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Chapter

Numerical Simulation Modelling of Building-Integrated Photovoltaic Double-Skin Facades

Siliang Yang, Francesco Fiorito, Deo Prasad and Alistair Sproul

Abstract

Building-integrated photovoltaic (BIPV) replaces building envelope materials and provides electric power generator, which has aroused great interest for those in the fields of energy conservation and building design. Double-skin façade (DSF) has attracted significant attention over the last three decades due to its bi-layer structure, which improves thermal and acoustic insulation and therefore increases the energy efficiency and thermal comfort of buildings. It is hypothesised that the integration of BIPV and DSF (BIPV-DSF) would help buildings in reducing energy consumption and improving indoor thermal comfort concurrently. However, the prototype of the BIPV-DSF has not been well explored. Thus, the investigations of the BIPV-DSF are worthwhile. Numerical simulation is a cost and time effective measure for the design and analysis of buildings. This chapter spells out a comprehensive method of numerical simulation modelling of the novel BIPV-DSF system in buildings, which is carried out by using a graphically based design tool – TRNSYS and its plugins. TRNSYS has been validated and widely used in both the BIPV and building related research activities, which are capable in analysing the effects of BIPV-DSF on building performance such as energy consumption and indoor thermal condition.

Keywords: numerical simulation modelling, TRNSYS, TRNFlow, double-skin facades (DSF), building-integrated photovoltaic (BIPV)

1. Introduction

Either building-integrated photovoltaic (BIPV) or double-skin façades (DSF) is widely adopted in buildings; however, few studies or real applications of the hybrid mechanism of BIPV and DSF have been implemented in either academic or industrial settings [1]. Therefore, it is worth understanding the behaviour of this novel integrated system – BIPV-DSF. As shown in **Figure 1**, the BIPV-DSF is analogous to a typical DSF, which consists of an outer façade, an inner façade and an air cavity between the two facades; and there are ventilation openings within the BIPV-DSF [2]. However, a semi-transparent PV panel serves as the external window glazing on the outer facade of the BIPV-DSF, while the window of the inner façade is composed of a normal glazing unit. The outer façade of the BIPV-DSF provides protection against the outdoor environments and the ventilation in the air cavity is driven by the stack effect through the ventilation openings to cool the indoor area down in
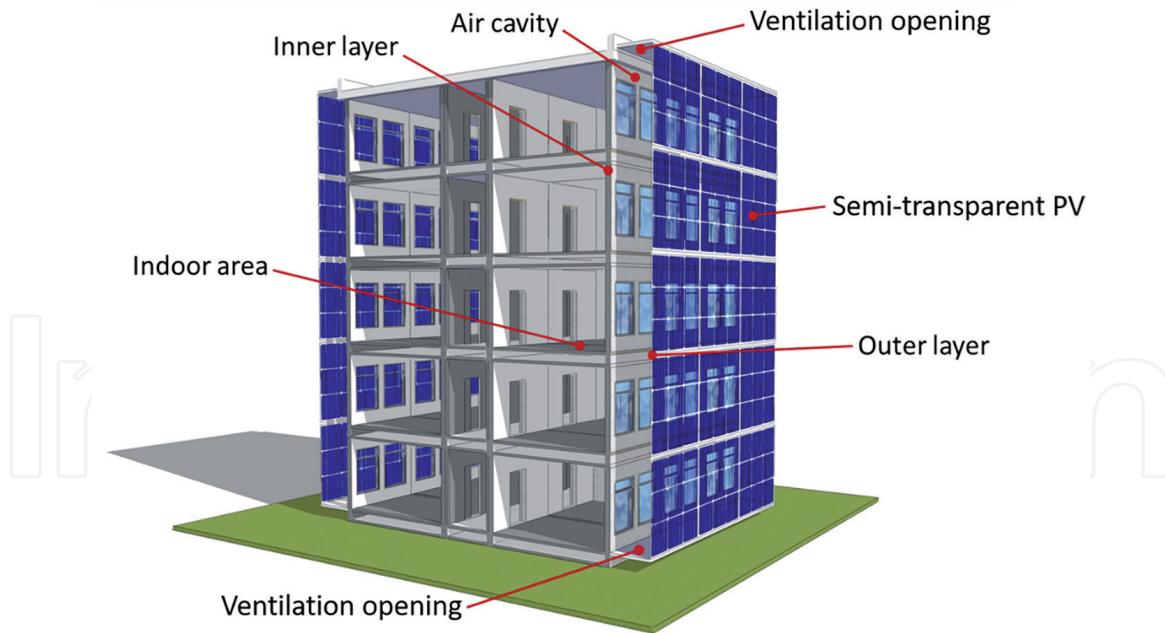
Figure 1.
Schematic diagram of the BIPV-DSF.

summer, while the openings are closed to reduce heat loss in winter, hence delivers a comfortable indoor thermal condition [2]. Moreover, the energy production (electric power generated by PV panel and thermal energy from the heated air in the cavity) can be obtained from the BIPV-DSF, which contributes to the reduction of the energy consumption of buildings.

