JANUARY 17TH 2019 – MUNICH

POWERSKIN CONFERENCE

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The building skin has evolved enormously over the past decades. Energy performance and environmental quality of buildings are significantly determined by the building envelope. The façade has experienced a change in its role as an adaptive climate control system that leverages the synergies between form, material, mechanical and energy systems in an integrated design.

The PowerSkin Conference aims to address the role of building skins to accomplish a carbon neutral building stock. Topics such as building operation, embodied energy, energy generation and storage in context of envelope, energy and environment are considered. The 2019 issue of the conference PowerSkin focuses on the digital processes in façade design and construction, showcasing presentations about recent scientific research and developments in the field.

The **Technical University of Munich**, Prof. Dipl.-Ing. Thomas Auer, **TU Darmstadt**, Prof. Dr.-Ing. Jens Schneider and **TU Delft**, Prof. Dr.-Ing. Ulrich Knaack are hosting the PowerSkin Conference in collaboration with the trade fair **BAU 2019**, supported by the national funding initiative **Zukunft Bau (BBSR)**. It is the second event of a biennial series. On January 17th, 2019, architects, engineers, and scientists present their latest developments and research projects for public discussion.

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Reliability and Performance Gap of Whole-Building Energy Software Tools in Modelling Double Skin Façades

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Abstract

The careful design of the façade is one of the most influential strategies to lower the energy use in a building. A double skin façade (DSF) is one type of façade that allows the interaction between the outdoor and the indoor environment to be managed in a more advanced way, by increasing the control over the energy transfer between the two environments, while providing high architectural flexibility and transparency. The design of the thermophysical performance of a DSF is a complicated process that has to take into account several aspects, such as geometric parameters, thermal properties, ventilation strategy, shading devices, and the integration between the façade and the building energy concept.

There exist different whole building energy software tools (BEST) that practitioners can use to predict the energy and indoor environmental performance of a building and to support an informed choice to select the most appropriate building components during the design phase. However, when it comes to the simulation of DSF in BEST, complexity and inaccuracies in prediction usually rise, as these envelope systems are characterised by a thermophysical behaviour that requires a more advanced modelling than the possibilities conventionally embedded in BEST.

This paper reviews the scientific literature to show evidence on how BEST are used to predict the thermophysical behaviour of DSF, together with reporting the existing modelling capabilities for some selected BEST. The purpose is to highlight the challenges associated with the modelling of DSFs and to identify the major gaps between measured performance and prediction though BEST. The findings indicate that gaps are mostly connected to the dynamic behaviour of the DSFs and in particular the airflow within the façade cavity. The challenges associated with the modelling and simulation for each software tool, and the skills necessary to recognise and implement the best-suited model among the different options available are also discussed.

Keywords

double-skin façade (DSF), whole-building energy software tools (BEST), literature review, performance gap

1 INTRODUCTION

In recent years, the need to achieve low-emission building has led to improved energy performance of building envelopes, increased building equipment efficiency (Justo Alonso, Liu, Mathisen, Ge, & Simonson, 2015), and increased harvesting of renewable energy sourced (Torcellini & Crawley, 2006). Within this context, the façade, and the building envelope in general, can play a very relevant role. Many studies have shown that the use of double skin façade (DSF) systems can lead to reduced energy use while providing high transparency, access to daylight and natural ventilation (Chan, 2011; Singh, Garg, & Jha, 2008), thus representing a possible building envelope technology that addresses all the above mentioned tasks. However, the prediction of the behaviour and design of a DSF is not a simple task. The full potential of such a technology is probably not yet reached, and the gaps between the prediction capabilities and the actual performance of these systems are important barriers that prevent their efficient implementation.

The modelling and simulation of a DSF, as more in general of an adaptive building envelope, have to accurately represent a sequence of time-varying building envelope system states (or properties), instead of a static representation of the building enclosure (Loonen, Favoino, Hensen, & Overend, 2017). During the design of a façade, practitioners and consultants can make use of several whole-building energy software tools (BEST), which allow the impact of a building envelope solution to be assessed in conjunction with all the other components of a building. The simulation of DSFs, when their impact and integration within the entire building is searched, is also carried out through BEST. However, it is questionable whether such tools can accurately describe or not the transient heat and mass transfer that occur in the complex environments of DSFs, since these tools have been developed to replicate conventional building envelope components (Loutzenhiser, Manz, Felsmann, Strachan, & Maxwell, 2007). As previously reported by Kalyanova & Heiselberg (2008), the different calculation algorithms of each tool can lead to different performance prediction and simulation errors of the DSFs. Furthermore, known phenomena occurring in DSFs are still not always replicated by BEST.

When selecting the method (and tool) for DSF modelling, attention should be primarily given to the results that are expected to be achieved. This refers to the expected level of accuracy of the results, the time required for the simulation run, and the complexity of the model and the level of knowledge of the future users.

