Modelling of active solar building envelopes for cost-effective evaluation

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Abstract

Active building envelopes have provided cost reductions of 40% compared to the separate installation of solar collectors on a building envelope. However, solar building envelopes are more complex than conventional building envelopes due to their additional solar function. Firstly, the paper explains this complexity before describing methods of handling it. The focus of the simulation models is to obtain high levels of accuracy at low costs. From the development of innovative solar envelopes to the general planning and construction of solar architecture, this paper provides seven recommendations to optimize the cost-benefit ratio of simulations of active building envelopes.

Keywords

solar building envelopes, building-integrated solar thermal (BIST), building-integrated photovoltaics (BIPV), building-integrated solar systems (BISS), solar architecture

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1 INTRODUCTION AND METHODOLOGY

The active solar building envelopes discussed here are defined as multifunctional building envelopes that can convert incident solar energy, so that it can be used at another time and/or location. Such solar building envelopes offer a competitive cost-benefit ratio by providing the additional solar energy function at little extra cost when compared to conventional building envelopes. For building-integrated solar thermal (BIST) systems, it has been shown that 40% of the investment costs have been saved in two analysed BIST building projects (Maurer, Cappel, & Kuhn, submitted). This means that the additional investment cost of building a solar thermal building envelope, as opposed to a conventional building envelope plus a conventional solar thermal collector, can be 40% cheaper per square metre of collector area. Therefore, IEA SHC Task 56, for example, is currently investigating solar building envelopes.

One challenge for solar building envelopes is that their additional function makes them more complex than conventional building envelopes. This paper first analyses these challenges. From the analysis and the discussion, seven recommendations are derived for the cost-effective evaluation of solar building envelopes. Many simulation models have been presented in the past (Lamnatou, Mondol, Chemisana, & Maurer, 2015b, 2015a; Quesada, Rousse, Dutil, Badache, & Hallé, 2012a, 2012b). This paper focuses on how to model active building envelopes in order to evaluate them at low cost. Innovations will only succeed in the market, if their benefits can be quantified inexpensively. The methods and recommendations described in this paper are not limited to active solar building envelopes. They may also be helpful for other multifunctional building envelopes that do not convert solar energy.

2 RESEARCH

Compared to conventional solar thermal collectors, BIST is more complex, not only because the ambient temperature influences the solar thermal performance, but also the temperature of the building interior. Figure 1 illustrates this situation, which influences the solar thermal performance. Additionally, the energy flux to the building interior needs to be quantified, which goes beyond the conventional measurements of solar thermal collectors e.g. according to (ISO 9806).

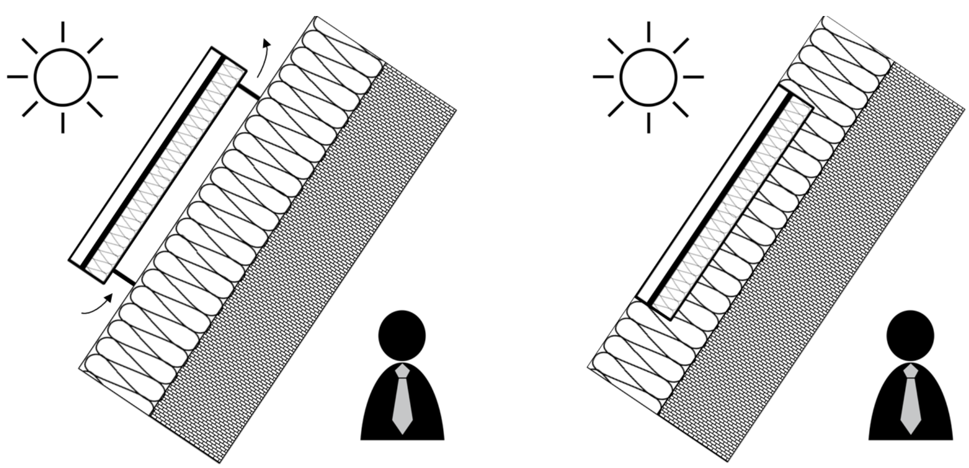

FIG. 1 Schematic drawings of a building-added solar thermal collector (left) and building-integrated solar thermal collector (right)

Compared to conventional elements of the building envelope, BIST is more complex because the heat flux through the building envelope without irradiance not only depends on the temperature difference, but also on the operating mode of the collector. This means that a constant U value does not characterize solar thermal envelopes correctly. The energy flux to the building interior with solar irradiance on the collector also depends on the operating mode of the collector. This means that a constant g value (also known as solar heat gain coefficient SHGC or solar factor or total solar energy transmittance) does not characterize solar thermal envelopes correctly (Maurer & Kuhn, 2012).