Numerical simulation modelling of buildings and building systems has been developing and carrying out for over 30 years, during which time the accuracy, depth and speed of the simulation have been widely verified and significantly improved for the design and analysis of new buildings [3]. It has been proved that numerical simulation modelling is much more cost-effective and less time consuming than experimental study, especially for those inaccessibly experimental conditions in real life [4]. In this context, the proposed chapter presents a comprehensive method of numerical simulation modelling of the novel BIPV-DSF system in buildings.

The proposed numerical BIPV-DSF model can be used to investigate the advantages of double-skin façades and building-integrated photovoltaic technology in terms of thermal and electrical performances of the entire BIPV-DSF integrated onto buildings, which are related to indoor thermal condition and energy consumption of buildings.

2. Overview of the proposed numerical simulation modelling

TRNSYS and TRNFlow programmes are selected for carrying out the proposed numerical modelling, which are able to predict the effects of the implementation of the BIPV-DSF on building performance such as energy consumption and indoor thermal condition, based on the capabilities of the software. TRNSYS is a graphically based software, which has been validated and widely used in the BIPV and building related research activities [5–8]. In addition, TRNSYS output data files are in a (human) readable and editable plain text format, which allows users to convert dataset simulation results to Excel spreadsheet; hence, they precisely present the result plots and effectively observe the errors of simulations. Energy consumption of thermal building models and electricity productions of the BIPV

systems can be directly predicted in TRNSYS. TRNFlow is an external engine for TRNSYS for assisting in the calculation of ventilation [9], which can be integrated into the TRNSYS thermal building model (Type56) to analyse the performance of ventilation within the DSF and therefore the indoor thermal comfort due to the ventilated DSF.

3. Building simulation modelling in TRNSYS

TRNSYS was initially developed by the University of Wisconsin and the latest programme and external plugins of the software are the outcomes of international collaboration of the US, France and Germany [10]. TRNSYS and its plugins can be used for functions, such as electric power simulation, solar design, building thermal performance analysis, HVAC system sizing as well as airflow analysis [10]. TRNSYS provides a modular structure for simulating the transient systems, especially energy systems, such as solar systems (PV systems) and HVAC systems [11]. The simulation activities in this chapter are demonstrated by using the version of TRNSYS 17. The main programmes of TRNSYS 17 [11] include:

- TRNSYS Simulation Studio (**Figure 2**) – a visual interface used for model design, parametrisation and system simulation. Type 56 (the "Building" icon in **Figure 2**) includes the details of a multi-zone building model such as building geometry, load profiles, construction and window glazing properties, while the desired weather file can be uploaded in the "Weather data" component (**Figure 2**).

- TRNDII – a simulation engine of TRNSYS which is called by TRNEXE (an executable program).

- TRNBuild (as shown in **Figure 3**) – a visual interface used for creating and editing the simulation input data for non-geometry information of the multi-zone buildings.

- TRNEdit or TRNSED – an editor programme that to create stand-alone applications for proposed models.

In general, TRNSYS Simulation Studio in association with TRNBuild are used to assess energy performance of the proposed BIPV-DSF building model. In addition, as mentioned earlier, an external plugin, namely TRNFlow (as shown in **Figure 4**), is chosen for the integration with the TRNSYS thermal building model, in order to assess the performance of ventilation (for example, natural ventilation) within the DSF.

In the Simulation Studio interface (as shown in **Figure 5**), Type 56-TRNFlow (the green "Building" icon) contains the specific numerical information of the multi-zone building model, which is not only including building geometry, load profiles, construction and window glazing properties, but also including the airflow input and output values for the purpose of the simulation of ventilation.