This paper aims to provide a general overview of the use of different BES tools in replicating the DSFs behaviour. A particular focus is placed on the degree of accuracy achieved in the analysed examples, and in general of this entire category of simulation environments, and at the same time the paper also tries to identify which are the main difficulties in modelling DSFs which affect the results (both due to the user's experience lack and the tools gap).

2 METHODOLOGY

This work builds upon existing literature reviews reporting the capabilities of BEST (Clarke & Hensen, 2015), and how BEST can be used to simulate adaptive façades (Loonen et al., 2017). This paper is, therefore, a review of articles published in scientific journals showing how DSFs are modelled and simulated using BEST. Relevant publications have been searched in scientific literature databases using as keywords "double skin façade" and the name of some selected BEST (Energy Plus, Esp-r, IDA ICE, IES VE, TRNSYS.). Since the simulation of DSF with BEST is a relatively widely used research method, the search produced a significant amount of papers. This database of paper was subsequently narrowed down by applying some restrictive criteria: first of all, only recent papers published in the last decade (2008 – 2018) have been analysed. The background for this choice is the aim to analyse approaches, limitations and gaps occurring with the use of state-of-the-art BEST, while the interest on how BEST simulation capabilities has changed along the time is not the focus in this paper. However, by applying this restriction, there were no results for some of the BEST tools (ESP-r) selected. Therefore, for this case, an exception has been made, and a paper published before 2008 was included in the analysis. Secondly, to obtain information related to the reliability of the tools, only those papers presenting an experimental validation were considered.

The information gathered from these papers was then categorised according to the following criteria (see Tab. 3 and Tab. 4): BEST used, geometry (box window or multi-storey window), ventilation mechanism and path, and the type of analysis run in the paper. For each paper, the achieved accuracy in simulating the energy performance of the DSF was highlighted, in particular focusing on the prediction of the cavity temperature and airflow. Any other information that may affect the simulation results, like the number of thermal zones in which the cavity was divided, the presence or not of shading devices, etc. has also been reported in the tables, if provided in the paper.

3 CHALLENGES IN PERFORMANCE PREDICTION OF DSFS

3.1 BACKGROUND ON PHYSICS OF DSFS

Many types of DSFs have been developed over the last decades; the literature classifies DSFs according to the construction type, the geometry, the cavity ventilation and the different flow path (Barbosa & Ip, 2014; De Gracia, Castell, Navarro, Oró, & Cabeza, 2013; Haase, Marques da Silva, & Amato, 2009; Jiru & Haghighat, 2008; Oesterle, Leib, Lutz, & Heusler, 2001; Poirazis, 2004; D. Saelens, Carmeliet, & Hens, 2003). A DSF is generally composed of an outer glazed layer and an inner glazed layer, separated by an air gap that can be ventilated (either mechanically or naturally). The air gap often hosts a shading device (usually a roller shade or a venetian blind) to increase the control over direct solar gain. The external glazing and the internal glazing can be realised through multi-layered glazed units (Fig. 1). The airflow path (i.e. the origin of the airflow and the destination) can differ according to several working to fully integrated façades).

The evaluation of the thermal performances of this system is not a trivial task, and especially when the airflow is not mechanically induced. The pressure and temperature fields in the façade's cavity and surfaces are the results of many simultaneous thermal, optical, and fluid flow processes, which interact with each other and are highly dynamic. Notably, the airflow in the cavity can be highly variable when based on wind or thermal stratification, which makes the problem even more complicated. Short-wave radiative heat transfer occurs through the glazed surfaces of the façade and leads to absorption, reflection, and transmission of the solar radiation hitting the façade.

The long-wave radiative exchange occurs between the surfaces of the façades, and at the interfaces with the surrounding environments. Conduction takes place within the solid surfaces of the façade. Convective heat exchange is the crucial mechanism in the fluid-dynamics of a DSF and influences the airflow within the cavity, as well as the global heat transfer within the system.

