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Modelling of double skin facades in whole-building energy simulation tools. A review of current practices and possibilities for future developments.

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Abstract

Advanced building envelope systems can contribute to the reduction of greenhouse gas emissions and improve the energy flexibility of buildings while maintaining high levels of indoor environmental quality. Among different transparent envelope technologies, the so-called double skin façades (DSFs) have been since long time proposed as an effective, responsive building system.

The implementation of DSF systems in a real building is highly dependent on the capabilities of the prediction of their performance, which is not a trivial task. The possibility to use whole-building energy simulation (BES) tools to replicate the behaviour of these systems when integrated into a building is, therefore, a crucial step in the effective and conscious spread of these systems. However, the simulation of DSFs with BES tools can be far more complex than that of more conventional façade systems and represents a current barrier.

This article is based on evidence from the scientific literature on the use of BES tools to simulate DSF, and provides: (i) an overview of the implementation of DSFs systems in BES tools, with the current capabilities of some selected BES tools; (ii) a comprehensive review of recent, relevant simulation studies, where different approaches to modelling and simulating DSFs are reported; and (iii) the identification of current gaps and limitations in simulation tools which should be overcome to increase the possibilities to correctly predict the performance of DSFs when integrated into a building.

Keywords: Whole-building energy simulation (BES); Double Skin Façade (DSF); EnergyPlus; ESP-r; IDA-ICE; IES Virtual Environment; TRNSYS

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1. Introduction

1.1. Background

The name "double skin façade" (DSF) refers to a rather large spectrum of façade solutions that can be generally described as a *"system made of an external glazed skin and the actual building façade, which constitutes the inner skin, [where] the two layers are separated by an air cavity, which has fixed or controllable inlets and outlets and may or may not incorporate fixed or controllable shading devices."* (Pomponi et al. 2016). The adoption of a DSF aims primarily at realising a building with a "fully-glazed" appearance, while still preserving high energy and indoor environmental performance by using the air zone between the two skins as an integrated element of the building energy concept.

Efficacy of DSFs is a long-time debate (Oesterle et al. 2001), with studies showing that DSF can increase the indoor environmental quality and reduce the energy use in operation compared to traditional single skins (Singh et al. 2008; Chan 2011), as well as other studies which unveiled some controversial aspects of DSFs performance (Gratia and Herde 2004).

A conclusive answer to the debate whether DSFs are more or less efficient than high-performing single skin facade is far from being found, and it cannot probably be reached in absolute terms. This is due to the fact the effectiveness of one solution or the other depends to a great extent on the detailed conditions of each specific situation, and the assessment needs to be carried out case by case.

The impossibility to define general rules in the design of DSFs and the need to optimize these systems in relation to the entire building energy concept, thus calls for suitable design tools, such as whole-building energy simulation (BES) tools, which can address the performance of such systems in combination with that of the entire building, thus supporting architects and engineers in the design process towards energy efficient buildings.

In this context, the successful design of DSFs remains a challenging task. The untapped potentials given by a carefully design DSF, suitably integrated in a high-performance building energy concept, and properly controlled while in operation, can be partly attributed due to a lack of thorough understanding of the benefits and possible risks, and the inability to measure them reliably during the design (and preliminary design) phases.

1.2. Challenge in the use of BES tools for the simulation of DSFs

BES tools have the potential to provide information to several stakeholders (Clarke and Hensen 2015), and in particular to façade engineers when it comes to DSFs. However, the historical development of BES tools has always followed the development of new technologies with a certain delay. While current tools are reliable when it comes to the modelling and simulation of conventional building envelope systems (Loutzenhiser et al. 2007), the modelling and simulation of DSFs though BES tools is still a challenging task even if DSF is nowadays considered an “established” technology, and it is still questionable whether such tools can accurately or not describe the transient heat and mass transfer phenomena that occur in these facade systems.

The reason for this is that the detailed description of the physical behaviour behind each building component is not the primary consideration in BES tools, which instead focus on the evaluation of the energy loads of an entire building (Oh and Haberl 2016), and on the interaction between the various parts. Moreover, even in the case of very advanced or flexible engines, some limitations in the implementation of more sophisticated models might be related to the graphical user interface of the tools, rather than to the calculation engine, or to the possibility to implement more advanced control strategies and to run multi-domain analyses within the same software (Loonen et al. 2016).

BES tools have since years considered a necessary element to move forward with the real uptake of advanced building systems, and among them DSFs, and the reliability of these tools was tested in a series of research activities. For example, the first systematic approach to the evaluation of the performance of BES tools in replicating the behaviour of DSFs was presented ten years ago in the final report of IEA ECBCS Annex 43 and SHC Task 34 “Testing and Validation of Building Energy Simulation Tools” (Kalyanova and Heiselberg 2008). However, since this activity, no significant follow up on this topic was carried out. New, custom-made models for DSFs were developed, but minimal upgrades have occurred in BES tools in the last decades when it comes to the possibility of simulating DSF systems.

1.3. Aims and structure of the paper

This paper intends to provide those researchers and designers who are approaching the simulation of DSFs though BES tools, with an overview of existing information and practices in this domain, in order to enable them to make an informed decision on the tools and approaches, given the current panorama of possibilities implemented in BES tools.

The paper presents, in Section 2, a brief re-cap on few selected background topics related to DSF technologies and their physical-mathematical models. This information can be useful for the readers, especially those less familiar with DSF systems before the following sections are read. The overview of the current capabilities of some selected BES tools for the modelling and simulation of DSFs is then presented in Section 3, followed by a review of recent selected simulation studies appeared in the scientific literature, where different approaches for modelling DSFs are seen, together with their effects (Section 4).

Furthermore, the article presents a comprehensive identification of gaps and limitations in present-day simulation tools, which should be overcome to increase the possibilities to correctly predict the performance of DSFs when integrated into a building (Section 5).

In order to frame the information to be elaborated and conveyed through the paper, and to base the paper on a clear set of records, the analysis has been limited to five of the most popular BES tools – EnergyPlus, IDA-ICE, IES Virtual Environment, ESP-r, and TRNSYS (Crawley et al. 2000, 2008; Aschaber et al. 2009; Hand 2011) – and to a relatively recent time range (after year 2000).

The planned audience for this paper is composed by both, researchers and practitioners who want to use, evaluate, and develop BES tools for the simulation of DSFs. It is not the intention of this paper to provide a comprehensive and comparative evaluation of the performance of the different BES tools in replicating one or another specific DSF (i.e. the paper does not report a quantitative estimation of each software's reliability, nor an inter-software comparison). However, the paper has the ambition to gather the most recent trends and report evidence of modelling of DSFs through BES in order to become a reference document for those who approach this topic and are willing to contribute to the development of the field of simulation of advanced window technologies. This is, in fact, a clear gap in the current scientific literature, where information on the simulation of DSFs though BES tools is not gathered in an easy to use way.

2. Briefs of double skin facade systems and their modelling

Comprehensive reviews and focused studies can be found in the literature on a wide range of different elements related to DSFs, including:

- the analysis of the performance of DSF systems (Shameri et al. 2011; Barbosa and Ip 2014; Pomponi et al. 2016);
- the typology of glass that is usually used for the different layers of the façade (Roth et al. 2007) (Baldinelli 2009);
- the shading systems that are usually hosted in the ventilated cavity between the two layers of the façade (Jiru and Haghighat 2008; Barbosa and Ip 2014);
- the cavity depth of the DSFs, which may vary, usually, in the range from 200 mm to more than 2 m (Chan et al. 2009);
- the different overall typology of DSFs according to the geometrical features of the façade (Kim and Song 2007; Wong 2008).

While DSFs have been primarily investigated as solutions to allow thermal loads to be reduced, both in winter and in summer (Chan et al. 2009), acoustics, daylighting and fire protection behaviour (Ding et al. 2005) are also among the analysed aspects of the performance of these systems.

2.1. Typologies and classification of DSF

DSFs are usually classified according to specific characteristics such as the type of construction, the geometry, the ventilation mechanisms in the cavity, and the different flow paths. The classification of DSF according to the structure of the cavity (Oesterle et al. 2001) (i.e. as box-window, shaft-box, corridor type and multi-storey façade) is among the most used ones. Barbosa et al. (Barbosa and Ip 2014) and Poirazis (Poirazis 2004), have classified DSF between a narrow cavity and a wide cavity, with narrow being cavity width up to 40 cm and wide being cavity width more than 40 cm. This limit was determined by the minimum width required for maintenance purposes in the cavity, and not based on considerations on the thermofluid behaviour within the cavity. Other studies (Saelens et al. 2003; Jiru and Haghighat 2008; De Gracia et al. 2013) have categorised DSF cavity based on ventilation, which can be either mechanical or natural. Mechanically ventilated facades are usually strongly integrated with the HVAC system of the building (where the airflow is an imposed quantity set by the HVAC plant). In a naturally ventilated facade, the driving force for natural ventilation is either thermal buoyancy or wind pressure, or both. Therefore, the airflow is in this latter case not easy to control nor to predict, as it continuously changes depending on the weather conditions.

Other classifying dimensions of a DSF involve the origin of the airflow and its destination (Saelens et al. 2003), which eventually define the airflow concepts as summarised by Haase et al. (2009). The possible flow paths, illustrated in Figure 1, are:

- Supply air: the DSF supplies air to the indoor environment.
- Exhaust air: the DSF removes indoor air.
- Static air buffer: the DSF acts as a buffer with convective air movement only within the cavity.
- External air curtain: the DSF cavity is ventilated by outdoor air with no connection to the indoor air.
- Internal air curtain: the DSF cavity is ventilated by indoor air with no connection to the outdoor air.