The functionalities of those programmes of TRNSYS are implemented by using the common computer programming languages for instance "Fortran", which establishes mathematical models for the components and types (in TRNSYS) of the proposed systems in terms of their ordinary differential or algebraic Equations [12]. The general procedures of the simulation modelling in TRNSYS are as follows, in sequence:
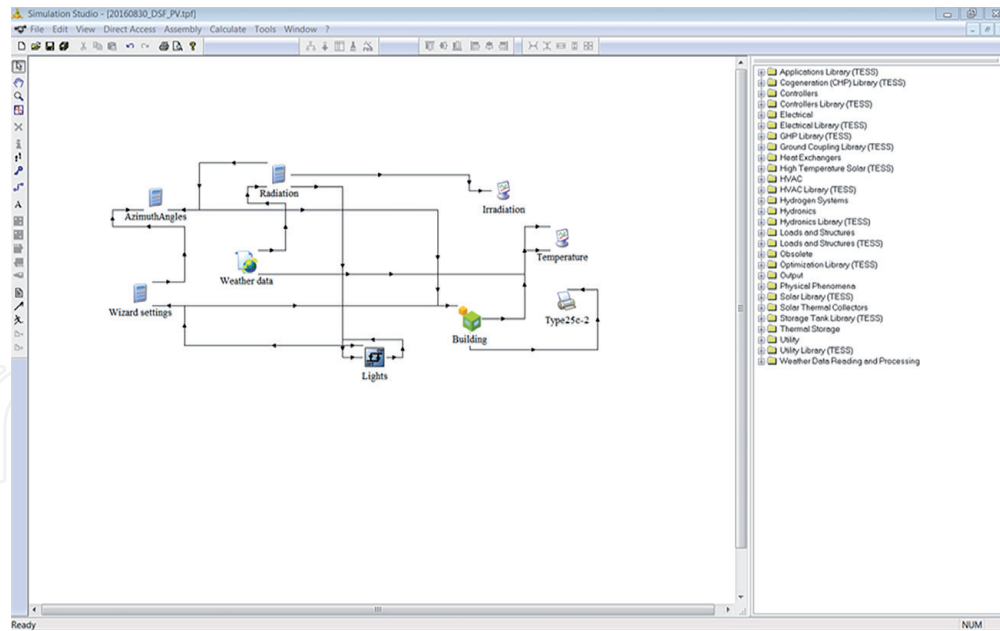
Figure 2.
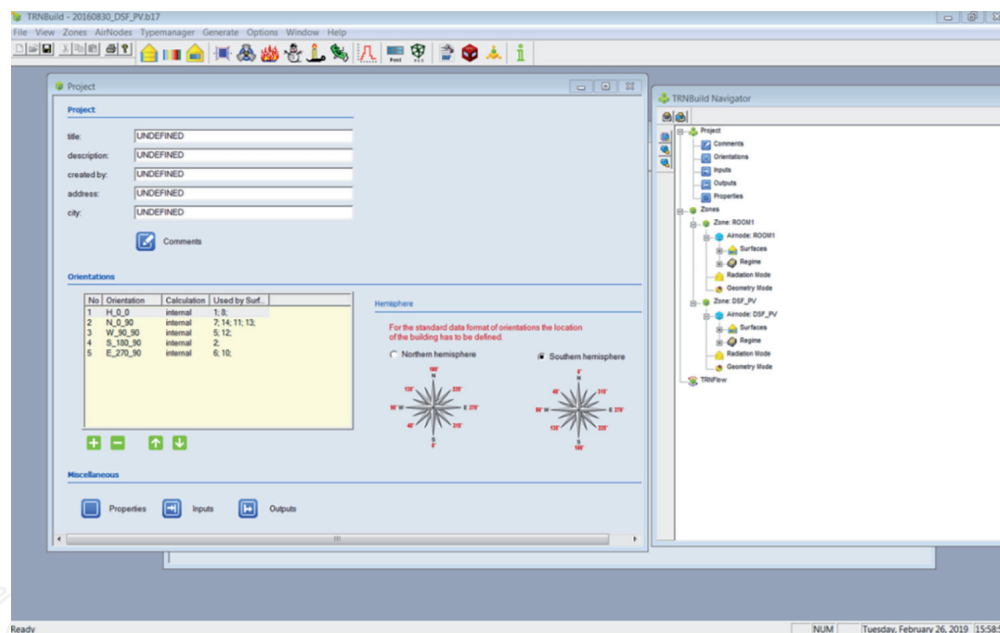*Simulation studio user interface in TRNSYS 17.*

Figure 3.
TRNBuild user interface in TRNSYS 17.

First, the user needs to identify if the available system component and the type of models of the proposed system in TRNSYS will satisfy the specific needs of the real system [11].