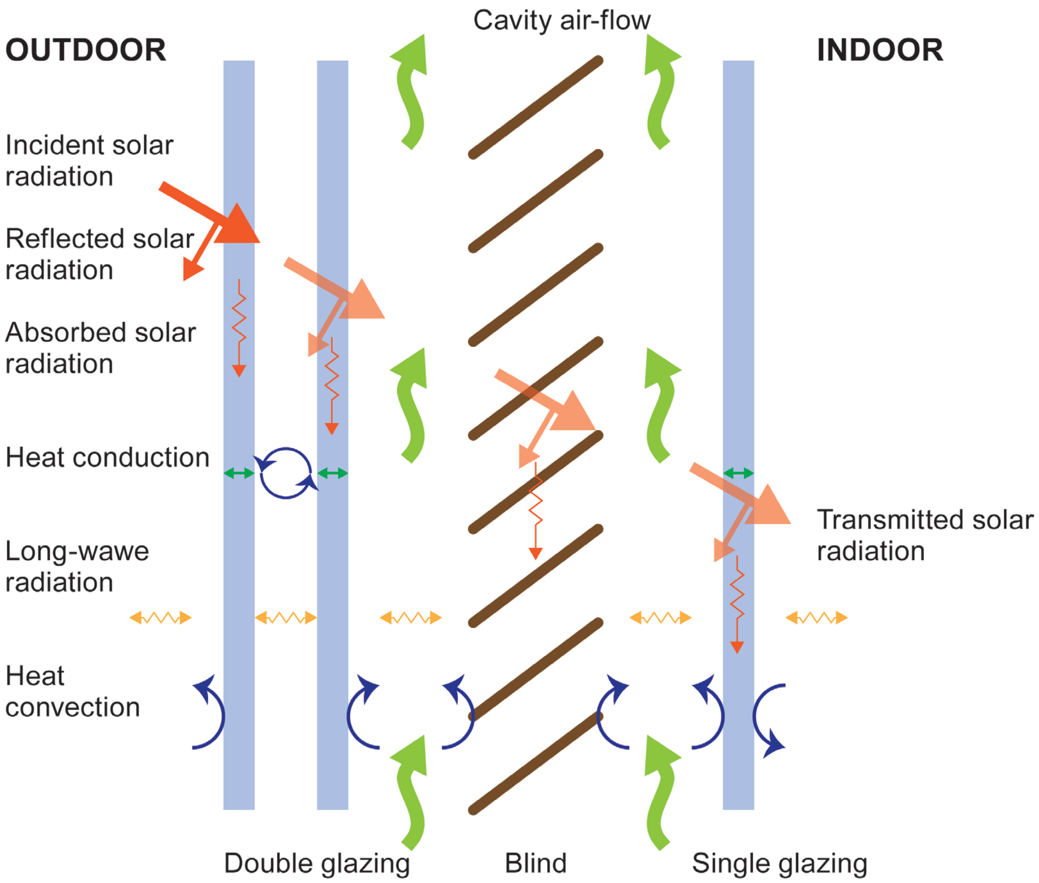

FIG. 1 Heat transfer transmission in a DSF *(Adapted from Wang, Chen, & Zhou, 2016)*

In mechanically ventilated DSF, the airflow is primarily induced by mechanical means. The fluid motion problem is, to some extent, decoupled by the thermal field within the façade construction, but it influences the thermal environment in the façade – which instead does not mainly affect the fluid motion. Conversely, in DSFs based on naturally induced ventilation, the fluid motion problem is dominated by the thermal field within the façade, which is itself affected by the airflow. This integrated thermal and fluid-dynamic problem is the primary source of complexity in modelling and simulating the heat transfer in DSFs.

3.2 DYNAMIC OPERATION STRATEGIES OF DSFS AND SYSTEM INTEGRATION

When looking at the various airflow concepts, it is important to note that all the types of DSFs (in terms of layers of glazing, shading, dimensions, etc.) can be combined with both types of ventilation (natural and mechanical) and all types of airflow concepts. This results in a great variety of DSF configurations. Fig. 2 shows the different airflow concepts that can be applied to DSFs. Moreover, DSFs act as climate responsive elements with hybrid ventilation (natural and mechanical) concepts with a possibility to change the airflow path due to different weather conditions in different seasons (Loonen et al., 2017). This requires a control system that allows changing the physical behaviour according to the outdoor climate or requirements set by a building management system. Predicting this dynamic air-flow strategy is not trivial.

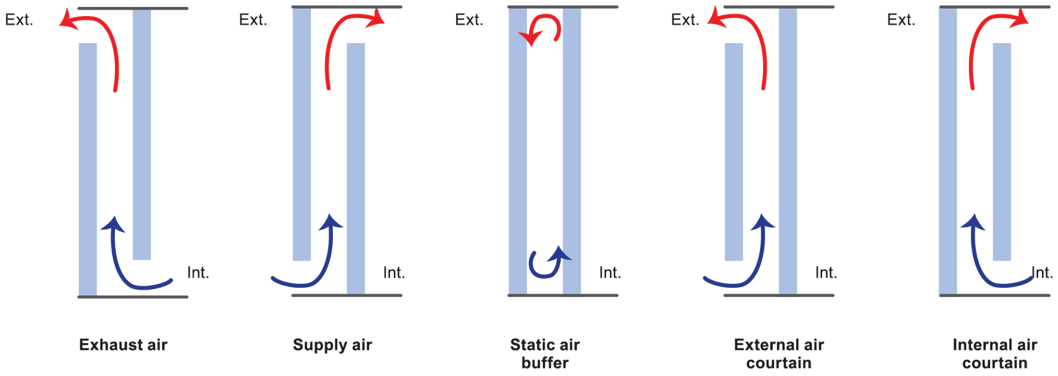

FIG. 2 Possible air-flows in double skin façades *(Haase, Marques da Silva, & Amato, 2009)*