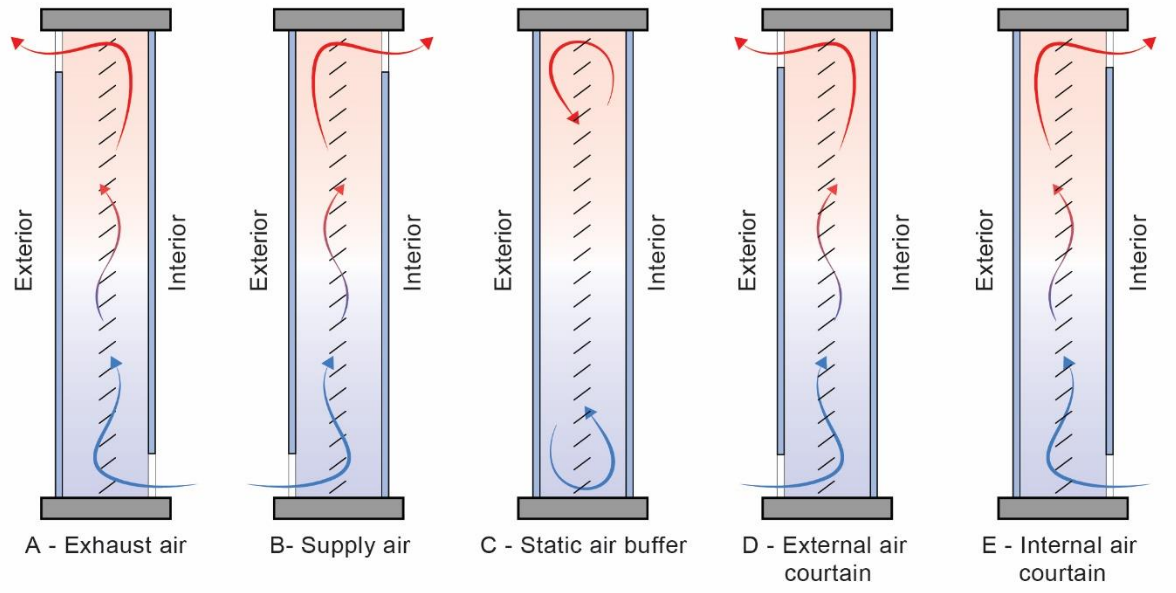


Figure 1 Possible air-flows in double skin façades (redrawn from Haase, Marques da Silva, & Amato, 2009)

2.2. Numerical Modelling of DSF

Numerical simulation of DSF systems consists in the modelling of both heat transfer phenomena inside solid components, and between solid components and air, as well as the mass transfer (airflow) within the (ventilated) cavity and the indoor/outdoor environment. All these phenomena can be modelled with different degree of accuracy/detail, following established methods for building physics modelling in buildings (Underwood and Yik 2008). A survey in the scientific literature (De Gracia et al. 2013) shows indeed that there is a very broad spectrum of approaches that have been adopted in this context. These approaches can be grouped into four categories, as illustrated in Figure 2, ordered by the level of complexity (and associated computational time):

i) empirical correlations and simple analytical models;

ii) combined thermal and airflow networks models;

iii) intermediate explicit models;

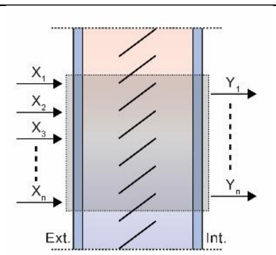
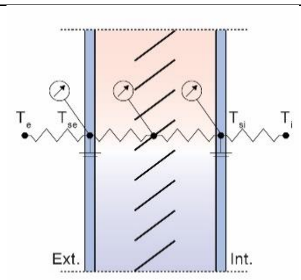
iv) computational fluid dynamics (CFD) models.

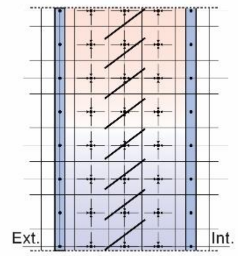
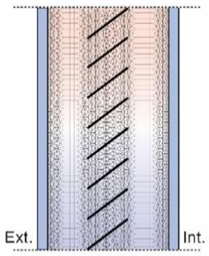
2.2.1. Empirical correlations and simple analytical models

This modelling approach focuses on the overall performance of the DSF as a single component, and therefore without defining the performance of its subsystems. This strategy is based on either empirical correlations or simplified analytical relationships (usually derived by solving a simple version of the energy balance conservation equation).

An interesting sub-group in this category is represented b models based on a non-dimensional analysis (application of Buckingham theorem) of the thermofluid-dynamic behaviour of a DSF. For example, in a study 14 non-dimensional number have been proposed to model a DSF (Balocco 2004; Balocco and Colombari 2006).

Figure 2 Overview of Numerical modelling approaches

Modelling approach	Short description	Features (possibilities vs. limitations)
 i) empirical correlations and simple analytical models	• Empirical correlations or simplified analytical relationships. • The overall performance of the DSF as a single component. • Simple performance parameters.	✓ Very scalable and computationally efficient. ✓ Easily integrated into larger models. ✗ Outputs not useful for the optimisation of the DSF. ✗ Lack of sensitiveness to small variation in the configuration. ✗ Correlations obtained from experiments or simulations.
 ii) combined thermal and airflow networks models	• Directly derived from the architecture of BES tools. • Based on the integration of two equivalent networks: the thermal and the airflow network. • Different degree of complexity of R-C networks of the components of the DSFs • Pressure-driven network to account for air movement.	✓ Not too high computational demanding ✓ Implemented in most BES tools. ✓ It can be used for both mechanically and naturally ventilated DSF. ✓ It provides data on thermophysical properties, a geometrical feature of the DSFs. ✗ The reliability of the fluid-dynamic phenomena might be improved. ✗ Mass and heat convective transport based on empirical correlations. ✗ Calibration of the model often needed. ✗ Lack of comprehensive, freely available data set for the calibration of the models.
	• It is used when the level of explicit description of the phenomena is greater than the combined thermal and airflow networks models.	✓ Different levels of complexities in modelling the fluid dynamics processes. ✓ Suitable for integration (though co-simulation) in BES tools.

 iii) intermediate explicit models	• More comprehensive formulations of conservation equations are adopted. • The cavity is divided into control volumes that are coupled due to the presence of the air channel.	✓ A higher level of detailed analyses of the thermofluid dynamic behaviour of the DSFs. ✗ High(er) computational time. ✗ Currently, the co-simulation approach is not fully developed. ✗ Models may be readjusted to take into account different flow regimes.
 iv) computational fluid dynamics (CFD) models	• Based on the solution of the conventional set of conservation equations in computation fluid dynamics, in combination with turbulence models. • Detailed volume division of the cavity and coupling with detailed masse/energy transport equations.	✓ Provide different levels of analysis (from a complete system to sub-system/components). ✓ Very detailed information on the thermofluid phenomena. ✓ Fluid-dynamics, turbulence, thermal and radiation accounted into one model. ✓ A possible parametrisation of the complex multi-physics problem (only at the envelope level). ✗ Very high computational time. ✗ Only steady state conditions, or very short-time transient state phenomena. ✗ Not integrated with the entire building. ✗ Complexity in choosing the turbulence model.

Other examples of this type of models are those based on simple lumped-parameters representation of the 1-D (or sometimes 2-D) structure of the DSF (e.g. (Park et al. 2004), (Oliveira Panão et al. 2016)), which require relatively few input data.

One of the main strengths of these approaches is that they are very scalable and computationally efficient, and can, therefore, be easily integrated into larger models (for example in whole-energy building simulation tools). This method can provide some useful information in the early stage of the design process; however the information that can be extracted is usually limited to the overall behaviour of the system, and cannot be used for the optimisation of the design of the DSF (the approach is too little sensitive to small variation in the configuration). The main drawback of these methods is the need to rely on correlations, which are obtained through either experimental analysis or higher-order simulations.

2.2.2. Combined thermal and airflow networks models

This approach is directly derived from the architecture of BES tools and is based on the integration of two equivalent networks: the thermal and the airflow network. This approach has a rather long history, dating more than 20 years (Tanimoto and Kimura 1997), and is still at the basis of most of the simulation of DSFs carried out with BES tools, and can be used for both mechanically (Stec and Paassen 2005) and naturally ventilated DSF (Fallahi et al. 2010). Given its relevance and uptake in many BES tools, more information on this approach will be given in the following section 3. In short, these models are based on lumped-parameter descriptions (with different degree of complexity of R-C networks) of the components of the DSFs coupled with a (primarily) pressure-driven network to account for air movement between the different nodes of the model, which represent a certain domain of the DSF cavity.

These models still rely, in some aspects, on empirical correlations to solve some of the transport equations (especially the mass transport and convective heat transfer), and on a rather detailed information of the thermophysical properties and geometrical feature of the components constituting the DSFs (glazing systems, shading devices, openings, etc.).

The combined thermal and airflow networks approach has its main strength in providing fast, useful information about bulk flows still without consuming high computational resources. These models can, up to some extent, be used to select and optimise different configurations of DSFs and to carry out sensitivity analyses which can be useful not only at the preliminary stage of the design but also at a later phase when the configuration of the DSF need to be investigated further. Furthermore, because of their intrinsic architecture, they still can be easily integrated into BES tools.

However, the reliability, when it comes to the description of the fluid-dynamic phenomena (and, where these are strongly linked to the thermal phenomena, the reliability of the later ones too) might not be too high, and much is left to the sensitivity of the modeller when it comes to the selection of the empirical correlations to be used in different domains. In this context, the calibration of the models is often a necessary activity to assure robustness of the results, but the lack of comprehensive, freely available dataset for this activity is one of the main obstacles in the implementation of more accurate models based on this approach.

2.2.3. Explicit intermediate models

This group gather different approaches where the level of explicit description of the (especially fluid-dynamic) phenomena is greater than the combined thermal and airflow networks models, but less than more complex modelling approaches (computational fluid dynamics, CFD). In these cases, the simulation of the fluid motion in the cavity is not obtained only by pressure-driven equations, but more comprehensive formulations of conservation equations are adopted. Because of this, the computational time increases, together with the level of detail of the described phenomena, which therefore allows deeper analyses to be carried out.

Examples of explicit intermediates models are the so-called zonal approach (Jiru and Haghighat 2008) (Wang et al. 2016), and the so-called control volume approach (Faggembauu et al. 2003a, b) (Saelens et al. 2003, 2008)). In both these cases, the cavity of the DSF system is divided into control volumes (in a number greatly smaller than that typical of CDF) that are coupled due to the presence of the air channel. In this class of methods, different levels of complexities can be adapted to model the fluid dynamics processes, ranging from rather advanced empirical correlations up to the explicit formulation of the momentum conservation equation, in combination with conventional approximations of the physics of the fluid flow (e.g. Boussinesq approximation). These modelling are used to determine, in combination with the thermal flows through the DSFs, the airflow in the cavity.

Because of their architectures, these approaches are still suitable for integration (though co-simulation) in BES tools, even if as revealed by the research presented in this paper, such a combination is not really seen in the current panorama. Explicit intermediate models can allow when compared to combine thermal and airflow networks, more detailed analyses on the thermofluid dynamic behaviour of the DSFs to be carried out, and probably represents the most detailed model that can support the study of transient states without requiring too extensive computational resources. This means that such a modelling level can work well both regarding preliminary design and optimisation. However, as much as for the combined thermal and airflow networks, a large number of correlations and approximations are necessary to assure a short-time calculation time, and this calls for the need of validation and/or calibration of models, as well as high competence of the modeller to select the most suitable correlations and auxiliary equations, which can have a large impact on the results of the simulations.

2.2.4. Computational fluid dynamics analysis (CFD)

This method, based on the solution of the conventional set of conservation equations in computation fluid dynamics, usually in combination with turbulence models, cannot only accurately describe the flow regime, velocity, and turbulence of the airflow in the cavity, but also can determine the heat transfer coefficient of the DSF system (Bhamjee et al. 2013; Darkwa et al. 2014; Iyi et al. 2014; Dama and Angeli 2016).