The simulation modelling can proceed in TRNSYS if the proposed real system can be designed by the available components and types; otherwise, the missing components and types must be created by writing the corresponding programming language such as Fortran and C++. The "type" normally consists of inputs (variables such as input temperature or airflow rate), parameters (the fixed values such as the area of solar PV panel, dimension of buildings, and so on) and outputs (the resultant values such as output temperature or airflow rate). Moreover, the "type" in TRNSYS can also include external files (for example, weather file) and derivatives which specify the initial values (for example, initial room air temperature in a building) for the "type" [11]. For the proposed BIPV-DSF building model, all the
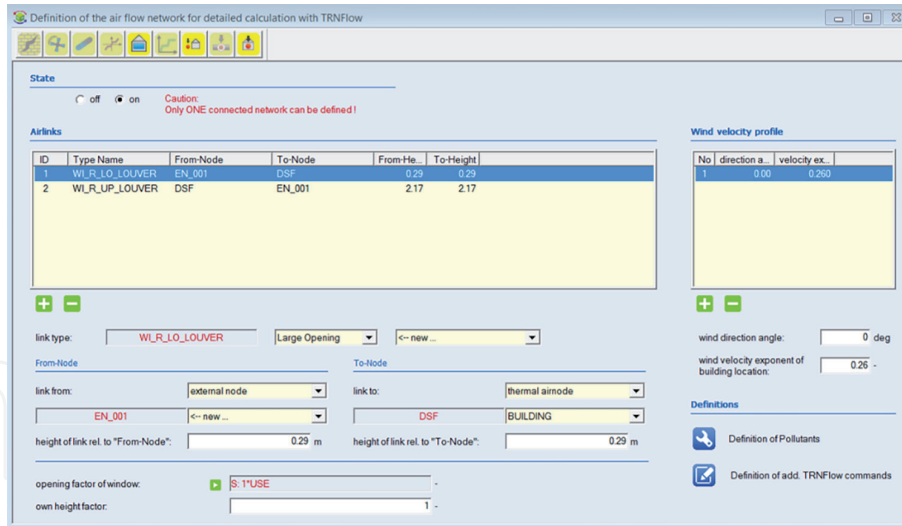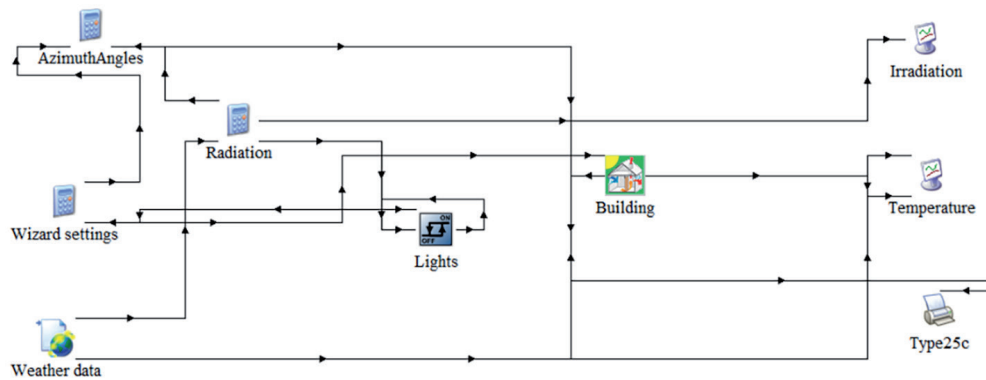
Figure 4.
TRNFlow user interface.

Figure 5.
Type56-TRNFlow in TRNSYS model.

required system components and types are available in TRNSYS 17, so the additional programming procedures are left out.

Once the components and types that represent the proposed real system are fully prepared, the system modelling can proceed in the visual interface – TRNSYS Simulation Studio. All the selected system components and types need to be connected to each other in the Simulation Studio, then the simulation parameters are defined accordingly by the user [11]. For the proposed simulation modelling (the BIPV-DSF), the building geometry information are created in TRNSYS 3D (**Figure 6**). TRNSYS 3D is a plugin for SketchUp (a 3D modelling software developed by Google) to draw 3D multi-zone buildings and export the building geometry information directly from the SketchUp interface into the visual interface of TRNBuild [13].

All the non-geometry information of the TRNSYS building model are then created and edited in TRNBuild (see **Figure 3**). The user can flexibly edit the material properties of building envelope, create ventilation and infiltration profiles, add internal gain and position occupants for the indoor comfort calculations [13].

As mentioned earlier, TRNFlow is used for the calculation of ventilation for the proposed BIPV-DSF building model. TRNFlow will work as a plug-in of TRNSYS, which can be accessed through the user interface in TRNBuild (see **Figure 7**). Basically, an airflow network of the ventilated building model needs to be created in terms of the selected airlinks (for example, the DSF and outdoor air) in TRNFlow. In detail, the model of airflow between the selected airlinks must be
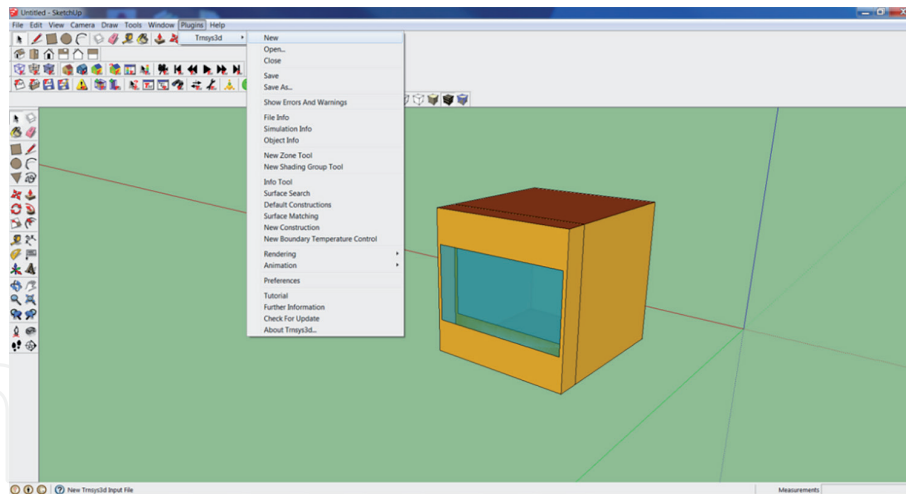
Figure 6.
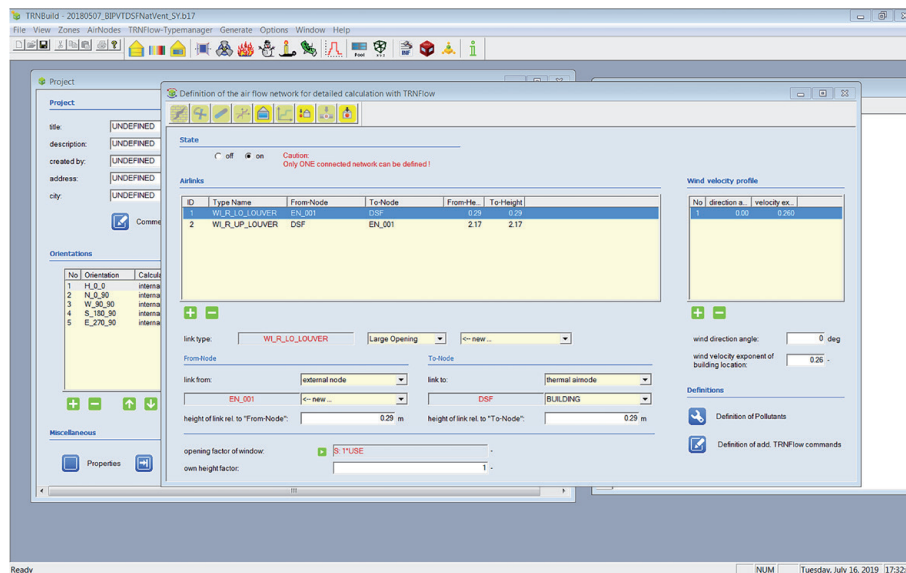*TRNSYS 3D user interface – A 3D BIPV-DSF model sample.*