DSF is not a traditional type of envelope that can be analysed independently from its surroundings. In particular, when it comes to mechanically ventilated façade, the coupled simulation of the building plant and this building envelope component is mandatory to obtain a correct assessment of the energy performance. This is the only way to model and assess the complex interaction between airflow in the façade and the HVAC system, and the building energy management system. Instead, when it comes to naturally ventilated façades, the boundary conditions may affect to a large extent the behaviour of the system, which in turns also affect the (indoor-side) boundary conditions. These are the reason why, regardless of the ventilation mechanics, all the different systems (façade, room, plant) need to be simultaneously simulated in order to optimise/verify the individual and overall performance, and in such a context whole-building energy simulation is an essential tool (Dirk Saelens, Roels, & Hens, 2008).

4 SIMULATION TOOL OVERVIEW - MODELLING POSSIBILITIES AND LIMITATIONS

A large number of software tools are available for predicting the energy and comfort performance of buildings (Crawley, Hand, Kurnmert, & Griffith, 2008; Crawley, Lawrie, Pedersen, & Winkelmann, 2000; Hand, 2011; S.A. Klein & et al, 2010; Sanford A Klein, 1976). Because these software tools are usually employed to determine the energy use of the whole building, the implementation and adaptability of advanced building components are not the primary consideration in conventional BEST (Oh & Haberl, 2016). Some extensive literary reviews of BEST can be found (Attia, Hensen, Beltrán, & De Herde, 2012); among them, the recent work of Loonen et al. (Loonen et al., 2017) focuses on the review of the opportunities for modelling adaptive building envelope systems (a broader category than DSF) in state-of-the-art BEST. In this work, the focus is placed on five simulation tools EnergyPlus, ESP-r, IDA ICE, IES VE, and TRNSYS) and their challenges in replicating the physical behaviour of adaptive façades. The background for the selection of these five BES tools lies in their popularity and complexity, and it is possible to state that they represent today the state-of-the-art tools for whole-building energy simulation. The selection of these software tools was based on the following criteria:

- Extensive building envelope modelling capabilities, as identified by Crawley and co-authors (Crawley et al., 2008)
- Subject to active development by their development team or user community;
- Thorough validation through compliance with ANSI/ASHRAE Standard 140 (BESTEST) and other quality assurance procedures;
- Use in both research and consulting engineering practice;
- International users;

- Based on the work of (Loonen et al., 2017), this paper also limits the analysis of the simulation possibilities and challenges in the simulation of DSF through BEST to the five software mentioned above.

4.1 HEAT TRANSFER PHENOMENA

The operational mode of the DSF can vary according to its function in one building or another, but the design of the DSF cavity is more or less the same: two layers of fenestration, separated with the air gap, which, in most of the cases, include a shading device. No matter what is the operational strategy of the DSF, the air temperature in the gap is the result of the solar radiation absorbed by glazing and/or shading device, the heat losses/gain from/to the cavity and from/to the ventilation airflow. As a result, the air temperature in the DSF cavity is mainly the result of the convective and radiative heat transfer between the heated surfaces of glass/shading and air (convective) and among all the different surfaces (radiative). Conductive heat exchange plays a significant role if one of the two transparent layers is a single glass pane, while if insulated units are adopted the weight of this mechanism on the overall behaviour of the system is limited. The floor or ceiling and side walls of the DSF rarely have significant importance, as in real life, the weight of their areas is minimal compared to the area of fenestration and shading (except DSF with very wide cavity, or DSF in façade module with reduced length). The estimation of the convective heat transfer is relatively more straightforward for the mechanically induced flow motion compared to the naturally driven flow, where the convection heat transfer depends on size, shape, orientation, flow regime, temperature etc. Different BES tools integrate different approaches for the estimation of the conduction, convection and radiation heat exchange coefficients. Concerning the selected 5 BES tools, the different approaches are illustrated in Tab. 1.

In the past years, to solve the heat transfer conduction problem, the most commonly adopted methods by BEST have been response factor techniques(Thermal response Factors (TRF) or Conduction Transfer Function (CTF)). This solution is considered computational efficient but with some limitations (it can only be applied if the thermophysical properties of the assembly are constant along the time). Numerical models based on Finite Difference (FD), Finite Volume (FV) and Finite Elements (FE) methods are used to modelling temperature evolution in systems with time-dependent material properties. These numerical methods, adopting an iterative procedure, treat the building envelope surface as made of discrete capacitances and resistances. For building walls modelled in one-dimension, a reasonable computational speed for annual energy analysis can be achieved with conventional simulation tools (Spitler, 2011). Model calculations to estimate the heat transfer of DSFs thought BEST do not usually include thermal storage effects because these used to be not so relevant when it comes to modelling transparent materials. However, this approach is not entirely correct when it comes to analysing a DSF. (Freire, Mazuroski, Abadie, & Mendes, 2011).

