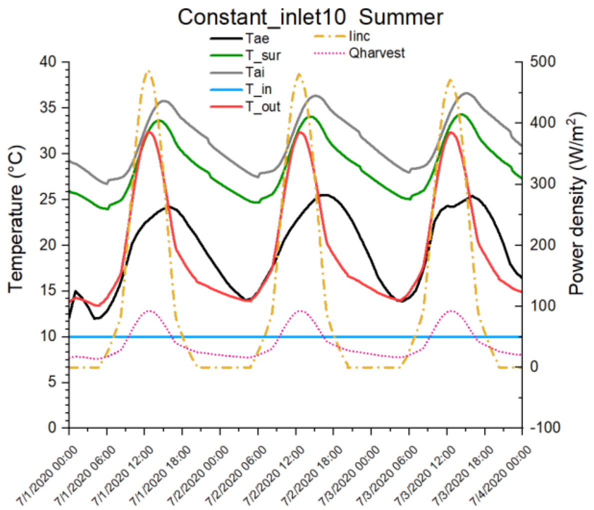

Figure 9: Performance underDifferent Working conditions in Typical Summer Days.

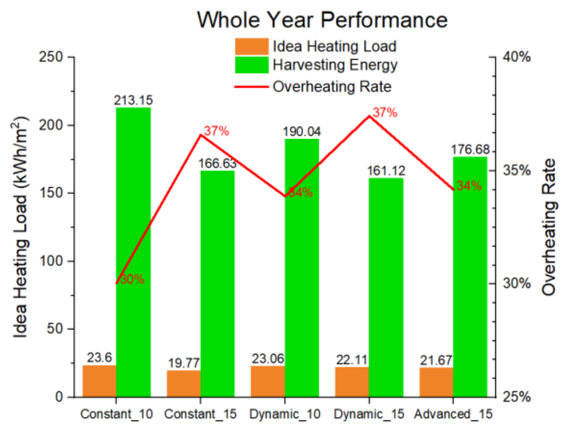

Figure 10: Performance under different working modes.

DSF

DSF is an innovative dynamic building envelope system, composed of inner and outer glass layers separated by an air cavity. Typically, a shading device is incorporated within the air cavity to control solar radiation, enhancing the overall energy efficiency and thermal comfort of the building. Whole BPS tools are not remarkably accurate in modelling the thermal behavior of DSF. For example, a comprehensive comparison of the four popular BPS tools (e.g., EnergyPlus, IDA ICE, TRNSYS and IES-VE) was conducted to investigate their ability to predict the physical quantities of the DSFs, both naturally and mechanically ventilated (Catto Lucchino et al. 2021, 2022; Gennaro et al. 2023). Comparing the simulation outcomes with the experimental data, the investigation showed that no software outperformed the others, that the air cavity temperature is the least accurate variable to predict and that EnergyPlus significantly underestimated the solar radiation transmitted through the façade. Moreover, only IDA ICE provides a dedicated sub-routine model developed for ventilated transparent facades. In contrast, the other tools must rely on simulative approaches not explicitly meant for ventilated facades, such as the Airflow Network (AFN) in EnergyPlus. However, with special workarounds and a good understanding of the thermal dynamics of the facade, it is possible to extend its use to simulate double-skin facades.

Therefore, in this context, it was deemed appropriate to integrate the detailed numerical model of the façade into EnergyPlus' routine through the generic co-simulation framework that we showed before. While the detailed numerical model of the DSF can accurately model the thermal behavior of the façade, the BPS tool can manage simulation at the building level.

The detailed numerical model of the double skin façade is based on the lumped-parameter thermal network proposed by Standard ISO 15099:2003, and it has been designed to be streamlined, flexible and easily parametrizable. The numerical model was improved by adding crucial parameters to describe the thermal behavior of DSF that the Standard overlooks. Indeed, when comparing the model outcomes with experimental data, the model fitness was unsatisfactory. The model calibration procedure is partly presented in this paper

(Gennaro et al. 2021). It is useless that the model includes the thermal capacity of glazing systems, infiltration in the cavity and losses due to the façade's sidewall ring (essential when all ventilation openings are closed) . Finally the outdoor air temperature was replaced with the sol-air temperature as inlet air temperature when the air source is the outdoor environment.

The diagram of the co-simulation approach for DSF is shown in Figure 11. The variables of the DSF model in Python passed to EnergyPlus are: Q_{sol} (transmitted solar radiation), T_s (surface temperature of the inner skin) and Q_v (ventilation heat gain or loss).

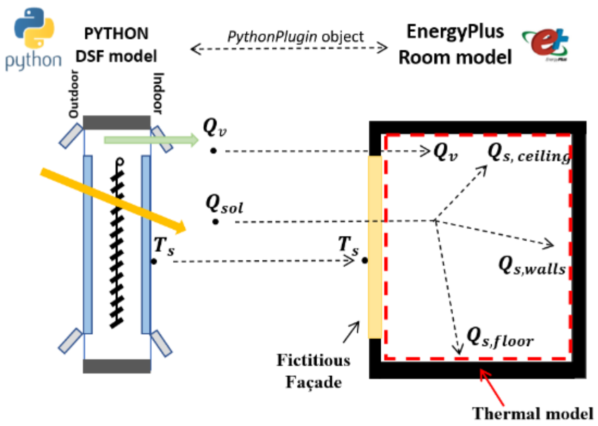

Figure 11 DSF Co-simulation framework.