Figure 7.
TRNFlow interface in TRNBuild.

modified accordingly. For the modelling of the BIPV-DSF, both the external air and DSF are linked together, in which the ventilation openings (for example, ventilation louvres) are modelled as large opening through the Link Type Manager (see **Figure 8**). There are 6-category of "links" in the selected version of TRNFlow (version 1.4) as follows:

a. Crack

b. Fan

c. Straight duct
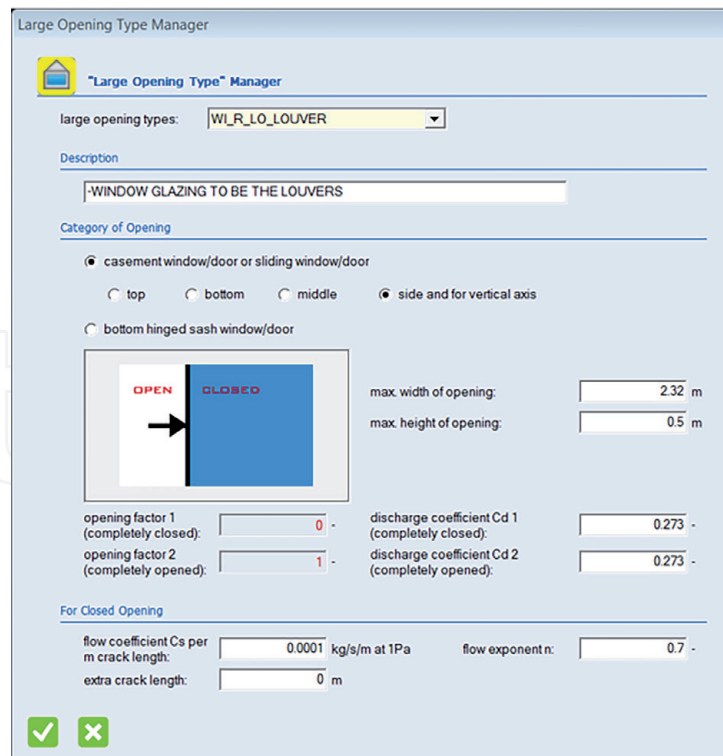
d. Flow controller

e. Large opening

f. Test data

Figure 8.
The link type manager of "large opening" in TRNFlow.

According to the TRNFlow user manual [14], "large opening" is the most fit type of link for modelling the ventilation openings.