Considering that BEST cannot implement detailed numerical analysis (CFD) to solve convective heat transfer under transient conditions because of the resource-intensity of such methods, the convective heat transfer is usually assessed through convective heat transfer coefficients (hc) calculated using empirical correlations. For external building surfaces, these coefficients (hc, ext) are essential to calculate convective heat gains and losses from building façades and roofs to the environment. They are complex functions of, among other factors, building geometry, building surroundings, building façade roughness, local airflow patterns and temperature differences.
The work of (Mirsadeghi, Cóstola, Blocken, & Hensen, 2013) provides an extensive overview of such models for HC, ext calculation and their implementation in BES tools. The considerable uncertainty in predicting these coefficients is translated into a different approach used by every software. Some of them, like Energy Plus or ESP-r, have several models implemented, providing the user with a broad range of options, giving the possibility to choose the most appropriate model for the specific problem.

Other programs rely only on one model while others simplify the issue without implementing any empirical model and by using a fixed value for hc, ext.

The calculation of the internal convective heat transfer coefficient is not much easier than the external one. It has to consider the effect of flow driving forces from mechanical and buoyancy forces. Several models are available (Peeters, Beausoleil-Morrison, & Novoselac, 2011) and not every BES tools adopt the same (Beausoleil-Morrison, 2002).

Usually, the coefficient is fixed as a constant value or, at most, the programs make the coefficients depend on the velocity and temperature difference between the surfaces. The most adopted model to estimate developed by (Alamdari & Hammond, 1983) and (Beausoleil-Morrison, 2000).

For the calculation of the radiative heat exchange, different methods are applied in BEST. The main difficulty in calculating radiation in an enclosure composed of diffuse grey surfaces arises from the treatment of the multiple reflections. (Le Dréau, Heiselberg, & Jensen, 2013) Some of these techniques are based on the calculation of view factors Fi–j between the different sections. Radiance methods can be applied to calculate with a higher precision radiative heat exchange in the short-wave region. However, because of the computational resources necessary to carry out these calculations, such an approach is often not used in BEST when it comes to DSFs.

CONDUCTION SOLUTION METHOD		**ENERGY PLUS**	**ESP-R**	**IDA ICE**	**IES –VE**	**TRNSYS**
		CTF, Finite difference[1]	Finite volume	Finite Difference	Finite difference	CTF[2]
Convection	**External**	6 empirical models[3]	12 empirical models[3]	Single empirical model (McAdams, 1954)	Single empirical model (McAdams, 1954)	Fixed value
	Internal	Several models[4]	Buoyancy correlations of (Beausoleil-Morrison, 2000)	DNCA (Brown & Isfält, 1974)	Buoyancy correlations: (CIBSE, 1986) or (Alamdari & Hammond, 1983)	(Beausoleil-Morrison, 2000)
Radiation		n-surfaces interaction, infinite reflections (exact solution)	2- and 3-surfaces interaction, infinite reflections	n-surfaces interaction, infinite reflections (exact solution)	Fresnel Equations applied to 2 surfaces interaction, 10 angles of incidence, infinite reflections	n-surfaces interaction by using (Gebhart, 1961) factors

1 By default, EnergyPlus uses the CTF method, but it was recently extended with a new finite difference scheme for conduction, to allow for modelling temperature- or time-dependent material properties (Pedersen 2007; Tabares-Velasco and Griffith 2012). The usage of this new approach has been largely unexplored in the literature.

2 Simulation users can also choose to bypass the CTF approach by coupling TRNSYS Type 56 with finite element or finite difference schemes such as Type 260 or Type 399 (Kosny 2015)

3 The work of (Mirsadeghi et al., 2013) identify 17 different models used in BPS tools

4 There are four different settings to direct how EnergyPlus managers select hc models during a simulation. There are numerous individual model equations for hc in EnergyPlus to cover different situations that arise from surface orientations, room airflow conditions, and heat flow direction (Energy Plus, 2010)

TABLE 1 Characteristics of whole BPS tools with respect to conduction, convection and radiation heat exchange

4.2 AIRFLOW MODELLING

Several numerical modelling approaches have been applied when it comes to studying DSFs (De Gracia et al., 2013). Among these, the airflow network model can provide fast, useful information about bulk flows without consuming high computational resources, and is usually integrated with a thermal network, and a building energy model, by solving the heat balance and the pressure balance in each node (Zhou & Chen, 2010). A "node" is used to describe each zone connected by one or more airflow paths, and external nodes characterise the external conditions. This ap-proach is the one used by the majority of building performance simulation tools, and it can be applied either if the DFS is mechanically or naturally ventilated.