Typically, an active solar envelope will not be operated without irradiance. Therefore, a constant U value with a variable g value may work in a number of cases. However, in general, active solar envelopes can supply energy to the envelope and therefore influence the U and g values; this applies not only to BIST, but also to building-integrated photovoltaics (BIPV).

To handle this complexity, detailed physical models of active solar envelopes can be generated.

In general, a simulation model of an active building envelope includes parameters to determine the characteristics of the envelope as well as inputs from, and outputs to, the rest of the building, including the building services and the surroundings of the building. Figure 2 presents a schematic drawing of this interaction. Inputs and outputs connected to the building environment typically involve the solar irradiance and the heat exchange between the environment and the envelope. These inputs and outputs can range from simple values to very detailed data. Similarly, the inputs provided by the building interior and the output to the building interior typically involve radiance and heat transfer. Depending on the functions provided by the simulation model for the active building envelope, additional inputs and outputs, e.g. those relating to acoustics and air handling, can be used. Regarding the inputs from, and the outputs to, the building services, typical data includes information such as the control of the active envelope, the exchange of heat and electricity, as well as materials such as the supply and return of air and water. Of course, the active building envelope can consist of different kinds of building envelope components that are connected. In general, the performance of an active building envelope needs to be evaluated together with the building interior, the building services, and the surroundings, and compared to carefully chosen reference cases without this active envelope.

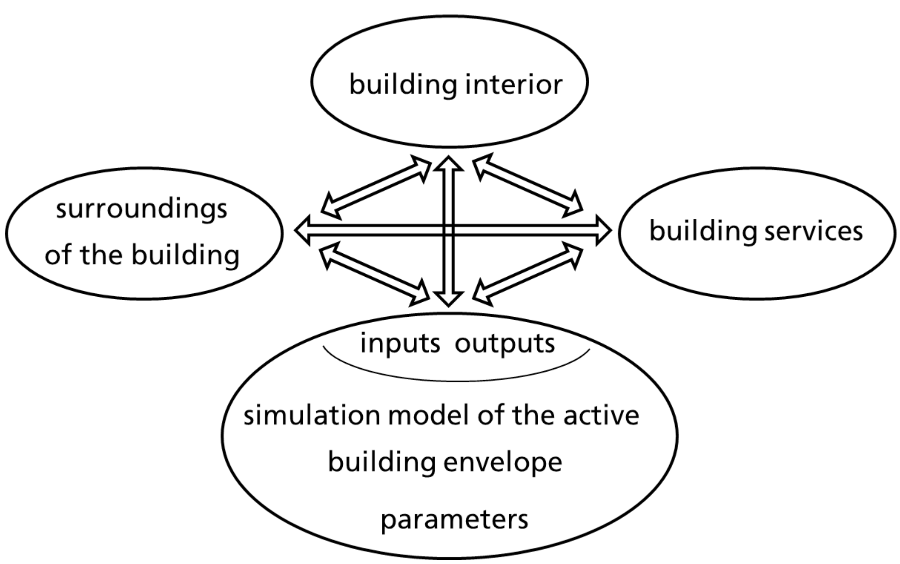

FIG. 2 Schematic drawing of the links between the simulation model of an active building envelope and the surroundings, the interior, and the building services of the building.

The energy simulation model of an active building envelope typically consists of an optical simulation, which calculates the effect of multiple reflections, and a thermal simulation with thermal nodes and energy fluxes between these nodes, as illustrated in Figure 3. Detailed physical models may involve large numbers of parameters in order to characterize all subcomponents accurately (Lamnatou et al., 2015b, 2015a; Maurer, 2012; Sprenger, 2013). One challenge can be integration of the detailed collector simulation model into an existing building simulation, especially if the source code of the building model is not accessible. For TRNSYS, (Hauer & Streicher, 2013; Maurer & Kuhn, 2012; Saelens, 2002; Saelens, Roels, & Hens, 2008) have presented different ways to connect simulation models of active building envelopes to the closed-source building model.