If from the one hand this method has its main strength in the possibility of obtaining very detailed information on the thermofluid phenomena in the skins and cavities, on the other hand, this comes at the cost of the very long time necessary to carry out the calculation. This means that such an approach is only suitable to analyse steady state conditions, or very short-time transient state phenomena, but are instead not suitable to investigate transient states. This limitation clearly reveals that CFD is usually reserved for a very detailed analysis of phenomena in DSFs, which are usually accounted for at the stage of optimisation of the system, or system development. CFD has proven to be a useful tool on the study and optimisation of DSF due to its ability to conjoint fluid dynamics, turbulence, thermal and radiation models into a single computer simulation, allowing to parameterise such complex multi-physics problem numerically (Pasut and De Carli 2012), but only when the focus is placed on the building envelope system alone – i.e. not integrated with the entire building. Because of the discontinuity in terms of time-scale, space-scale, and computational time between CDF and BES tools (Srebric et al. 2000), the coupling of these two approaches is, for the time being, not an exploited solution, as this leads to an exponential increase in the computational time in the BES tool (Tian et al. 2018).

3. Numerical modelling approaches in five selected BES tools.

3.1. Overview and methodology

In the following sections, two alternative ways of modelling DSFs in five selected BES tools are presented. The first one (combined thermal and airflow networks) is the most general one and can be implemented, though in different ways, in all the selected BES tools. This modelling approach is capable of handling very different configurations of DSF, thus allowing researchers and designers to evaluate solutions that are fully custom-made.

Table 1 Overview of different features of BES tools concerning modelling phenomena of DSFs. Table derived from Catto Lucchino et al. 2019.

	Energy Plus	ESP-r	IES –VE	TRNSYS	IDA ICE
Airflow - Thermal coupling	Airflow network “AIRNET”	Airflow network	Airflow network “MACROFLO”	Airflow network model “CONTAM” Or “COMIS” - TRNFLOW	Airflow network model
DSF component	“Airflow Windows”	-	-	-	“Double-Glass Façade”

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Conduction solution method		CTF, Finite difference[1]	Finite volume	Finite difference	CTF, Finite difference[2]	Finite difference
Convection	External	6 empirical models[3]	12 empirical models[3]	Single empirical model: McAdams (1954)	Fixed value	Single empirical model McAdams (1954)
	Internal	Several models[4]	Alamdari and Hammond (1983)	5 different models[5]	2 models[6]	DNCA (Brown and Isfält 1974)
Radiation		n-surfaces interaction, infinite reflections (exact solution)	2- and 3-surfaces interaction, infinite reflections	Fresnel Equations applied to 2 surfaces interaction, 10 angles of incidence, infinite reflections	n-surfaces interaction by using (Gebhart 1961) factors	n-surfaces interaction, infinite reflections (exact solution)
Influencing parameters in the flow model	Wind force	X	X	X	X	X
	Wind fluctuations	-	-	-	-	-
	Buoyancy	X	X	X	X	X
Leakage area		Crack method or Effective Leakage Area (ELA) method	Crack method	Crack Flow Coefficient AIVC (1994)[7]	Crack method	Crack method or Effective Leakage Area (ELA) method

[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 2011). 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 (Kośny 2015)

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

[4] There are different settings to set the calculation routine: TARP Algorithm, Simple natural convection, Trombe Wall, Adaptive, Adaptive Convection Algorithm (Energy Plus, 2010). In the last one, there are 29 different settings of hc equations For vertical surfaces, according to room airflow conditions and heat flow direction different correlations are available. For simple buoyancy: Fohanno and Polidori (2006), Alamdari and Hammond (1983), ASHRAE Vertical Wall. Mechanical ventilation: Khalifa (1989). Mixed: Beausoleil-Morrison (2000).

[5] Fixed coefficients specified by CIBSE; Variable coefficients calculated according to CIBSE methods; Variable coefficients calculated from the relations proposed by Alamdari and Hammond (1983); User-specified fixed convection coefficients (IES VE 2014)

[6] The routine used by Type 80 applies two different correlations. No reference to existing models has been found (TRNSYS 17 2009).

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

The second one (a dedicated sub-routine that simulates specifically a DSF component, and that can be based either on simplified models, or on combined thermal and airflow networks, or on explicit intermediate models), is only seen in some of the five tools, and can be adopted only if an ad-hoc module has been developed (either by researchers or by a software house) to explicitly model a DSF system in a specific simulation environment. The key features of these BES tools are summarised in Table 1, as shown in Catto Lucchino et al 2019.

The choice of the BES tools to limit the investigation presented in this paper is based on both evidence from the literature about the most used BES tools in research and consulting engineering practice (Loonen et al. 2016), as well as, on the first-hand expertise of the authors. The analysis presented in this section focuses on how each software deals with the thermal and airflow analysis of DSFs and is based on the analysis of both the available technical information on the tools (e.g. manual, engineering references), relevant information found through the scientific publications, and on the experience of the authors.

3.2. Combined thermal and airflow networks

In general, an airflow network in combination with a thermal network is based on the discretisation of the temperature and pressure field of a thermodynamic system (i.e. of a volume of air, or of a building element, or a combination of the two) through the identification of a suitable number of representative nodes where the energy (thermal network) and mass (airflow network) conservation equation is computed. Each node is linked to the adjacent nodes by relevant transport equations for both the thermal network (different heat transfer equations depending on the nature of the heat exchange) and airflow network (Bernoulli equation), and can including the source or sink for both heat and pressure. Airflow, which is primarily attributed to pressure differences between two nodes, can also take into account the air motion due to the wind – and not only the temperature difference across two nodes resulting in a buoyancy-driven flow (Zhai et al. 2015). Elements capable of storing internal energy are associated with thermal capacity.

The two networks can be coupled in two different ways, following the classification proposed by Hensen (1995): though a "ping-pong" method, in which the thermal and flow model run in sequence (i.e. each use the results of the other model in the previous time step); and through the "onion" method, in which the thermal and flow model iterate within one-time step until satisfactory small error estimates are achieved. Even if the second way is more accurate than the first one (but less computationally expensive), both techniques are suitable to realise an overall algorithm that keeps together the two aspects of the thermal fluid model of the DSF (Stec et al. 2003).

Integrated thermal and airflow networks are implemented differently in each software tools, as illustrated in the next five sub-sections. The modelling of a DSF through this approach consists in realising a combined thermal and airflow network that represents the DSF's cavity and its boundary layers, and to connect this with the overall thermal and airflow network representing the building. In this approach, a DSF becomes an "integrated" part of the building, and is not a building envelope component, with the advantage of (usually) high flexibility in the way the airflow can be connected to the different parts of the building, including the integration with HVAC systems.

3.2.1. EnergyPlus

In *EnergyPlus* the pressure and airflow model is based on AIRNET (Walton 1989). A detailed description of the airflow network model may be found in the work of Waldon and Dols (Walton and Dols 2013). This model can be used to accurately simulate the sophisticated relationship between the airflow and the transient heat transfer phenomena, including multi-zone airflows driven by outdoor wind, buoyancy, and forced air (Energy Plus and US Department of Energy 2010).

In order to model a DSF using the thermal and airflow network model in *EnergyPlus*, the zones of the ventilated cavity and room are divided into several stacked zones, where each zone is an airflow network node. These nodes are linked by using different airflow network objects in *EnergyPlus,* which calculates the pressure at every node, and airflow through each linkage, which then calculates (in an iterative way) the node temperatures and humidity ratios with the given zone air temperatures and zone humidity ratios. These multizone airflow calculations combined with heat transfer calculations are performed at each HVAC system time step which determines the final zone air temperatures, pressures, and humidity ratios (Le et al. 2014; Peng et al. 2016).

In order to predict the leakage phenomena, two ways are available in *EnergyPlus*: (i) the crack method and (ii) the Effective Leakage Area (ELA) method. For the use of the crack method, the following inputs such as air mass flow coefficient, reference condition temperature correction factor and air flow exponent (dimensionless) are required. Their values are not easily found in literature, while leakage area values are available for different building component types (Organisation ASHRAE 1993).

When it comes to the thermal network, *EnergyPlus* offers a wide selection of different methods for calculating both exterior and interior heat transfer coefficient (ranging from the so-called TARP (Sparrow et al. 1979; Walton 1981)), to the MoWiTT correlation, (Yazdanian and Klems 1994), and to more basic, simple ASHRAE models (Organisation ASHRAE 1993)), as well as, different algorithms for the solution of conduction in building assembly.

3.2.2. ESP-r

ESP-r’s building thermal model is based upon a finite-volume heat balance discretisation method. A nodal network is also incorporated into *ESP-r* for airflow modelling and is integrated with the thermal model network in the “onion” form.

Following the same approach adopted in *EnergyPlus*, the ventilated cavity of a DSF can be studied through *ESP-r* by virtually dividing this environment in a stack of a certain amount of thermal zones, which are separated one from the other by fictitious transparent surfaces with high conductivity, negligible thermal mass, and high emissivity. These zones are interconnected to the adjacent one or the external nodes by air ducts and inlet/outlet air openings (network components).

Different convection regimes can be used in *ESP-r* to model the operations of a DSF. For example, the cavity can be enclosed and have only internal circulation, or it can be open with air flowing through the cavity from outside which can be both stack effect driven and wind-driven. When the DSF is ventilated, the Bar-Cohen and Rohsenow (1984) correlation can be used to predict the convective heat transfer for the surfaces facing the cavity; when the cavity is closed, the default Alamdari and Hammond (1983) correlation is instead adopted. For calculating the external convection heat transfer, several methods are implemented in the tool (McAdams, CIBS, MoWiTT, etc. (Mirsadeghi et al. 2013)).

3.2.3. IES-Virtual Environment

In opposition to *EnergyPlus* and *ESP-r*, two simulation environments developed and maintained with a strong focus on research, and characterised by being open-source tools, *IES* Virtual Environment is a commercial program whose code is not accessible, and the user cannot add any additional simulation modules to enhance either application-oriented or general-purpose modelling capabilities. This limits the application of *IES* Virtual Environment to “application oriented” models already included in the software.

The airflow network approach integrated into the software is called *MacroFlo* and is based on (macroscopic) zone mass balance and inter-zone flow–pressure relationships (Environment; Hensen and Djunaedy 2005). The flow through each opening is calculated as a function of imposed pressure difference and the characteristics of the opening. These characteristics differ for cracks and larger openings. For a given set of room conditions (temperature and humidity), *MacroFlo* solves the air flow problem by balancing net air mass flows into and out of each zone by considering the net air inflow for each of the room’s openings, and any net room airflow imbalance imposed by the system simulation program *ApacheHVAC* (the sub-routine that models the HVAC of the building).

The main driving forces of natural airflow are the pressure field generated by the wind and the buoyancy effect. Wind pressures on the building exterior are calculated at each simulation time step from the weather data file. Wind speed and direction data is combined with information on opening orientations and wind exposures to generate wind pressures on each external opening. The calculation involves wind pressure coefficients derived from wind tunnel experiments, combined with an adjustment for wind turbulence.