The airflow path calculations are based on the Bernoulli's principle. Some properties, like wind and temperature outside the building, are described in the external nodes, while the indoor air properties are described in the internal nodes. Those nodes are then interconnected through flow paths, such as crack, openings, or windows. The conservation of mass equation is applied to each of the system's nodes; an airflow is attributed to the pressure differences between the nodes, taking into account the air motion due to the wind and the temperature difference across the opening resulting to buoyancy-driven flow (Zhai, El Mankibi, & Zoubir, 2015). This method applies either the orifice law or the power-law relationships for determination of the airflow rate by mean of the pressure difference (Awbi, 2002). The application of one or another relationship is a sensitive matter, as the classic orifice equation is more suitable for the large openings and fully developed turbulent flow, while the power-law equation is more flexible and can be adjusted to different conditions and opening sizes via the exponent n and coefficient C (Kalyanova, 2008).

When calculating the airflow in naturally ventilated façades, the approach used to determine the infiltration rate in building simulation is usually adopted. The most used methods are (1) the crack method (Bring, Sahlin, & Vuolle, 1999) and (2) the Effective Leakage Area (ELA) method (ASHRAE 62.2, 2016). The crack method requires the use of input data that can be hardly found in the literature. For this reason, the ELA method is more often adopted, even if is a more simplified approach. ELA can in fact make use of the results of the blower door test or tabulated values.

		ENERGY PLUS	ESP-R	IDA ICE	IES –VE	TRNSYS
Influencing parameters in the flow model	**Wind force**	X	X	X	X	X
	Wind fluctuations	-	X	-	-	-
	Buoyancy	X	X	X	X	X
Leakage area		Crack method or Effective Leakage Area (ELA) method	Crack method	Crack method or Effective Leakage Area (ELA) method	Crack Flow Coefficient (AIVC, 1994) [1]	Crack method
Airflow - Thermal network coupling		DSF component (Airflow Windows) Or Airflow network model (AIRNET)	Airflow network model	DSF component Or Airflow network model	Airflow network model (MACROFLO)	Airflow network model (CONTAM Or COMIS -TRNFLOW)

1 The equation used represents the best fit to a large range of experimental data analysed by the Air Infiltration and Ventilation Centre

TABLE 2 Air-flow models used in the BES tools

The calculations of the airflow in a naturally ventilated (multizone) building, however, is the one that makes the users face more difficult issues (Kalyanova & Heiselberg, 2008), as a series of challenges is seen, due to:

- the wind speed reduction from the meteorological data to the local microclimate near the building
- the determination of the wind pressure coefficients

- how to decide on appropriate discharge coefficients and pressure loss coefficients in general
- how to agree on an appropriate relation between pressure loss and air flow rate through the opening (determination of coefficients in the relationships).

5 ANALYSIS OF CASE-STUDIES IN LITERATURE

Some of the recent studies (2008 – 2018) on DSFs have been analysed in this paper to underline better the capabilities and limitation of the various software (Table 3). For each software, among the numerous papers available, the analysis focuses only on those studies that have validated results with experimental data. Except one software tools (IES-VE), it was possible to find papers where numerical simulations were compared to experimental data. The software tool that does not present empirical validation is however compared to additional simulations (CFD). Many of the analysed papers deal with naturally ventilated façades, and this is because most of the difficulties encountered are related to the estimation of the air flow inside the cavity. In a mechanical ventilated façade, this parameter is given as input of the HVAC system and therefore leads (in general) to lower model complexity and associated uncertainty.

Software	Reference	Type of Double Skin Façade technology	Type of analysis (Thermal/ Visual/ Airflow)	Validation of Results	Cavity Ventilation	Airflow path	Shading devices in the cavity	Type of shading device
EnergyPlus	(D. W. Kim & Park, 2011)	Box Window	T, A	Yes	Natural	Varying[1]	Yes	Venetian blind
EnergyPlus	(Anđelković et al., 2016)	Multi-storey	T, A	Yes	Natural	External air curtain	No	-
ESP-r	(Leal et al., 2004)	Box Type	T, A	Yes	Natural	External/ Internal air curtain[2]	No	-
IDA ICE	(Eskinja et al., 2018)	Box Type	T, A	Yes[3]	Mechanical	NA	No	-
IES VE	(Pomponi et al., 2017)	Multi-Storey	T, A	No[4]	Natural	External air curtain	Yes	Venetian blinds
Trnsys	(Y. M. Kim, Kim, Shin, & Sohn, 2009)	Multi-Storey	T, A	Yes	Natural	Buffer mode	Yes	Venetian blinds
Trnsys	(Khalifa et al., 2015)	Box Window	T, V, A	Yes	Natural	Supply air	Yes	Roller blind

1 The DSF was operated in four different ventilation modes (supply air, exhaust air, internal air curtain and external air curtain) by controlling the four ventilation dampers located at the top and bottom of exterior and interior glazing. During the experimental period, the ventilation modes were changed arbitrarily at 2-h intervals.
2 The absorptive glazing is placed externally during the summer analysis and internally during winter.
3 The results were also compared with the MATLAB-based model HAMBASE
4 IES VE results are compared against those obtained from a FLOVENT model, a computational fluid dynamics (CFD) software package.