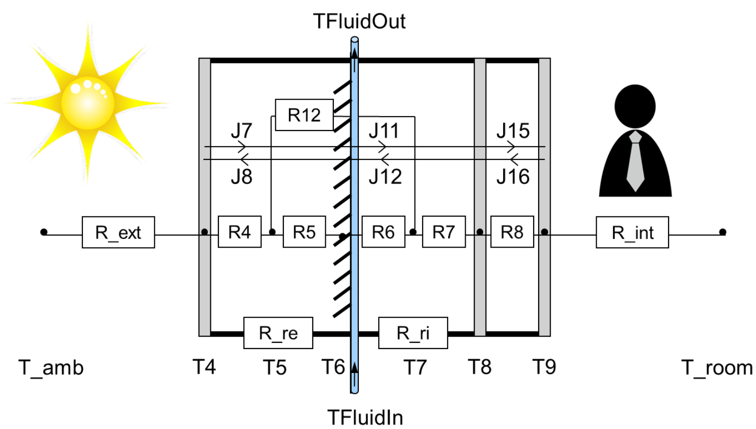

FIG. 3 Schematic drawing of a detailed physical model of a semi-transparent solar thermal facade collector with the average temperatures of the surroundings, T_amb, of the layers of the facade T4 to T9, the temperature of the interior, T_room, and the fluid inlet and outlet temperature, TFluidIn, and, TFluidOut. R indicates the thermal resistances between the layers, and J represents the infrared radiation within the element

Simple BIST models were investigated (Maurer et al., 2013; Pflug, Di Lauro, Kuhn, & Maurer, 2013) and newly developed (Maurer, Cappel, & Kuhn, 2015). Figure 4 schematically illustrates all four simple approaches. Table 1 provides an overview of the cases for which the four approaches are recommended, the inputs, outputs and parameters of the model and the data needed to calculate the parameters. All four approaches need the irradiance and the temperatures of the ambient and building interior as inputs and provide the solar thermal performance and heat flux to the building interior as ouputs.

Approaches A and B of (Maurer, Cappel et al., 2015) are recommended for cases where conventional solar thermal collectors are integrated into the building envelope and where the conventional solar thermal performance parameters for building-added solar thermal (BAST) collectors according to (Cooper & Dunkle, 1980; ISO 9806) are available.

Approach A is recommended for cases where there is a high thermal resistance between the absorber and the building interior. The parameters for the solar thermal performance of the BIST case are then calculated from the fraction of back losses and the parameters of the BAST case. The heat flux to the building interior is calculated based on the thermal resistance between the absorber and the interior.

For BIST cases with poor insulation between the absorber and the building interior, Approach B uses the BAST solar thermal performance parameters and the thermal resistances between the absorber and the back of the BAST unit, as well as the thermal resistance between the absorber and the BIST interior side, in order to calculate the BIST solar thermal performance and the heat flux to the building interior.

Approach C is recommended for special cases where data from detailed measurement of the collector performance is available for deriving the solar absorptance and the parameters of the thermal resistances.

Approach D is recommended, for example, in cases where there are new technologies with measurement data for the collector yield and the energy flux to the building interior. Approach D proposes a very simple node model with only four constant thermal resistances and solar absorptance which achieves relatively good agreement with the results of a detailed model.