MacroFlo calculates buoyancy-related pressures, which vary with height in accordance to air density, on the assumption of a uniform air density in each room.

For the outside air mass, both wind and buoyancy-induced pressure must be included. At the start of a flow calculation the wind pressures are known (from the weather file), but then a buoyancy component of pressure in each room is only determined up to an additive constant. This constant is established from the opening flow characteristics and the requirement for flow balancing in each room.

ApacheSim is the name of the sub-routine dedicated to the dynamic thermal simulation program (IES 2004), based on a finite difference approach for the solution of the heat transfer in solid components. When it comes to convective heat transfer coefficient, the external surfaces of the building, where wind-driven forced convection is dominant, are modelled using McAdams' empirical equations (McAdams 1954). Five options are available for modelling the convective heat exchange between air masses inside the building and the adjacent building elements, ranging from CISBE fixed and variable coefficient to the "Alamdari & Hammond" (1983) calculation method, from the European standard BS EN 15265 to user-specified fixed convection coefficients that can be set directly in the construction database (IES 2004). Air temperature and humidity values are assumed to be uniform within the room.

IES couples the airflow and the thermal network by using the “onion” approach. *MacroFlo* and *ApacheHVAC* run in tandem with *ApacheSim*, and the calculations of the programs are interdependent. In the course of an iterative procedure, zone temperature and humidity conditions (together with any net supply or extract from *ApacheHVAC* supply or extract rates) are repeatedly passed to *MacroFlo*, which calculates the resulting natural ventilation flows. These flows are then used by *ApacheSim* to update the zone conditions, and so on. Upon convergence, this procedure balances both air flows, and heat flows for each zone.

The theory applied in *MacroFlo* is based on the flow characteristics of openings that are small if compared with the volumes they connect. While this is a good approximation for most windows, doors and louvres, it is a poor approximation in some other modelling situations, notably, flow in façade cavities and flues. For this type of situation, where the openings have a diameter similar or equal to the diameter of the adjacent spaces, adjustments to the opening parameters are necessary in order to achieve a good model. For this reason, it is possible in a ventilated cavity to adopt different types of resistance for the airflow. These can be: the resistance associated with the exchange of air between the cavity, the outside environment, and the adjacent building spaces; the resistance due to the obstructions in the cavity (internal blinds, constrictions, obstructions protruding from the sides, walkways etc.); the frictional resistance with the walls of the cavity.

3.2.4. TRNSYS

TRNSYS is a simulation code originally developed by solar thermal systems (TRNSYS 17 2013), which also offers the possibility to model and simulate multi-zone buildings through the so-called “Type 56”, a sub-routine of the software specifically developed for the solution of the

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energy balance in a building. Since the release of version 17, a thermal zone can have more than one air node. Each node represents a volume of air perfectly mixed, characterised by one temperature. It is possible to define the thermal capacity of the air enclosure and additional heat capacity (i.e. blinds) within the air node itself. Moreover, the exchange of the heat flow is not automatically defined as "mutual" among adjacent air nodes. The reason for this is to allow the user to describe cross ventilation or a ventilation circle within three or more air nodes.

The treatment of long-wave radiation exchange with the outside (sky, ground, external obstructions and shading devices), as well as long-wave radiation resulting from multiple reflections on interior surfaces within the cavity, applies the so-called "Gebhart" factor (Gebhart 1961). The view factors are the key tools of this method; in contrast to the purely geometric view factor, the factor by Gebhart includes optical properties, and it is defined as the part of the emission of a surface that is absorbed by another surface including all alternative paths within reach. The implementation of this detailed approach has been applied to a highly-glazed atrium with good outcomes (Aschaber et al. 2009). At the same time, a detailed model of the beam and diffuse solar radiation is available to model a DSF cavity. Standard treatment of solar radiation, beam and diffuse separately is now applied when passing the second layer of fenestration (the inner skin of the DSF). The specification of solar properties of the glazed façades is performed using the LBNL tool "Window" that generates the glazing description data to be added to the standard TRNSYS windows library.

To perform combined heat transfer and airflow simulations, TRNSYS provide two different approaches, through two different sub-routines/software: CONTAM and TRNFLOW. CONTAM is the bulk airflow modelling program developed by NIST (Walton et al. 2002; Walton and Dols 2013). In TRNFLOW the multi-zone airflow model COMIS has been integrated into the thermal building model Type 56 (Weber et al.). CONTAM uses the so-called “ping-pong” approach, while TRNFLOW applies the “onion” method.

- CONTAM

The process of creating a link between CONTAM and Type56 involves three steps. The utility link to do this is called “Type 97”.

As the first step, the building’s thermal model with appropriate inputs and outputs is created using TRNBuild. The second step concerns the creation of an airflow model of the same building in CONTAM. Thirdly, the CONTAM building model and the TRNBuild building model are linked together using either the TRNSYS Simulation Studio or TRNSHELL (TRNSYS 17 2009). The process of creating a model in CONTAM involves defining zones and defining air links that connect the zones to one another and that connect the zones to ambient conditions. By using the utility link Type 97, the thermal model takes infiltration and interzonal air flows and calculates zone temperatures in return. Then Type 97 takes these zone temperatures and recalculates the interzonal airflows based on the updated information. Iteration continues until both the zone temperatures and the interzonal air flows converge upon a solution.

- TRNFLOW

TRNFLOW is the integration of the multizone airflow model COMIS (Conjunction of Multizone Infiltration Specialists) into the thermal building module of TRNSYS (Type 56). The data for both models can be input with the enhanced user interface TRNBUILD.

Using air mass conservation in each node, a system of nonlinear equations is built and solved to determine the node pressures, and the mass flows. Four classes of nodes are used to define the airflow network: constant pressure nodes, thermal air nodes, auxiliary nodes, and external nodes. It is important to notice that TRNSYS distinguishes between zones and air nodes. TRNFLOW interacts with the air nodes, not zones. Cracks, window joints and openings, shafts as well as ventilation components like inlets and outlets, ducts and fans represent the links among nodes (University of Wisconsin 2005). For each type of connection, there exists a relationship between the flow through the component and the pressure difference across it. The driving forces of the flow are, as always, wind pressure and buoyancy (resulting from temperature and air composition differences). On the latter, specifying the height of each air node and air-link to each other is important in order to account the pressure distribution correctly.

3.2.5. IDA-ICE

In IDA-ICE the thermal model is fully integrated with the airflow network. As the other BES tools, each thermal zone is schematized as an air-node, which represent the conditions of the room. The information available is not only the temperature but also the humidity and the CO_2 ratio for each thermal zone. Wind and buoyancy driven airflows through leaks and openings are taken into account via a fully integrated airflow network model (Kalamees 2004).

IDA-ICE handles a wide range of simulation problems by using equation-based modelling adopting a variable time-step differential-algebraic (DAE) solver. The model library of IDA-ICE is written in Neutral Model Format (NMF), a common format of model expression that allows users to interconnect different modules, as well as develop sub-routines directly in the programming interface. The link concept also allows a user of a simulation environment to connect sub-models at the interface level rather than variable by variable (Sahlin et al. 1996). IDA-ICE provides three different user interface levels; at the most advanced one, the "Mathematical" level, the models can be changed and own models can be written by using the NMF language. Among the different components available, there is a specific component for

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modelling DSF, called “Double-Glass Façade”. This component, which will be discussed in chapter **Feil! Fant ikke referansekilden.**, is in practice a node (representing the indoor air of the cavity) connected to the thermal-airflow network of the entire building, as well as to all the other objects (surfaces, blinds) that constitutes the DSF. This air-node can be linked to other nodes of the thermal-airflow network according to the need of the user, and can, therefore, represent in a relatively easy way different configurations of DSF. Because of this feature, the simulation of a DSF in IDA-ICE through the establishment of an ad-hoc, thermal-airflow network (as seen in all the previous software tools) is, to some extent, not very different than the use of the dedicated sub-component.

3.3. DSF Component

In addition to the modelling strategy where an airflow network is combined with a thermal network to represent the cavity of the DSF, and to connect the component to the outdoor and indoor environment of the building, some software directly integrate a sub-routine dedicated to the modelling of DSF systems. These sub-models follow in the category of building envelope systems and are object linked to the other components of the simulated environment according to the requirements and possibilities set by each of the simulation environment. While on the one hand this approach should lead to more accurate simulation (as the models for DSF are on-purpose developed to replicate the thermal-fluid behaviour of these systems), on the other hand, this approach is usually less flexible than the one where an ad-hoc, combined thermal and airflow network is created by the modeller.

3.3.1. EnergyPlus

A dedicated component is available in *EnergyPlus* to simulate ventilated glazed cavities, under the name “Airflow Windows”. The component models only forced airflow between glass panes. It can run in five different modes, i.e. supply, exhaust, indoor air curtain, outdoor air curtain, and dual airflow window (U.S. Department of Energy 2018). In this simplified configuration, the convective heat transfer coefficient from the glass pane to the air gap is calculated as the combination of the glass-to-glass heat transfer coefficient for non-vented (closed) cavity and the effect of the mean air velocity in the gap. The mean temperature of the gap air is calculated as a function of the inner glass surfaces' temperature and the inlet and outlet air temperature, and the change in the temperature across the height of the window is calculated using a logarithmic correlation between the height of the cavity and the air temperature. The modelling approach implemented through this model is, therefore, a simple analytical model when it comes to the airflow calculation algorithm, coupled with a quite detailed modelling when it comes to heat transfer in the window assembly. The entire module is then linked to a larger BES tool (*EnergyPlus*) based on combined thermal and airflow networks. One of the major limitations of the current module is that only mechanically ventilated cavities can be modelled, and therefore the airflow rate needs to be given as input (either as a fixed value or as a variable value through a schedule).

In the case of a shading device installed in the cavity, the software allows to couple this component with a detail thermal model, which accounts for the thermal interactions between the shading layer (shade, screen or blind) and the adjacent glass. It is assumed that the shading device is centred between the two panes of glass so that the airflow is divided equally between the two gaps.

3.3.2. TRNSYS

The official releases of TRNSYS do not contain any dedicated DSF component model. However, due to the architecture of the software, which allows add-on sub-routines to be realized (primarily in Fortran, C, C++, or more in general, any other language provided a DLL can be created), some researchers have developed on-purpose Types, which perform as a plug-play codes, that model DSF systems (Safer et al. 2005, 2006; Gavan et al. 2007).

In these studies, a DSF was modelled with single glazing as the external façade and internal double-glazing with internal Venetian blinds as solar protection. The whole model was divided into a series of temperature nodes with balance equations to calculate convection exchanges between the air of the channel and glazing; short/long wave exchanges and enthalpy exchanges between the air of each band are also considered.

However, while the descriptions of the models can, up to some extent, be found in the published article, the codes are often not released together with the publications, and therefore not easily accessible.