TABLE 3 List of recent papers analysing the energy performances of double skin façades

The results of the different models analysed are gathered in Table 4. It is possible to notice that there is not a common trend among the different tools in overestimating or underestimating the experimental results. It is also essential to point out that most of the studies do not report the validation of the mass flow rate, but the quantity used as performance parameter in the validation process is a temperature (either a surface temperature of the different glass layers or the temperature of the air in the cavity).

Software	Reference	Number of thermal zones	Cavity width	Cavity height	Convective heat transfer method		Temperature comparison	Airflow comparison	Average error		R^2	
					Exterior	Interior			°C	m/s	T	V
Energy-Plus	(D. W. Kim & Park, 2011)	3	50 cm	2.16 m	MoWITT	ASHRAE Vertical Wall algorithm	Over-estimation	Over-estimation	3.89	0.99	-	-
Energy-Plus	(Anđelković et al., 2016)	-	NA	NA	MoWITT	Adaptive Convection Algorithm	Underestimation	Over-estimation	-	-	0.93 – 0.96	0.86
ESP-r	(Leal et al., 2004)	up to 16[1]	NA	NA	Different settings[2]	Different settings[3]	Overestimation	Under-estimation	2.3	0.11	-	-
IDA ICE	(Eskinja et al., 2018)	NA	NA	3.6 m	-	-	Overestimation	-	-	-	-	-
IES VE	(Pomponi et al., 2017)	8[4]	100 cm	3.5 m^2	-	-	-	Under-estimation	-	-	-	-
Trnsys	(Y. M. Kim et al., 2009)	5	50 cm	3.6 m	-	-	-	-	1.87	-	0.96 - 0.98	-
Trnsys	(Khalifa et al., 2015)	6	30 cm	2.7 m	-	-	Under-estimation	Over-estimation[5]	0.5	-	0.98	-

1The paper presents a parametric study of the number of zones into which the window air channel should be divided and the comparison of results with measurements in the test cell. The average errors are related to the case of 4 thermal zones were

2 The default setting (McAdams method) and a fixed value of h= 17.5W/m^2

3 The default correlations (Alamdari-Hammond), fixed values h= 3 W/m^2 and h= 8 W/m^2, Bar-Cohen and Rosenhow correlation and the SOLVENTcorrelation developed by Molina and Maestre. The average errors listed in this table are related to the default correlations, which give the same results of the fixed values.

4 One per each floor

5 Since no measurements of airflow rates were available from the experiment, the data have been compared with the quantities during winter and summer measurements presented in Saelens (2000). The average simulation resulting airflow rates are in a good agreement with measurements.

TABLE 4 Comparison of the estimated results and the experimental data

In their analysis, Kim and Park (2011) simulate different flow paths in a naturally ventilated box window DSF by using Energy Plus; they identify in the airflow calculation algorithm as the first responsible of the difference between simulations and measured data. At the same time, the significant differences in estimating the surface temperatures, according to the authors, is understood to be caused by the applied convective heat transfer coefficient correlation. In a similar study, where a multi-storey DSF of an office building is modelled using EnergyPlus, Anđelković, Mujan and Dakić (2016) identify the main obstacle to be the time step-resolution of the software, which is not low enough to predict the airflow correctly in the cavity. The authors adopt the statistical indicators provided by the Guideline 14 (ASHRAE, 2002; DOE, 2008; EVO, 2012) to assess the level of simulation model accuracy. Leal, Erell, Maldonado and Etzion (2004) use ESP-r to simulate a box window in which an absorptive glazing with a low shading coefficient is adopted as a shading device. The authors try to establish a correlation between different parameters and the accuracy of the results. It is found that the most critical parameter is the number of zones into which the window is divided; the number of vertical divisions is especially critical, but dividing into more than four zones brought only marginal improvements. The second parameter in order of importance is the heat transfer coefficient. The least essential parameter is the local pressure loss coefficient.

By means of the software IDA ICE, Eskinja, Miljanic and Kuljaca (2018) investigate the air temperature in the cavity of a box window using the airflow network approach. In their analysis, the authors compared the results with the experimental results of a scaled system, showing some disagreement with the results, but the background for this behaviour is not of easy interpretation.

The model applied by the software to calculate the convective heat transfer is identified, in another study (Pomponi, Barbosa, & Piroozfar, 2017), as the reason of the inaccuracy of the simulation results. The paper analyses a multi-storey building with a naturally ventilated DSF. In the authors' view, IES-VE applies a method which is the most indicated for DSF buildings, but yet not entirely suitable to narrow cavities. Such an approach underestimates the heat transfer to the air, subsequently causing a weaker buoyant force to drive air through the channel.