Figure 12 compares the outcomes from the standard approach (AFN), co-simulation approach, and the experimental data of a campaign conducted at the outdoor test facility of Turin, Italy (Gennaro et al., 2023). During the campaign, the DSF was operated by changing the façade configuration daily (as reported at the top of the graph). For the meaning of the façade configuration, please refer to Gennaro et al. (2023). The results show how the co-simulation framework significantly improved the prediction of EnergyPlus. Indeed, the AFN cannot accurately predict any of the three quantities shown in Figure 12 (air cavity temperature, inner surface temperature and transmitted solar irradiance). EnergyPlus failed to predict solar radiation when using AFN due to a limitation caused by the solar distribution algorithm (Gennaro et al., 2023). Additionally, the inner surface temperature trend exhibited a time lag compared to the measured data. However, the co-simulation framework eliminated the time lag by introducing the capacity node in the glazing system. Moreover, the AFN approach overestimated the cavity air temperature due to incorrect modeling of the air flow between the cavity and the indoor zone (the air flow direction is inverted, as explained in Gennaro et al. (2023)). Overall, the co-simulation method can accurately model the façade, as shown by the time profile of the air cavity temperature.

Figure 13 shows the whole-year simulation results, implemented using the co-simulation framework, regarding two Rule Based Controls. RBC1 (Gennaro et al. 2021) operates the façade by choosing between TB and OAC modes, whilst RBC2 (Catto Lucchino et al, 2022) operates the façade in a highly flexible way, considering all possible configurations that a DSF can assume. Additionally, two benchmark controls are reported, TB and OAC, which correspond to more winter-oriented and summer-oriented control, respectively. The blinds control is the same in all controls, based on the cut-off strategy, which is state of the art for blinds control. The results show that the RBC2 led to an improvement in energy performance: the ideal heating load was in line with the TB strategy, while reducing the cooling load by 30%. On the other hand, the RBC1 did not allow for a reduction in the cooling load, compared with the OAC benchmark, as it was limited between TB and OAC alternatives.

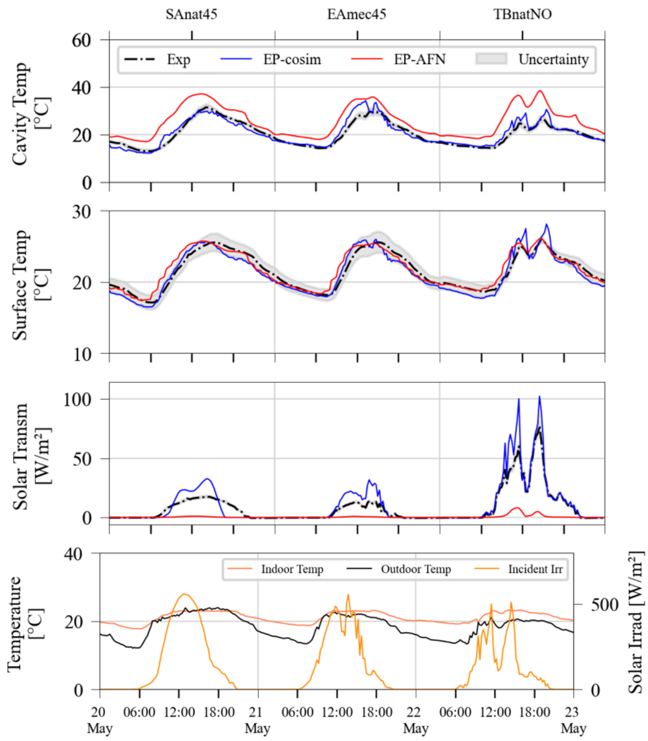

Figure 12 Comparison between EnergyPlus with AFN and Co-simulation Framework by Means of Experimental Data

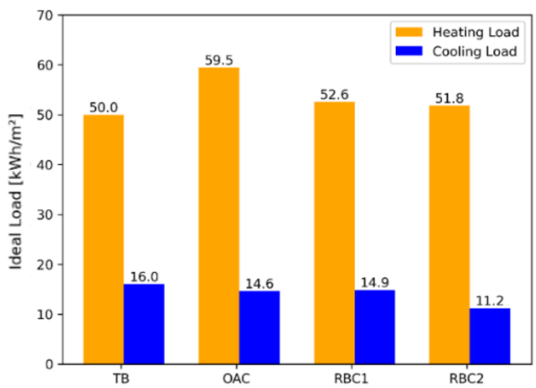

Figure 13 RBC's Performance Comparison

Conclusion

This study aims to develop a scalable, Python-based library of ABEs sub-models that can be evaluated and optimized at the building scale through a generic co-simulation approach. A generic co-simulation framework

https://doi.org/10.26868/25222708.2023.1628

that employs EnergyPlus as the master controller to slave ABE models is presented. Two case studies are examined: MFTG, which cannot be evaluated in BPS now, and DSF, which lacks flexibility and accuracy in BPS.

By co-simulating the façade model at the building scale, this research highlights not only the sophisticated performance of the ABEs but also the flexibility and accuracy of their operation and optimization. The detailed explanation of the co-simulation mechanism provided enables other researchers to leverage this approach and incorporate their validated sub-models within the ABEs library to evaluate and optimize their facade designs.

It should be noted that the MFTG model hasn't been fully refined, and without slaving Radiance. Additionally, the potential use of heated water remains under investigation. In future work, we aim to conatin more models and explore alternative co-simulation approaches with other BPS tools. This will further enhance the capabilities and applicability of the proposed framework in the field of building performance optimization.

Acknowledgement

The Author would like to express deep gratitude to Manuela Baracani, a PhD student in the Energy Department of Politecnico di Torino. Her generosity in sharing her knowledge and kindness in providing help greatly facilitated the preparation of this work. The research activities of MFTG were carried out in the framework of POWERSKIN PLUS project. The project has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 869898. The research activities of DSF were carried out in the research project "REsponsive, INtegrated, VENTilated - REINVENT – windows" (research grant no. 262198) sponsored by the Research Council of Norway.

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