3.3.3. IDA-ICE

A separate component called “Double-Glass Façade” exists in IDA-ICE (Equa AB 2013). The integrated double façade model is based on specified leakage areas at the top and bottom of a window system. The leakages represent the systems openings and the airflow through them is based on air pressure differences between the façade cavity and the external environment. It should be noted that the program accounts both for thermally driven airflow through the cavity and wind effects. The model can however also be run to represent a mechanically ventilated system, by imposing a known airflow rate, which then overwrites the automatically calculated airflow based on natural mechanisms.

The window detailed calculation method makes a layer by layer computation of multiple reflections. Entering direct and diffuse short-wave radiation is absorbed first by the outer window plus possible curtain, and then by the inner window. The external convective heat transfer coefficient is calculated using the equations given by (Clarke 1985).

The component has been investigated with comparative and empirical tests under the IEA SHC Task 34 (Kalyanova and Heiselberg 2008). It is fully integrated with the thermal and airflow network of the rest of the building. Natural airflow through the air gap is driven by the density difference between the gap and ambient air and the wind. All airflows can have arbitrary directions, and through the connection to other components (e.g. HVAC), it is possible to apply an induced flow into the cavity. The component creates a wall adjacent thermal zone in which the air mass, the moisture and CO_2 balance are conducted.

The software also conducts a heat balance at the level of the inner wall, in which is accounted the convection between the interior glass and the air node of the cavity. Accordingly, to which is the dominant flow (natural or forced convection), the software chooses the appropriate convective heat transfer coefficient. Convection from surfaces is treated non-linearly using a standard IDA-ICE function called *u_film* for natural convection. The forced convection is calculated as a function of the airspeed and dominated one from natural and forced convection is selected with a maximum function.

4. Capabilities and limitations of BPS tools in modelling DSFs

4.1. Methodology

In this section, a collection of selected simulation studies focusing on the modelling of DSFs through a BES tool is presented. The systematic review was conducted by mean of the scientific literature databases (i.e. SCOPUS and Google Scholar), coupled with a chain-sampling technique. The following keywords were used to identify the primary documents in the search: “Double skin façade”, “DSFs”, “Simulation”, “BPS” and “name of the software”. Identified papers investigating only the energy use of the system, without taking into account in the analysis of any parameters related to the thermal/airflow domain (e.g. temperature, mass flow, air velocity, etc.) (Leigh et al. 2004; Sala and Romano 2011; Marinosci et al. 2011; Seferis et al. 2011; Cheong et al. 2014; Shan 2014; Barecka et al. 2016; Fantucci et al. 2017) were also included in the review, as well as few, selected studies where interesting modelling approached for opaque ventilated cavities were investigated, to provide the readers with a wider overview of the possibilities and challenges of these systems.

At first, the analysis was restricted only to a time period ranging from 2011 to 2018, in order to catch the latest development in the field. However, by applying this criterion, it was noticed that the reference collected did not fully cover the five software tools previously identified. For this reason, the search was later extended to publications dating back until 2000. This decision has probably reduced the degree of novelty of the studies analysed, but it also allowed to track the evolution of some tools (for example, *EnergyPlus* and *TRNSYS*), as well as to unveil trends in the use of one software or another. Notably, it is possible to see that *ESP-r*, very used in the early years of the Millennium, when it was one of the very few codes available, has been in the latest years is less and less used compared to the other simulation environments.

4.2. Overview

The focus of the review of the selected simulation studies presented in the section is primarily placed on the analysis of the choices of the modelling strategy and the different parameters in the simulation environment. The studies reported in this review are listed in Table 2, and discussed in the following section, by grouping them according to the BES tool used for the simulation instead of using other categories (such as the type of DSF with respect to the geometry or the airflow type), and by placing them in chronological order. The selection of studies does not aim to comprehend all the analysis appeared in the literature, as it is almost impossible to assure full coverage of available studies, but rather to be fully representative of the different adopted modelling strategies, the variety of DSF configurations analysed, and the large spectrum of study's objectives (the reason of the study). In particular, this last aspect, which can give some insights into the use of one or another type of BES tool, will be deepened further in Section 4.9 with the information provided in Table 3.

The review also reports if validation of the simulation study results through comparison with experimental data has been done. It is herewith important to highlight that calibration and validation of the model, which are two distinct procedures, aiming at two different scopes, are sometimes blurred into a single activity. This makes it complicated to understand what is the actual performance of the simulation tools when predicting the behaviour of a DSF system without a calibration process – something that it is not always possible.

However, it is important to remember that it is not the aim of this paper to compare the software tools in terms of performance, nor in terms of usability. The scope of the review is instead to obtain an overview of the different possibilities and challenges (as identified by the modellers and by the authors) of different implementations of DSF modelling in BES tools, as well as to review current practices in the use of different BES tools in the simulation of DSF systems.

4.3. Key elements searched in the simulation studies

When it comes to the key elements of the review of the selected studies, it is evident that the modelling of a naturally ventilated cavity is most difficult one (Kalyanova and Heiselberg 2008), as the uncertainty in the modelling regards not only some simulation's assumptions, like the number of thermal zones in which the cavity needs to be divided but also other issues related to the heat transfer phenomena and the airflow modelling. These aspects still need a more detailed study as only a few studies deepened them (Charron and Athienitis 2006; Eicker et al. 2008; Kim and Park 2011b; López et al. 2012; Mateus et al. 2014; Khalifa et al. 2015).

The heat transfer phenomena is a complex problem that has to take into account the simultaneous action of conduction, convection and radiation heat exchange. One of its most challenging aspects is the determination of the convective heat transfer coefficients, both internal and external. The choice of the internal convective heat transfer coefficient is fundamental for the estimation of the air velocity, and greatly affects the overall performance of the DSF, in particular when a shading device is present in the cavity.

On the side of the airflow modelling, the main challenge is probably to set or estimate the appropriate discharge coefficients and pressure loss coefficients for each part of the DSFs, and to estimate the correct relation between pressure loss and airflow rate through the opening, especially when the DSFs is connected with the outdoor air. It is challenging to find alternative values to the default ones offered by the software, which are not always suitable to model the pressure drops in a DSF.

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Table 2 Overview of papers analysing the performances of double skin facades

BPS	Reference	Year	Climate (Koppen-Geiger)	Transparent Opaque	Type of DSF	Cavity width	Shading devices in the cavity	Cavity Ventilation (N, M)	Type of analysis (Thermal/Visual/Airflow)	Method of Modelling (DSF component vs T+A network)	Airflow rate or airspeed	Nr. of thermal zones	Validation of Results
EnergyPlus	(Kim and Park 2011b)	2011	Dfa	T	Box Window	50 cm	X	N	T, A	T+A network	max 0.16 m/s	3	Yes
EnergyPlus	(Choi et al. 2012)	2012	Dfa	T	Multi Storey	NA	-	N	T	T+A network	NA	1[1]	Yes[2]
EnergyPlus	(Soto Francés et al. 2013)	2013	Bsk	T	Box Window	NA	-	N	T	DSF component	NA	NA	Yes
EnergyPlus	(Papadaki et al. 2013)	2013	Csa	T	Corridor-type	100 cm or more	X	N	T	T+A network	Buffer zone or 6 ACH	NA	Yes
EnergyPlus	(Le et al. 2014)	2014	Cfa	T	Box Window	50 cm	X	N	T, A	T+A network	NA	3	No
EnergyPlus	(Mateus et al. 2014)	2014	Csb	T	Box Window	20 cm	X	N and M	T	T+A network	0.11 m^3/s [3]	3	Yes
EnergyPlus	(Anđelković et al. 2016)	2016	Cfa	T	Multi-Storey	NA	-	N	T, A	T+A network	NA	3[4]	Yes
EnergyPlus	(Peng et al. 2016)	2016	Cwa	Semi-T	Box Window[5]	40 cm	X	N	T, A	T+A network	NA	3	Yes
EnergyPlus	(Alberto et al. 2017)	2017	Csb	T	Different configurations	25cm, 50cm, 100cm	-	N	T, A	T+A network	NA	NA	No
EnergyPlus	(Abazari and Mahdavinejad 2017)	2017	Bsk	T	Box Window	NA	X	N	T	DSF component	NA	NA	No
EnergyPlus	(Kim et al. 2018)	2018	Cwa	T	Box Window	44cm	X	N	T, V	T+A network	NA	4	Yes
ESP-r	(Barták et al. 2001)	2001	Cfb	T	Multi Storey	NA	X	N	T,A	T+A network	0,7 m/s	1[1]	No
ESP-r	(Leal et al. 2003, 2004a)[7]	2003	Csb	T	Box Window	NA	-	N	T,A	T+A network	0,4 m/s	1, 2, 4 or 8[6]	Yes
ESP-r	(Kokogiannakis and Strachan 2007)	2007	Cfb, Csa	T	Multi Storey	10 cm	-	M	T,A	T+A network	NA	NA	No
ESP-r	(Leal and Maldonado 2008)[7]	2008	Csb	T	Box Window	NA	-	N	T,A	T+A network	0,4 m/s	4	Yes

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ESP-r	(Høseggen et al. 2008)	2008	Cfb	T	Multi Storey	NA	-	M	T	T+A network	NA	3	No
ESP-r	(Qiu et al. 2009)	2009	Cwa	T	Box Window[5]	60 cm	-	N	T,A	T+A network	min 0,08 m/s max 0,7 m/s	4	Yes
ESP-r	(Marinosci et al. 2011)	2011	Cfb	O	Multi Storey	24 cm	-	N	T,A	T+A network	0.12 m/s	3	Yes
ESP-r	(Seferis et al. 2011)	2011	Csa	O	One Storey	4 cm	-	N	T,A	T+A network	NA	3	Yes
ESP-r	(Fantucci et al. 2017)	2017	Cfa	O	One Storey	5 cm	-	N	T,A	T+A network	NA	3	Yes[8]
IES-VE	(Pekdemir and Muehleisen 2012)	2012	17 climates	T	Different configurations	2 ft -3 ft - 4 ft	-	N	T, A	T+A network	NA	NA	No
IES-VE	(Pomponi et al. 2017)	2017	Am, Cfb	T	Multi Storey	1 m	X	N	T, A	T+A network	Max 1.7 m/s	1[1]	Yes[10]
Trnsys	(Saelens et al. 2004)	2004	Cfb	T	Box Window	NA	X	N and M	T,A	DSF component	NA	NA	Yes
Trnsys	(Eicker et al. 2008)	2008	Cfb	T	Box Window	50 cm	X	N	T,A	DSF component	Max 0.6 m/s	NA	Yes[2]
Trnsys	(López et al. 2012)	2012	Dfb	O	One Storey	5 cm	-	N	T,A	T+A network	0.15 m/s	5	Yes[2]
Trnsys	(Aparicio-Fernández et al. 2014)	2014	BSk	O	Multi Storey	10 cm	-	N	T, A	T+A network	NA	2-3[1]	Yes
Trnsys	(Elarga et al. 2016)	2015	Bwh, Cfa, Cfb	T	Multi Storey[5]	14cm	X	M in Summer, N in Winter	T, A	T+A network	NA	2[1]	Yes
Trnsys	(Khalifa et al. 2015)	2015	Csb	T	Box Window	30 cm	X	N	T, A	T+A network	20 - 60 m^3/h	6	Yes[11]
Trnsys	(Khalifa et al. 2017)	2017	Csa	T	Box Window	30 cm	X	N	T, A	T+A network	NA	6	No
Trnsys	(Yu et al. 2017)	2017	Dfa	T/O	Multi Storey[5]	50 cm	-	N	T,A	T+A network	NA	NA	No
Trnsys	(Shahrestani et al. 2017)	2017	Cfb	O	-	15 cm	-	N	T,A	T+A network	NA	1	Yes
IDA-ICE	(Gelesz and Reith 2015)	2015	Cfb	T	Box Window	80 cm	X[9]	M	T	DSF Component	NA	NA	No
IDA-ICE	(Colombo et al. 2017)	2017	Cfb	T	Multi Storey	75 cm	X	N	T, A	T+A network[12]	1.6 - 1.7 m/s	NA	No
IDA-ICE	(Eskinja et al. 2018)	2018	NA3	T	Box Window	NA	-	M	T	T+A network	NA	1	Yes

[1]For each floor.