Kim et. al (2009) use TRNSYS to investigate only the winter thermal performance of a multi-storey façade. The validation of the simulation has been done through experimental data collected from a three-story building with double skins on its eastern and western façade located in South Korea. The analysis, conducted only in the buffer mode, shows a good agreement of predicted temperature inside the cavity and the experimental data, also taking into account the effects of the natural ventilation on it.

Khalifa and co-authors (Khalifa, Ernez, Znouda, & Bouden, 2015), by mean of the same tool, evaluate the thermal performance of a single-storey naturally ventilated DSF, and a good agreement with experimental results is found in the evaluation of the surface temperatures, (the absolute value average error does not exceed 0.5°C). The differences occurring are due to, in the authors' opinion, the combined effects of error propagation introduced by the simplification in the geometry (a single-channel cavity) and the lack of accuracy in some boundary conditions (no accurate or unknown data on relative humidity and wind speed and direction).

6 DISCUSSION AND CONCLUSIONS

In both research and engineering practice, it is increasingly common to adopt building energy software tools to study the energy performance of a double skin façade. Even though several studies on this topic have been carried out in the last years, different challenges usually arise when it comes to the estimation of the thermal behaviour of this complex type of envelope through models implemented in and modelling techniques adopted by conventional building energy software tools. In particular, the most relevant challenge is related to the modelling and simulation of the airflow inside the cavity, and how this is reflected in the heat transfer phenomena within the cavity. This difficulty affects, especially in naturally ventilated façades, not only the prediction of the airflow rate, but also the values of the temperatures of the various surfaces and the cavity air temperature, and in turn the entire energy flown through the façade.

There are substantial evidences in the literature which demonstrate the importance of modelling accurately the internal surface convective heat exchange within building simulation programs. Despite this, most programs still employ simplified approaches because of the computational efficiency of these methods when compared to more refined modelling approaches. In the studies available in the literature where the cavity air velocity is analysed, a high level of disagreement between measurement and simulation is reported. The uncertainty in the prediction of the airflow rate is the primary outcome of this analysis, and as previously mentioned, the airflow rate, the flow regime, the convective and the radiative heat transfer have all together an impact on the resulting air temperature in the cavity. Among the parameters that play a role in determining the accuracy of the results, the number of thermal zones into which divide the cavity and the correlations adopted to determine the convective heat exchange coefficient seem to have the higher impact.

The analysis has shown that there is not a particular trend in terms of overestimation or underestimation of the physical quantities based on the selected BES tool, or on the type of façade constructions. On the contrary, discrepancies seem therefore more linked to the intrinsic limitation of the entire class of BES tools rather than to some specific conditions. Such result is, unfortunately, of little use for the professional community, whose task is to select the most suitable BEST in the design phase, and for the research community, whose goal is instead to develop further the capabilities of BES tools to simulate more advanced building envelope systems. These results, in fact, does not show that one tool is superior to another, nor point towards some clear directions to be followed in order to improve these tools. Nonetheless, the authors' interpretations of the discrepancy between simulations and experiments can be useful information to identify areas of possible developments of BES tools.

In order to be considered successfully validated, a model has to demonstrate the consistency of its predictions for all parameters, and have a certain agreement with the experimental data. For the time being, it is questionable whether or not the models are consistent enough when comparing the results of simulations with the experimental data. Furthermore, the analysis has also shown that only a few authors present their results referring to standardise statistic indicators (the only one adopted in the surveyed papers is R2). Moreover, the validation is often limited to few physical quantities, while different aspects than temperature values (and, very seldom, airflow rate) are usually not considered (such as, for example, transmitted solar irradiance, convective and radiative, in the long IR region, heat fluxes). This is mainly due to the fact that, in the case of double skin façades (and building components in general), guidelines on validations of simulation tools are not available, and there is no standard that can provide a procedure, nor statistical accuracy level indicators (MBE, RMSE, R2, CVRMSE, etc.) to be adopted. Currently, there exist some standards, such as the ASHRAE Guideline 14 (ASHRAE, 2002), which provide a minimum acceptable level of performance, identified through statistical metrics, for models of entire buildings through BES tools. However, a similar standard dedicated to the validations of models of building components does not exist. Hence, the evaluation of the performance of different BES tools in simulating the behaviour of DSFs is not a standardised procedure, and it results in a lack of common methodologies. The development of more robust modelling approaches and strategies for the simulation of complex building envelope systems calls therefore not only for more detailed and accurate physical-mathematical modelling and efficient algorithms but also for shared procedures to evaluate and benchmark the newly proposed models or simulation approaches, which can make the validation process more reliable.

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