The simulation can then be performed when all the inputs, parameters, and outputs are completely edited. The TRNSYS Simulation Studio will report errors if the connections among different components and types are not correct or logically functionable. It will also report errors if any non-geometry information is not correctly created and edited in TRNBuild. The simulation results will be printed in external files through a printer component (see **Figure 9**) or visualised in an online plotter (implemented by TRNEXE, as shown in **Figure 10**, reporting the value of solar radiation as an example) in the Simulation Studio interface [11]. In the proposed simulations of the BIPV-DSF, the online plotter (**Figure 11**) is used to view the output variables during and after the simulations for ensuring the simulations run properly, while a .OUT formatted file (**Figure 12**) as an external text file is used to print the numerical simulation results. The various numerical results can be directly copied from the .OUT file and pasted in an Excel sheet, which are then plotted as viewable graphs accordingly to simplify the analysis of the results.
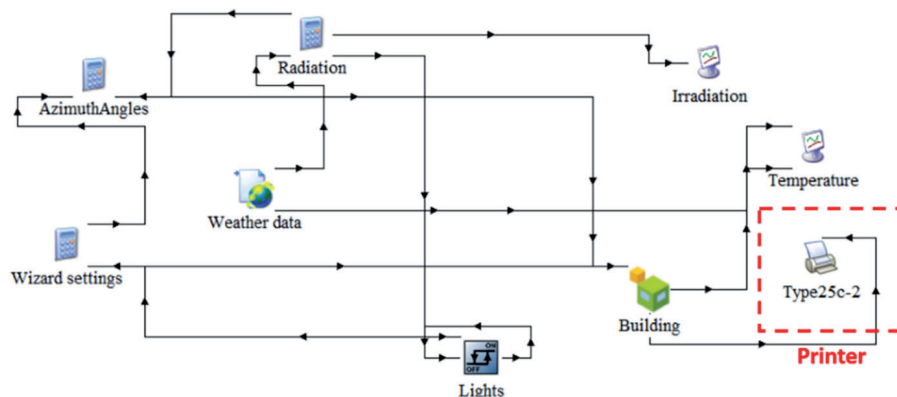

Figure 9.
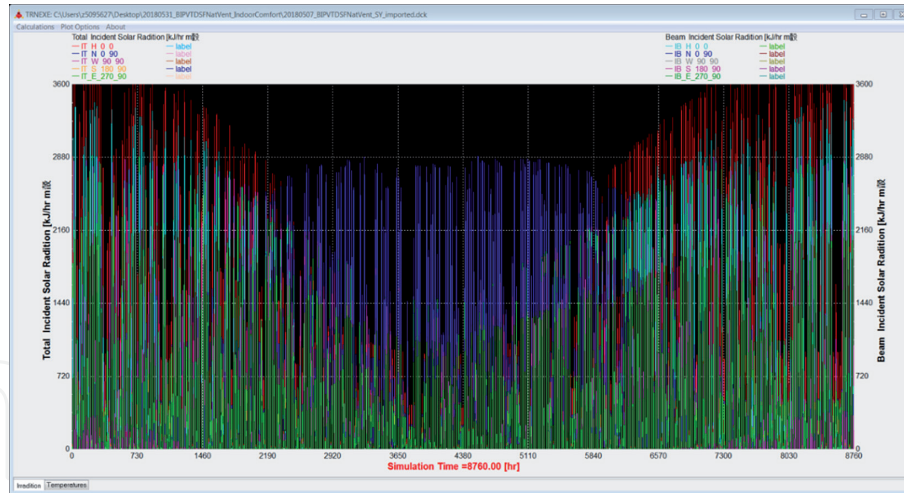*The printer that loads the external files.*

Figure 10.
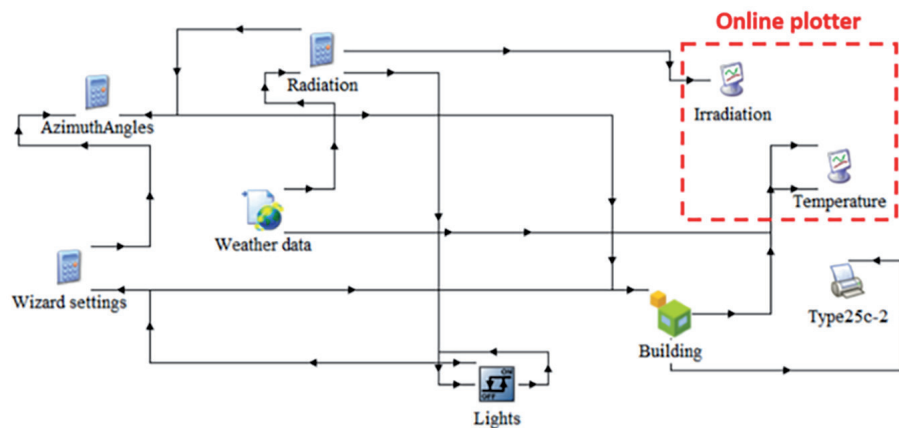*The online plotter is implemented by TRNEXE.*

Figure 11.
The online plotter as part of the simulation model.

4. The BIPV-DSF simulation modelling in TRNSYS

As specified in Section 3, the "Type 56-TRNFlow" component is adopted in the TRNSYS model, which contains the numerical information of the multi-zone building model including building geometry, load profiles, construction, window glazing properties as well as the airflow input and output values for the proposed BIPV-DSF. The numerical building information is read by the Type 56 or Type 56-TRNFlow from a set of external files having the extensions *.bui, *.bld and *.tm. These files can be generated by running TRNBuild [15]. An available weather data processor Type 15–3 in TRNSYS, which can read data in the IWEC (International Weather for Energy Calculations) format, is used to read the weather data at regular time intervals (for example, one hour for the simula-tions) from the external IWEC weather file [15]. As shown in **Figure 13**, both the "Irradiation" and "Temperature" (they both are Type 65d) are online graphical plotters that display the selected system variables (that is, solar irradiation and air temperature) while the simulation is progressing, which allows the users to immediately view the output variables; hence, they can know if the simulations run properly [15].