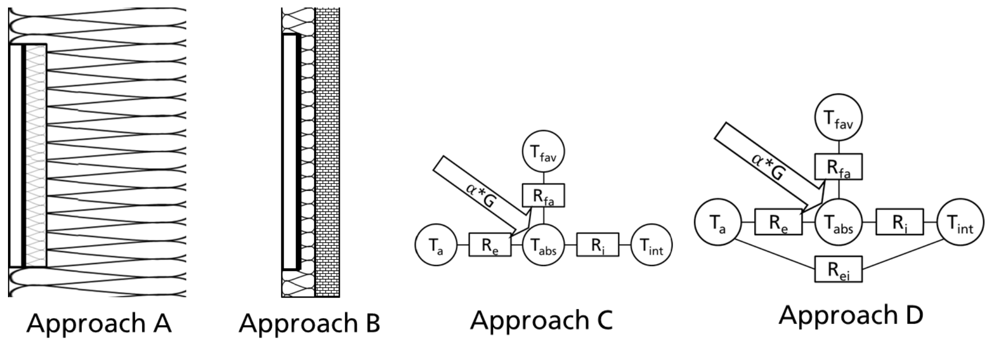

FIG. 4 Schematic illustration of the four simple approaches to model BIST

	APPROACH A	APPROACH B	APPROACH C	APPROACH D
Recommended application case	Building integration of BAST collectors		Monitoring data available	New components
	well insulated	poorly insulated		
Inputs	Irradiance, ambient and building interior temperatures			
Outputs	Solar thermal performance and heat flux to the building interior			
Data needed to calculate the parameters	3 BAST parameters, fraction of back losses, thermal resistance	3 BAST parameters, thermal resistances	Collector yield	Collector yield + energy flux to interior
Parameters	3 BIST parameters, thermal resistance		solar absorptance, thermal resistances	

TABLE 1 Data needed for the simple BIST models and recommended cases

The modelling approaches mentioned above can be extended for the description of building-integrated photovoltaic-thermal (BIPVT) elements (Maurer, Sprenger, Lämmle, & Kuhn, 2015). Simple approaches to include the photovoltaic function consider only the PV efficiency and its temperature dependence as parameters. More accuracy can be reached for low irradiance values by including the three parameters of the Heydenreich model (Heydenreich, Müller, & Reise, 2008). Very accurate models of the PV function are based on the current-voltage curve of the cells and the electric circuit between them e.g. to model the effects of partial shading. The methods for the modelling of BIPVT, described by (Maurer, Sprenger et al., 2015), can also be used for BIPV elements without solar thermal functionality.

3 RESULTS

The simulation of active solar envelopes should provide the necessary level of accuracy at lowest possible costs. The first step is therefore to analyse what level of accuracy is needed in order to choose the most cost-effective modelling approach.
Semi-empirical models are often the best choice for the evaluation of custom-built collectors or concepts for new multifunctional building envelope elements that actively convert solar energy. Semi-empirical models combine parameterized physical calculation models and specific measurements to determine unknown “fit parameters” or “model parameters”. The experimental determination of the model parameters ensures that non-ideal properties of the building envelope elements are taken into account in the evaluation. The combination of parameterized physical calculation models and measurements for the calibration of the model therefore offers the best ratio of costs to benefits in most cases.
For innovative products of active solar building envelopes, calorimetric measurements are often crucial for the validation and calibration of simulation models. To date, there is no standard that defines the criteria for a validated simulation model of a solar building component. Such a standard could increase confidence in simulation models that have been validated and calibrated according to the standard, and may also decrease the costs.

The mathematical complexity of simulation models for multifunctional building envelope elements is irrelevant as long as the models are easy to use. An important next step is therefore a user-friendly front end, integrated into a powerful whole-building energy-simulation environment. The feasibility of a “plug and play interface” has been shown for the case of semi-transparent solar thermal facade collectors (Maurer et al., 2013). Here, the semi-transparent solar thermal facade collector was represented by a TRNSYS Type with a similar user interface to other solar thermal collectors or walls. The new TRNSYS Type was used by HVAC planners to perform a complex simulation of the whole building energy demand, including the detailed modelling of the control of the technical building systems. Accurate simulation models that are easy to use make the evaluation of building envelopes cost-effective because each stakeholder can focus on his main competences.

However, different stakeholders in the building process use different simulation environments due to the very specific advantages of each. To address this issue, it is recommended to provide the same simulation model of a solar building component in all necessary (or at least in the most important) simulation environments. This is cost-effective if the models for different simulation environments can be generated automatically.
At different times throughout the building process, the multifunctional building envelope components are specified with different levels of detail, and simulations with different accuracy levels are needed. One approach is to combine, for example, a model with few inputs and low accuracy and a model with many inputs and high accuracy within one adaptive multi-environment simulation model that can switch its accuracy depending on the available input data at this stage of the building process. Adaptive simulation models reduce costs because one model can be used right from the early planning phases to the commissioning and to the facility management. At each stage, depending on the available input, the desired outputs and the acceptable computing time, the best level of accuracy is chosen. For example, a low accuracy may be acceptable in early planning phases, when only few inputs are available. In later planning phases, when more inputs are available, the adaptive model provides a high accuracy.