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[2] Calibration of the model

[3]The value is referred to the mechanically ventilated DSF

[4] The facade is divided into three zones (lower (1st and 2nd floor), middle (2nd and 3rd floor) and upper (4th and 5th floor) zone)

[5] The DSF has integrated PV panels

[6] In (Leal et al. 2004a) the authors test the accuracy of a 16-zones and 4x2-zones model. While the 16-zones model performs as or better than the 8-zones model, the 4x2 ones perform worse.

[7] The SOLVENT window has been studied in different test cells. (Leal et al. 2003, 2004a) in PASSYS test cell and (Leal and Maldonado 2008) in PASLINK test cell, both in Porto, Portugal

[8] In all performed tests, simulations were carried out with artificial weather conditions, adopting constant temperature for some time and then applying a temperature gap from 0 to 35°C. The tests were performed without solar radiation or any other disturbance with the intention to isolate only one single event. Authors consider solar influence, regarding HVAC control, to be only disturbance.

[9] The shading devices are modelled only in the summer configuration

[10] Proper validation of the results has not been carried out; nevertheless, a calibration of the model with the results of a CFD analysis has been conducted.

[11] The airflow rates, since no data were available, come from the measurements presented in Saelens (Saelens 2002)

[12] The results obtained by the thermal network are coupled with a CFD analysis

4.4. EnergyPlus

Kim and Park (2011b) simulate different flow paths in a naturally ventilated box window DSF by using *EnergyPlus 6.0*. The major errors between the simulation results and actual measurements were addressed to the uncertainty of measurement and simulation input parameters, the assumptions and simplifications of the reality needed during the modelling process and the limitations of the tool. The limitations pointed out are mainly connected to the several calculation methods available for estimating the interior convective heat transfer coefficient, which does not consider the cavity airflow pattern for the calculation of the convective heat transfer. In this case, the ASHRAE Vertical Wall algorithm has been chosen. As for the exterior convective heat transfer coefficient, the authors choose the "MoWiTT" method, which is known to be suitable for very smooth vertical surfaces (e.g., windows) in low-rise buildings. It is important to underline that *EnergyPlus* also gives the possibility to calculate the convective heat transfer of the air-gap between each blind opening. However, the software simplifies the complex geometry and features of the blinds: for example, the blind opening is assimilated to equivalent hole area which leads to an inaccurate air gap velocity and the effect of the cavity air velocity on the interior convective heat transfer coefficient is ignored. The effect of the uncertainty in simulation inputs relevant to the airflow (heat transfer coefficients, leakage area, and wind pressure coefficient) in and around buildings is a potential cause of inconsistency between the simulation and measurement.

For this reason, the authors run a calibration of these parameters on the model, showing a better agreement, with the measured values. Successively Kim and Park (2011a), the authors compared these results with the ones of an in-house DSF component (written in MATLAB language) and co-coupled with *EnergyPlus*. In terms of temperature prediction, the results are more accurate because the model includes an airflow velocity term in the heat transfer coefficients expression. Nevertheless, the simulated cavity air velocity of both models does not precisely mimic the actual physical phenomena.

Similar conclusions are reached by Le et al. (2014) while studying a box-window DSF modelled under a typical hot summer and cold winter climate in Changsha via *EnergyPlus 7.0*. The paper presents a simulation method, which is suitable for designers to establish some optimal configurations of DSF. The modelled cavity has been divided into three stacked zones. The authors, as already stated by Kim and Park (2011b), identify the calculation method of the interior convective heat transfer coefficient as one of the main liability of the software.

In a similar study, Mateus et al. (2014) carry out the validation of a DSF box-window model, both naturally and mechanically ventilated, developed using *EnergyPlus 7.1*. The developed model uses an internal and external convection coefficients, the TARP algorithm, using ASHRAE correlations. In the natural ventilation mode, DSF ventilation was modelled using the effective leakage area (ELA). In both cases, the authors opted to consider only buoyancy-driven natural ventilation, without accounting the wind effects. The errors, from the measured temperature, result smaller in the mechanically ventilated configuration; yet the difference in the prediction of internal temperatures in a free running DSF is considered acceptable. In their study, they conduct a sensitivity analysis on the number of thermal zones to adopt in the modelling; the use of a single vertical thermal zone for the DSF (as opposed to three vertical zones) lead to significant increase in error in radiant temperatures. Moreover, the authors investigate the impact of solar radiation measurement accuracy on the simulations; the standard single horizontal global radiation sensor technique is proved inadequate.

In the process of establishing the best control strategy during the heating operation phase, Choi et al. (2012) carry out a calibration of the model, developed using *EnergyPlus 6.0*, of a multi-storey DSF of a building located in South Korea. Although the airflow network method is adopted, the wind pressure coefficient was calculated by using CFD, which can lead to more accurate results than by using data from wind tunnel experiments or analytic models. The whole façade was modelled as four discretised thermal zones (one per floor) with virtual horizontal openings set as always open, while the temperature measurements were referred to four vertical points. Since the software cannot account for temperature stratification in one node, the average value of the temperature recorded during the experiment was adopted in the validations process. The limitations of this tool, as well as the absence of the cavity's air velocity validation, affect the reliability of the model. In a follow-up study (Joe et al. 2013), the calibrated model is furtherly enhanced to take into account the effect of the BIPV and the catwalks present in the façade. Moreover, each storey is divided into two thermal zones rather than one. In this paper, the authors provide more information regarding which parameters adopted in developing the model (opening discharge coefficients, crack flow and air mass coefficient, interior and exterior convection algorithm, etc.).

Anđelković et al. (2016) model a multi-storey DSF of an office building in Serbia using *EnergyPlus 8.2*. The choice of some model parameters is based on the previously mentioned studies (Kim and Park 2011b; Choi et al. 2012; Joe et al. 2013; Mateus et al. 2014). The major obstacles identified in this study is the time step-resolution of the software, which is not low enough to predict the airflow correctly in the cavity. Whereas, the authors consider *EnergyPlus* to be a reliable choice when it came to the relation between simulation accuracy and the time required for the simulation.

Peng et al. (2016) developed a PV-DSF model representative in *EnergyPlus*. The interactions among thermal, power and daylighting performances were reasonably well modelled by coupling the heat-transfer model, airflow network model, PV power model and daylighting model in *EnergyPlus*. The limitation of the software in representing the inlet and outlet louvres of the real PV-DSF was overcome by adopting four openable windows with interior Venetian blinds in the PV-DSF model. This approximation was proved to be a reasonable solution by comparing the results with experimental data.

Other studies analyse the performance of double skin facades by mean of *EnergyPlus* without mentioning the challenges of the modelling process. Papadaki et al. (2013) carried out a parametric analysis to evaluate the DSFs' configuration in hot climatic condition; the outcomes show the importance of an adequate ventilation rate in the cavity. Alberto et al. (2017) conducted a parametric study performed for a DSF, applied in a building with indoor gains corresponding to office type occupation and located in Porto. The reduction of the cooling load is directly connected to reducing air temperature inside the air gap.

The possibility to implement a different numerical model was studied in the work conducted by Soto Francés et al. (2013). An opaque-façade model was integrated into the simulation code of *EnergyPlus* by using a non-dimensional approach (Balocco 2004). The model was then compared with experimental data; the significant discrepancies are found in the air velocity prediction, mainly due to the difficulties to predict the wind direction correctly. Among the simplifications adopted by the authors, the model ignores the thermal inertia of the outer layer of the façade.

4.5. ESP-r

One of the first examples of using ESP-r in analysing a DSF can be found in Barták et al. (2001) (Barták et al. 2001). The authors compared the results of different configurations of a multi-storey DSF during summer: naturally ventilated and as a buffer zone. In this case, the influence of the wind is not relevant; the buoyancy forces are the dominant driving force for the airflow. The results of their analysis show the strict correlation between the airflow in the cavity and the temperatures both in the cavity and on the panes' surfaces.

Leal et al. (2003, 2004a) study the SOLVENT prototype, a box window in which absorptive glazing with a low shading coefficient is adopted as a shading device. In summer, it is applied on the exterior side while in winter it is applied inside. A parametric study is carried out about the number of thermal zones into which the window air channel should be divided (1, 2, 4 or 8). Results show that there is the dependence of the simulation results upon the number of zones into which the window is divided. The air gap velocity and cooling needs are predicted noticeably better by the 4-zone and 8-zone models, while none of the models correctly predict the air gap temperature. It should be noted that the models do not take in consideration the effect of wind. Moreover, they investigated which heat transfer and localised loss coefficients should be adopted in order to obtain satisfying simulations results. The results show that these parameters have little effect on the accuracy of the predictions for the air temperature and the velocity in the air gap. There is, also, a perceptible overestimation of thermal inertia in ESP-r simulation, which may have a substantial impact if there is a dynamic HVAC control of the zone. In a later study, Leal and Maldonado (2008), conduct another analysis of the SOLVENT window, adopting slightly different assumptions (4 stack thermal zones, “MoWiTT” method for external convection). The developed model is then calibrated with the results of a more detailed study on the nature and quantification of the heat convection at the open air channel (Leal et al. 2004b). This improved model shows a good agreement between the measured and the calculated air velocity.

Høseggen et al. (2008) studies the performances of a multi-storey DSF on an office building in Nordic climate. The simulations predict a reduction of 20% in heating demand when a DSF alternative was used instead of a single skin façade. In order to guarantee a tolerably accurate prediction of the façade performance, the cavity convection regimes and the connection between the cavity fiction divisions were assessed. The zones are divided by fictitious transparent surfaces with high conductivity, negligible thermal mass and high emissivity, and

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coupled by an airflow-network, which also includes the inlet opening at the bottom and the top outlet opening at the top of the façade. The Bar Cohen & Rohsenow correlation is used to predict the convective heat transfer for the surfaces facing the cavity when it is open. When the cavity is closed, the default Alamdari and Hammond (1983) correlation is adopted. The paper also details on how a DSF with controllable windows and hatches for natural ventilation can be implemented in the simulation program. The operation of the window was set to depend on both the temperature in the office and the cavity of the DSF, but since in ESP-r there is no option to control two parameters at the same time, a dummy air node was introduced. This made it possible to have two openings between the indoor air node and the node in the DSF, where one represented the actual window, and other represented the negligible fluid resistance when open.