Type 25c is a printer component that prints the variables (for example, zone air temperature, ambient temperature and heating/cooling demand) of the proposed multi-zone building model (for example, the BIPV-DSF) at specified intervals of
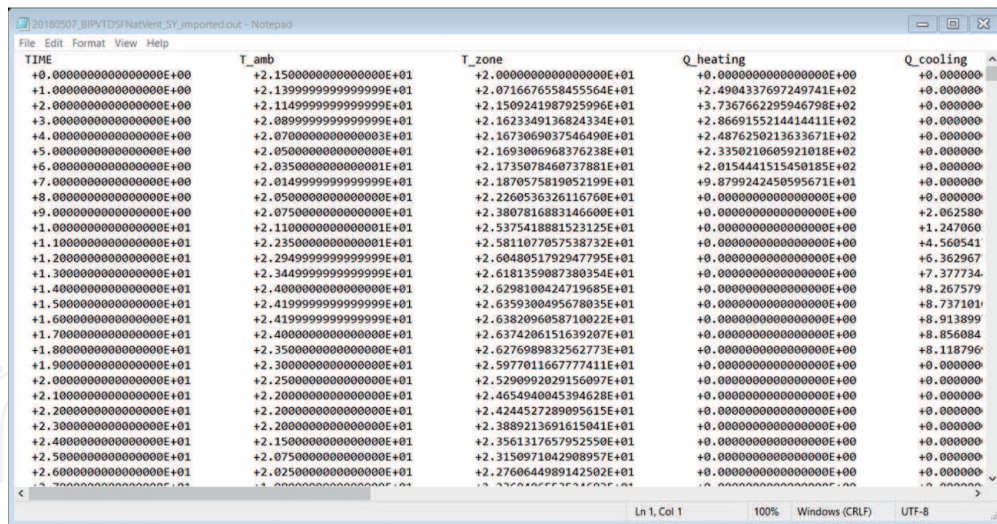
Figure 12.
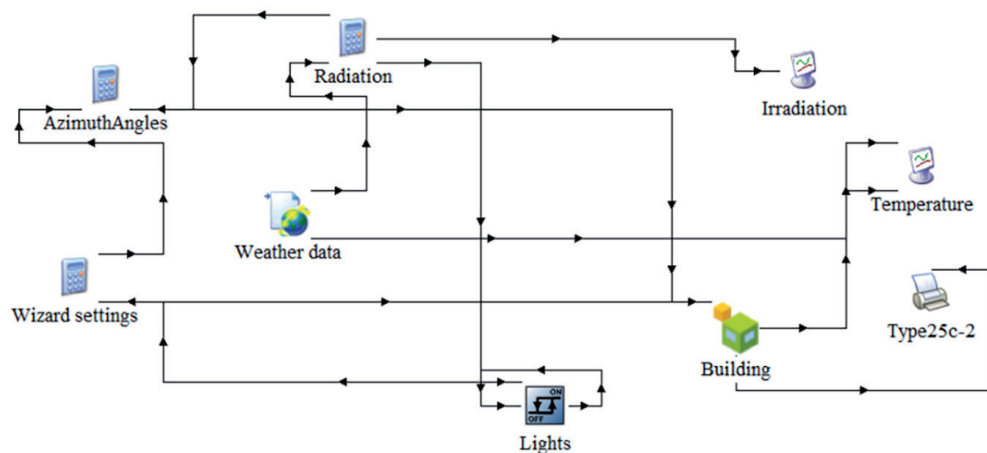*The .OUT formatted external file.*

Figure 13.
Basic model of a multi-zone building in TRNSYS simulation studio.

time [15]. In addition, as noted in Section 3, Type 25c is the available component to print simulation results to an output file (an external file), of which the numerical results can be more easily edited by exporting the values from the output file into the Excel spread sheet. It should be noted that daylight or artificial light condition analysis for the multi-zone building cannot be modelled in TRNSYS 17, so the lighting will be only considered as a part of the heat gains for the energy aspect in this case.

The "Weather data" component (Type 15–3) will send the value of outdoor luminous intensity which is directly tied to its calculation of the controllers (AzimuthAngles and Radiation) of solar radiation as shown in **Figure 13** [16]. The "Lights on–off" is an on/off differential controller that generates a control function having a value of 1 or 0 [15]. If the Lights are on, they will stay "on" until the amount of horizontal solar radiation exceeds 200 W/m^2; while if the Lights are off, then they will stay "off" until the amount of horizontal solar radiation drops below 120 W/m^2 [16]. For the proposed simulations, the "Building Wizard" type in TRNSYS Simulation Studio is selected to make faster and easier simulation processes for the multi-zone building, in which the "Wizard setting" as a calculation controller is directly created under the Building Wizard and used for adjusting the orientation of the multi-zone building in terms of the pre-defined degrees of the Z-axis [17].