Building information modelling (BIM) aims to improve the exchange of data within the building process. To date, the industrial foundation classes (IFC) define a structure of text data which can be exchanged within this format. It is therefore recommended by (Maurer, Sprenger et al., submitted) to include functions in machine code in this data exchange. This could lead to greater accuracy and lower costs for the planning, construction and facility management of buildings due to the increased knowledge exchange.

4 CONCLUSIONS

Active building envelopes offer exciting advantages such as significant cost reduction when compared to the installation of building-added solar elements. However, they are more complex than conventional building envelopes with additional conventional solar elements. This paper first explained this complexity before describing methods to handle this complexity by choosing cost-effective simulation models:

1. If a simple model is accurate enough, no detailed model needs to be developed.
2. If some parameters cannot be calculated accurately enough, measurements should be performed to derive them.
3. It is recommended that a standard for the validation of simulation models of building envelopes be developed. It is then easy for companies to choose the cheapest simulation model that performs to the level of accuracy that they need.
4. Models can be detailed and accurate as long as they are easy to use. Such models save costs for the planners as well as for the owner because the simulations are more realistic.
5. The model of an innovative building envelope should be available in all relevant simulation environments, because it reduces the costs for planners to get used to a new simulation environment.
6. Adaptive models can provide an initial estimate with little input data even at early planning stages and a higher accuracy with more input data at later stages of the building process. This reduces costs by making the planning more realistic.
7. The next version of the IFC should include the possibility of exchanging models as machine code. The exchange of knowledge in the form of compiled models reduces the costs because the stakeholders can focus on their main competences.

The recommendations no. 1, 2, 4, 5 and 6 are ready to be used for simulation models, which make the evaluation of solar building envelopes cheaper.
The development of a standard for simulation models of solar building envelopes is a challenge that will require effort and input over many years.

Efficiently exchanging simulation models in machine code in building processes, from the early planning stages until the end of the lifetime of the building, is a challenge that starts today but will not be solved soon. Rather, it is a continuous task of making the building process progressively more efficient.

With these recommendations, the evaluation of solar building envelopes based on simulation models can already be made more cost-effective, with the potential for additional cost reductions in the future.

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References

Cooper, P. I., & Dunkle, R. V. (1980). A non-linear flat-plate collector model. *Solar Energy,* 26(2), 133–140. doi:10.1016/0038-092X(81)90076-1

Hauer, M., & Streicher, W. (2013). Gebäudegekoppelte Simulation fassadenintegrierter Kollektoren mit TRNSYS. *OTTI - 23. Symposium Thermische Solarenergie*.

Heydenreich, W., Müller, B., & Reise, C. (2008). Describing the World with three Parameters: A new Approach to PV Module Power Modelling. *23rd European PV Solar Energy Conference and Exhibition* (EU PVSEC), 2786–2789. doi:10.4229/23rdEUPVSEC2008-4DO.9.4

ISO 9806 (2013): International Organization for Standardization.

Quesada, G., Rousse, D., Dutil, Y., Badache, M., & Hallé, S. (2012a). A comprehensive review of solar facades. Opaque solar facades. *Renewable and Sustainable Energy Reviews*, 16(5), 2820–2832. doi:10.1016/j.rser.2012.01.078

Quesada, G., Rousse, D., Dutil, Y., Badache, M., & Hallé, S. (2012b). A comprehensive review of solar facades. Transparent and translucent solar facades. *Renewable and Sustainable Energy Reviews*, 16(5), 2643–2651. doi:10.1016/j.rser.2012.02.059

Saelens, D., Roels, S., & Hens, H. (2008). Strategies to improve the energy performance of multiple-skin facades. *Building and Environment*, 43(4), 638–650. doi:10.1016/j.buildenv.2006.06.024

Saelens, D. (2002). *Energy performance assessment of single storey multiple-skin facades* (Ph.D. thesis). Katholieke Universiteit Leuven, Leuven. Retrieved from https://bwk.kuleuven.be/bwf/PhDs/PhDSaelens

Sprenger, W. (2013). *Electricity yield simulation of complex BIPV systems*. Stuttgart: Fraunhofer-Verlag.