Kokogiannakis and Strachan (2007) use the EN ISO 13790 (2007) standard to set the boundary conditions for modelling and simulating a multi-storey DSF. The authors discuss the differences that might occur when the DSF is modelled using inputs mentioned in standard (e.g. fixed values of inside and outside convective and radiative heat transfer coefficients) instead of adopting values generated by a transient simulation program, such as ESP-r. For both annual heating and cooling demand, the results are lower than those obtained by the simplified ones. During the cooling season, the results between the two calculation methods differ on a larger scale (more than 50%) than of those obtained for the heating cases. Moreover, the analysis investigates the behaviour of the façade cavity works as a supply duct or an external curtain. In both cases, regarding heating and cooling demand, the external air curtain settings performs worse than the external supply.

Qiu et al. (2009) developed a model of a box window DSF with PV panels integrated. The authors divided the air cavity into four stack zones and the “MoWitt” method has been adopted to calculate the external convection coefficient. The outcomes show that the simulated temperatures of the glass and the solar electricity output are in good agreement with the measured data. The outward ventilation of the ventilated photovoltaic double skin facade could reduce the cooling load in summer and, in contrast, increase the heating load in winter. The results show a higher chimney effect, with airflow rates sensitively more significant, in winter rather than in summer.

Some studies (Marinosci et al. 2011; Seferis et al. 2011; Fantucci et al. 2017) where an opaque ventilated façade was modelled and simulated also uses the approach of multiple vertically stacked thermal zones which represented the air gap in the ventilated façade. The number of these vertical zones depends upon the total height of the gap to give a reasonable representation of the stratified air. Each zone is interconnected to the adjacent one or the external nodes by air ducts and inlet/outlet air openings. In their works, the authors carry on a thorough analysis of the convective coefficients, even though in the different correlations are adopted in the different studies. Fantucci et al. (2017), run a calibration process of the model, in which among other parameters, different convective heat transfer correlations are. MoWiTT (external surfaces), Halcrow (low vert.) correlation (Halcrow 1987) (internal surfaces) and Bar-Cohen – Rosenhow (air cavity) produce the closest results to experimental data.

4.6. IES-VE

As in the *IDA-ICE* case, not many results matched the research keywords; a reason could be the prevalent commercial use of this tool. Not many details on how the model was developed are given if not only the material and geometric properties. Nevertheless, some application of the software highlights the speed in implement models and processing information. Pekdemir and Muehleisen (2012) compare various types of naturally ventilated DSFs in all seventeen ASHRAE climate zones, obtaining results from 187 models. The different types of DSFs are created following a set of parameters such as stratification type, the permissibility of airflow, and width of interstitial space. The depth of the DSF cavity was shown to influence the performance significantly with the narrowest cavities showing higher overheating occurrences. Pomponi et al. (2017) carry on a comparative thermal comfort analysis of a whole building model with DSF in both tropical and temperate climates (London and Rio de Janeiro). *IES-VE* has been used as the main software tool, but at the same time, the accuracy and reliability of the results were also cross-checked against a computational fluid dynamic (CFD) software package. *IES-VE* seems to underestimate induced airflow rates in comparison to CFD. Trying to reduce this difference, the authors performed other simulation changing the interior heat transfer coefficient (the commonly used ‘Alamdari & Hammond’ calculation method is not suited for narrow cavities (Dickson 2004)), the discharge coefficients (the default value 0.62 is adopted by the software) and the number of zones in which the cavity is divided. On this matter, *IES-VE* itself warns not to adopt too many divisions, as it would introduce an artificial resistance to the flow field because the software algorithm does not model stratification explicitly. Nonetheless, none of the tests conducted led to significant changes in the airflow prediction. The study shows that wind force plays a dominant role in driving airstreams in and through the DSF, which highly impacts the overall thermal performance of the buildings.

4.7. TRNSYS

Some authors developed external components to couple with *TRNSYS*. Saelens et al. (2004) (Saelens et al. 2004) highlights the significance of the inlet temperature as a boundary condition for numerical DSF models. Especially when the air flowing through the cavity is to be reused, a correct inlet temperature modelling is of significant importance to come to reliable energy assessments. A numerical model, of both mechanical and natural ventilation, based on a finite volume method, is developed externally and then coupled with the BPS tool *TRNSYS*. Eicker et al. (2008) implemented their model, with a new experimentally derived empirical Nusselt correlation, in Type 111. Experiments on a box window were done both in the laboratory and in a real office-building project in Germany. From the experiment results, the authors were able to calculate the heat transfer coefficient to use in the building simulation. The simulation results show that the air gap velocity, calculated using this coefficient, is a good approximation to the measured value.

In the other papers found in literature, the thermal model is coupled with the airflow network. Khalifa et al. (2015) coupled CONTAM with *TRNSYS* to evaluate the thermal/ventilation performance of a single-storey naturally ventilated DSF (provided with a shading device). The modelled temperature distribution was validated against experimental results, showing a maximum error of 3%. The differences occurring can be contributed to the combined effects of error propagation due to simplification in geometry and lack of accuracy in some boundary conditions. The enhanced radiation modelling, provided by *TRNSYS* version 17 plays a key role and shows very good results in estimating solar radiation, both in winter and summer. As for the airflow rates, since no data were available, the results were compared with the measurements presented in another study (Saelens 2002), an experiment on which the whole paper is based on. Some limitations were found in estimating the blind influence by using the shading factor defined in TYPE 56; it may not be so appropriate in the case of Venetian blinds where the complexity expected in airflow and shading modelling imposes further requirements. By using the same validated model, Khalifa et al. (2017) assess the impact of the inner layer composition in a double-skin façade system on the energy requirements of conditioned office buildings. The results show that using a high thermal mass is beneficial in both winter and summer.

Elarga et al. (2016) run a comparative analysis of the cooling energy performance of a DSF integrated with semi-transparent PV cells inside the façade cavity. Both naturally and mechanical ventilation has been modelled using TRNFLOW, in different climate conditions. In developing the transient model, the authors adopt characteristic flow parameters commonly found in the literature (Charron and Athienitis 2006) and international standards (American Society of Heating Refrigerating and Air Conditioning Engineers 2007). The comparison of the measured values of the exhaust air temperature from the cavity and *TRNSYS* calculated results shows a good approximation. The integration of PV system shows positively affect the building sensible cooling energy demands and in increasing the peak production power. Yu et al. (2017) conduct a similar study on a double skin façade with integrated PV panels in South Korea. The model uses both TRNFLOW and a specific DSF-PV component, Type 568 (TESS 2014) to calculate no convective and radiative losses at the back of the PV collector. This module allows to calculate the PV production and to model the heat through the rear of the PV. As in the other study, in terms of heating load, a PV-DSF is a better solution regarding using a double skin to prevent an increase in the cooling load. The positive influence on PV production of coupling a PV system with a ventilated opaque façade is also showed in Shahrestani et al. 2017). In order to obtain a more accurate simulation, the air cavity on the back of each PV module is defined as a single zone with thermal interaction with each other as well as the PV modules. The airflow network was modelled in TRNFLOW and it was coupled with the multi-zone model in *TRNSYS*.

In assessing the energy performances of an opaque façade, López et al. (2012) carry out an in-depth analysis of the parameters that mostly affect the thermal model coupled with TRNFLOW. Starting from the data collected from the experiment conducted in the Indoor Environmental Engineering Laboratory of the Department of Civil Engineering of the Aalborg University, the authors carefully calibrate the model. The experimental results showed that the flow rates induced in the façade cavity were due to mixed driving forces: wind and buoyancy.

In order to replicate these effects in the model, the pressure coefficient (Cp), the discharge coefficient (Cd), the convective heat transfer (interior and exterior), are evaluated from the measured data. Comparing the results of the modelling, the air and surface temperatures were predicted with better accuracy than flow and energy rates, even if the cavity airflow conditions were predicted correctly. If these precautions are not taken, not always the results are satisfying. The study conducted by Aparicio-Fernández et al. (2014), which use a TRNFLOW to model a multi-storey opaque naturally ventilated façade, shows the difference from the experimental data. The deviation from the mean distribution of the measured air temperature in the cavity is between 15% and 20%.

4.8. IDA-ICE

In the three studies of *IDA-ICE* found in literature, there is no deep description of how the DSF models have been built, neither of which parameters have been chosen; yet for the thoroughness of the review, they have been reported. Gelesz and Reith (2015) used *IDA-ICE* model for DSF to compare the energy effects of choosing a DSF over a traditional double glazed pane. They used the “double façade” component to model two configurations of DSF, one set as a buffer zone in winter conditions and the other one as a ventilated cavity with shading devices for summer analysis. Eskinja et al. (2018) investigate the air temperature in the cavity using the airflow network approach. In their analysis, the authors compared the results with the experimental results of a scaled system, showing a great disagreement about the results. In another study, Colombo et al. (2017) the thermal network is coupled with an external CFD simulator. In the iterative process, the results from the BES tool, at first performed with approximate values, are used as boundary conditions for the first CFD simulation that yields the flow field, the temperatures of the air and the heat fluxes to and from the façade components. The second iteration uses these heat fluxes instead of the initial approximate values to improve

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the BES tool estimation, yielding increasingly accurate values for the surface temperatures as input for the following CFD computation and so on until convergence is reached.

4.9. Summary of use of BES tools for DSF simulations

The review of the selected studies reveals that there is not a clear dependence on the selected BES tool and the type of DSF investigated. This information shows that BESTs are relatively flexible tools for the analysis of DSF systems, as different configurations can be modelled and simulated within the same environment. The only exception to this is represented by the dedicated DSF models implemented in EnergyPlus and in IDA-ICE. Both these systems are only possible for single-storey heigh DSFs; however, in IDA-ICE it is possible to connect in stack more DSF modules to create a multi-storey system – though the suitability and correctness of this modelling approach need to be further investigated. When it comes to EnergyPlus, it is also important to highlight that the use of the airflow window module is only possible in case of mechanically ventilated facades.

The use of an on-purpose modelled airflow-thermal network is the most common approach, and the most general one, which guarantees good flexibility in terms of characteristics of DSF. In this approach, one of the biggest challenges for the modeller is to decide the numbers of thermal zones to represent the cavity. The collection of studies shows that there is not a standard approach when it comes to this issue, and the number of zones usually ranges from a minimum of one thermal zone up to a maximum of six (referred to one storey DSF). The number of thermal zones adopted is usually driven by the limitation of the software and by the long computational time connected to a large number of divisions.

Moreover, analysing the data collected from these studies is not possible to identify a clear pattern between the tool chosen and the scope of the conducted analysis, as highlighted by the overview given in Table 3. The choice of the BES tool to be used is frequently the first step in

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the planning of the simulation task. This choice is, very often, not due the possibilities and limitations of one simulation environment in comparison to the others, especially in a panorama where all the tools are still under development and are pointing towards very similar goals. On the contrary, the decision to adopt one tool or another is more likely to be linked, as in the professional sector as in the research sector, to the previous expertise of the modeller, the availability of the tool (in terms of licence, if not open-source), as well as the possibility to have easy access to information (such as reference materials, technical documentation, and first-hand experience on the use of the tool).

Table 3 Correlation between BES tool adopted and the analysis conducted

	Energy Plus	**ESP-r**	**IDA ICE**	**IES VE**	**Trnsys**
Thermal, airflow or daylight analysis of DSF	(Choi et al. 2012) (Le et al. 2014) (Mateus et al. 2014) (Anđelković et al. 2016) (Peng et al. 2016) (Abazari and Mahdavinejad 2017) (Kim et al. 2018)	(Høseggen et al. 2008) (Qiu et al. 2009) (Marinosci et al. 2011) (Seferis et al. 2011)	(Colombo et al. 2017) (Eskinja et al. 2018)	(Pekdemir and Muehleisen 2012) (Pomponi et al. 2017)	(Saelens et al. 2004) (Eicker et al. 2008) (Khalifa et al. 2015) (Elarga et al. 2016) (Yu et al. 2017) (Shahrestani et al. 2017)
Energy Performance of DSF	(Choi et al. 2012) (Le et al. 2014) (Peng et al. 2016)	(Kokogiannakis and Strachan 2007) (Høseggen et al. 2008) (Qiu et al. 2009) (Seferis et al. 2011)	(Gelesz and Reith 2015)		(Elarga et al. 2016) (Yu et al. 2017) (Shahrestani et al. 2017)
Parametric study	(Kim and Park 2011b) (Papadaki et al. 2013) (Alberto et al. 2017)			(Pekdemir and Muehleisen 2012)	
Sensitivity analysis	(Kim and Park 2011b) (Papadaki et al. 2013) (Alberto et al. 2017)	(Fantucci et al. 2017)			(Saelens et al. 2004) (Khalifa et al. 2017)
Design or operation support of DSF	(Choi et al. 2012)	(Barták et al. 2001) (Høseggen et al. 2008)			(López et al. 2012) (Elarga et al. 2016)
Study of modelling approaches		(Leal et al. 2003, 2004a)			(Khalifa et al. 2015) (Shahrestani et al. 2017)

		(Kokogiannakis and Strachan 2007) (Leal and Maldonado 2008)			

5. Current gaps, limitations, and possibilities for future developments

The previous section of the paper has demonstrated that BES tools can be used to simulate DSFs, even if a series of limitations remain. The list of current gaps in the modelling of these facade systems with BES tools spans over a relatively large domain, which is briefly summarised in the following paragraphs.

Presently, not all of the BES analysed natively implement a capacitor node to model a glazed layer. This is due to the historical development of BES tools, which were created when a single glazed unit where standard solutions. In that case, and in case of conventional double glazed units, the influence of a capacitor node in the simulation is relatively small (Freire et al. 2011), and may, therefore, be neglected. However, in the case of a multi-layered facade, which can be characterized by three to four glass panes, and where some of them might have a thickness in the order of 1 cm (safety glass), the effect of the thermal inertia of the entire glazed package can become significant (in the order of 1 to 2 hours of delay in the peak of the heat flux). The development of more refined models for BES should, therefore, take into account this aspect, or at least deepen what is the effect of considering (or not) the inertial effect under these conditions.

A well-known effect in DSFs is that the air (either coming from the outside or the inside) can be heated up during the path in the inlet section at the bottom of the cavity, because of an overheated (due to solar irradiation) frame (Saelens and Hens 2001). The increase in the temperature of the inlet air depends, of course, on many variables, but can be in the order of few degrees, and therefore should not be neglected. While this effect can be modelled, in the case of the approach based on a combined airflow and thermal network, by injecting a certain heat gain in the thermal zone representing the inlet section of the paper (this an additional heat can be, for example, automatically calculated base on the solar irradiance), such a correction cannot be carried out in the two existing native modules for DSF modelling in EnergyPlus and in IDA-ICE.

One of the main potentials of DSFs is the possibility to dynamically change the airflow path in order to obtain the best possible behaviour by these systems, depending on the different boundary conditions. The modelling (and control) of a variable airflow path is not an easy task when the DSF is implemented in BES tools in the form of a combined thermal and airflow network. Moreover, when it comes to the existing stand-alone module in EnergyPlus and IDA-ICE, these capabilities become even more challenging to be implemented – in EnergyPlus, for example, only the adoption of a dedicated script for the EMS module can be suitable, yet the not trivial solution to overcome this limitation. The analysis and development of DSFs characterised by high performance can only be carried out in conjunction of advanced control systems, and the enabling of more user-friendly solutions that allow the airflow paths to be dynamically modified is, at the present, a relevant gap in BES tools that should be addressed.

Solar shading systems play a major role in the thermo-fluid behaviour of a DSF, and the type and placement of these devices in the cavity can improve or worsen the overall performance of the facade (Gratia and De Herde 2007). The placement of the shading device at the desired distance from the external/internal skin is not always an easy task, nor in the case of the dedicated modules for DSF simulations implemented in some BES environment, nor in the case of an integrated thermal and airflow network to replicate the façade cavity. Furthermore, while modelling of naturally ventilated cavities necessarily rely on the heat released by the shading devices to determine, together with other variables, the airflow rate, when mechanically ventilated cavities are modelled, the influence of the heat released to the airflow on the determination of the actual air mass rate is neglected. If this assumption can be valid for wide cavities with high airflow rate, in the case of narrow cavities characterised by relatively slow (forced) airflows such an effect might be not negligible. Improved models and modelling approaches for DSF in BES tools should, therefore, include the possibility to better specify the position of the in-cavity shading device and account for its influence on the airflow rates not only when under a natural convection regime.

For naturally ventilated facades and, to some extent, for mechanically ventilated facades too, realistic discharge coefficients (Heiselberg and Sandberg 2006) need to be used to model the inlet, outlet, and in general every section of the façade where a pressure drop can occur. The identification through a search in the literature, or experimental analysis, or more sophisticated simulations (e.g. CFD) is one of the most complex tasks that a modeller need to face when developing the DSF model. The development of more accurate and user-friendly models for DSF simulation need therefore to focus on these quantities and possibly provide the modeller with a series of “robust-enough” coefficients, capable of addressing the most common situations that can be met regarding the geometrical relationship between the openings and the cavity.

Finally, the complexity of the airflow can be far higher than what can be realistically expected as a simulation output from BES tools. Flow reversal and recirculation phenomena (Dama et al. 2017) are not uncommon in a DSF’s cavity, and especially for those naturally ventilated and characterised by being high and deep. While on the one hand it appears unrealistic to develop dedicated models directly integrated into a BES capable of fully accounting for these phenomena, on the other hands there is an almost untapped potential in the possible link (co-simulation) between models with different level of complexity (Kim and Park 2011a; Elarga et al. 2016). Future modules for DSF simulation should be constructed with having in mind the possibility to link them, through a middleware program (e.g. (Wetter 2011)) that allow data to be exchanged between the two software tools.

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6. Conclusion and recommendations

In this paper, an extensive overview of different topics related to the DSF) systems through whole-building energy simulation (BES) tools have been reported. The need to carry out reliable simulations to design a DSF lies in the higher complexity of these systems, which can represent an effective solution only when optimised and well integrated into the overall energy concept of a building. The stand-alone simulation of DSFs is of limited use when the focus is placed on the interaction between this technology and the entire building, and the simulation of DSF with BES tools represents the most comprehensive approach to support the design of highly efficient ventilated facades in the context of the building where they need to operate.

Even if the simulation of DSF in BES tools is an activity with a history of more than 20 years, there is an untapped potential in the development of dedicated sub-routines, integrated into a BES environment, to simulate these systems. While the most conventional approach to this simulation (through an integrated thermal and airflow network) presents some advantages in terms of flexibility, the resources necessary to set-up such a simulation, and the assumptions to be made over a long series of variables, especially affecting the airflow network, and in particular in the case of naturally ventilated cavities, are often a major barrier that limits the possibility of simulating with enough accuracy a DSF in a BES environment. On the contrary, the few examples of dedicated modules, natively integrated into some BES tools, are still at a young stage, and rather limited in the possibilities that they offer.

When it comes to the physical phenomena modelled in these environments, and especially in the case of the dedicated modules, it is seen that well-known gaps have not been yet implemented into the available tools. Furthermore, it is also evident from the review that a common agreement on detailed parameters to be implanted in the modelling a DSF has not been reached yet. In general, it is possible to say that modelling a natural ventilated cavity is far more challenging than when the ventilation is mechanical, due to loop generated between thermal domain and the fluid domain, and to a large number of (often unknown) parameters that affect the airflow rate, mostly driven by buoyancy forces. Among the parameters that play a role in determining the outcome of the simulation, the following ones can be listed as the most relevant: the number of thermal zones into which divide the cavity; the correlations adopted to determine the convective heat exchange coefficient; the discharge coefficient to apply to the inlet, outlet and fictitious openings of the DSF; the wind pressure effect on the airflow in the case of DSFs that are connected to the outdoor air; the shading systems' positioning, and its interaction with the airflow.

The validation of models is also a crucial aspect of the simulation of DSF in BES tools. While users of BES are very familiar with the concept of calibration and can make use of this procedure to obtain more reliable simulation output under specific conditions, it is also important to stress that the validation of models should become the best practice also when simulations are carried out with BES environments.

The future development of BES tools for the simulation of DSF systems should, therefore, focus on the following two activities. Firstly, systematic validation of existing models and approaches, by inter-software comparison between simulations of some selected representative configurations of DSFs, and reliable experimental data. Secondly, the definition, for different BES environments, of ad-hoc sub-routines, based on the extensive literature on physical-mathematical models for DSFs, in order to create specific integrated modules that are: easy to use by modeller with different degree of expertise; flexible enough to cover a wide range of configurations of DSFs, as well as, different integration with the building and building heating, ventilation, and air condition plan; planned for dynamic operations (i.e. changing the airflow path according to the need) in order to allow the study and design of DSFs as far as one of the most important aspects is concerned – i.e. dynamic control of the double skin to enhance its performance.

Finally, co-simulation may represent a large area of untapped potentials for the development of a more accurate simulation, in those cases where the BES tool alone is not enough to catch the desired level of detail because of its intrinsic nature of simulation environment aiming at the assessment of the whole building energy performance, and not at the particular thermofluid behaviour of just one component of the entire building.

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