The thermal and optical properties of the proposed semi-transparent PV panels can be created in WINDOW program (that is, an open access computer program for calculating total window thermal performance indices) [18] if the components of the PV panels are not available in the current TRNSYS database. Electrical productions of the PV panels are calculated separately using Type 567 which is an existing BIPV component in the Thermal Energy System Specialists (TESS) libraries. The TESS libraries (developed by TESS of Madison, Wisconsin) are the new component libraries that contain more than 250 components used in the TRNSYS simulation, in which the components are used for the simulation of PV systems, solar thermal systems, geothermal systems, HVAC systems, and so on. Each of the components has been extensively tested and has the compatible format with TRNSYS Simulation Studio environment [19]. Type 567–5 (**Figure 14**) is used to model a glazed solar collector for the numerical results of electric power and also take the collected thermal energy into consideration, which is the most suitable PV model for the simulation of the electrical performance of the proposed semi-transparent PV glazing in TRNSYS. This model type can be combined with the detailed multi-zone building model (Type 56) that provides the temperature of the back surface of the PV glazing by giving the mean surface temperature [20].

As mentioned earlier, TRNSYS has already been validated and widely used in the BIPV related research activities. Egrican and Akguc [5] calculated cooling and heating demands of an office building with BIPV building façade through TRNSYS simulation, in which the PV panel model (Type 567) was well coupled with the building façade model (Type 56). Kim and Kim [6] evaluated both the electrical and thermal performances of a building with BIPV façade by means of the simulation modelling in TRNSYS, which modelled different cases of the building façade (that is, single-skin and ventilated double-skin façades) using Type 567 as the PV panel model and Type 56 as the building model.

Kamel and Fung [7] developed a roof system model that integrated a BIPV collector with an air source heat pump (ASHP) for a residential house in TRNSYS, in which the Type 567 was selected to model the glazed PV collector and connected to the multi-zone building model (Type 56). The simulation successfully predicted the seasonal performance of the heat pump and the electricity cost savings from the PV production. Elarga et al. [8] created a similar model typology as the proposed BIPV-DSF in this chapter, and investigated the energy performance of a DSF coupled with BIPV system for an office building, but the semi-transparent PV panel
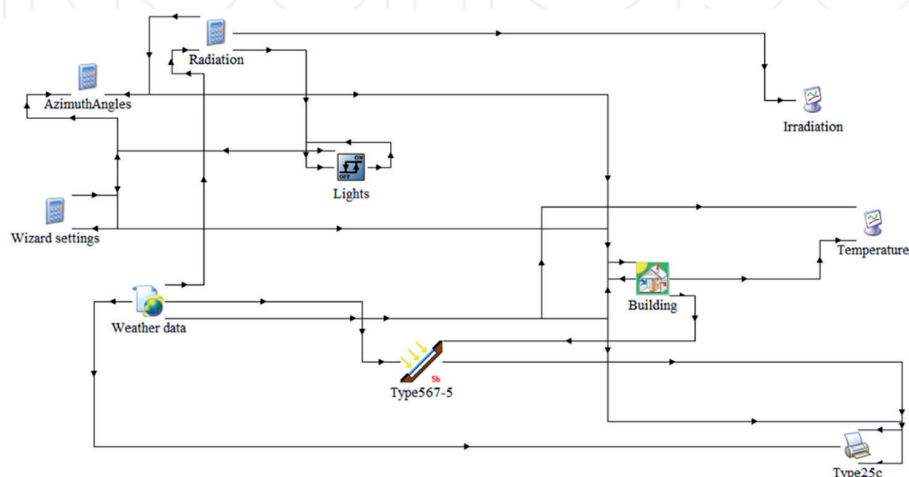

Figure 14.
Connection of Type567 and multi-zone building model in TRNSYS.

was mounted in-between the two skins of the DSF and Type 562 (it modelled the electric power of the PV only) was selected as the model of the PV panel. Also, in this case, the TRNSYS numerical model was validated against the experimental data and used for further analysis for different cases. Generally, the previous simulation studies have well proved the ability and capability of TRNSYS simulation in modelling the buildings adopt double-skin façade coupled with BIPV system, and the Type 567 is considered as the most appropriate component to model the electric and thermal characteristics of the proposed PV window glazing by coupling with the multi-zone building model (that is, Type 56 or Type 56-TRNFlow).

5. Summary of the BIPV-DSF model in TRNSYS

According to the descriptions in Section 4, the proposed BIPV-DSF model can be created in TRNSYS by employing the determined essential components and types. **Figure 15** shows a complete BIPV-DSF model with all the linked components and types in TRNSYS (Simulation Studio). The system components and types of the TRNSYS model presented in **Figure 15** are further described in **Table 1**.

"Type56-TRNFlow" is used to carry out the numerical building information of the BIPV-DSF model, which is able to model the ventilation of the façade/building model in TRNSYS Simulation Studio based on the characteristics of building geometry, while the non-geometry information (for example, building envelope properties, internal heat gains and occupancy) of the façade/building model is edited in TRNBuild.

As stated in above, the selected system components and types for the proposed TRNSYS models have already been validated and widely used in the BIPV related research activities, which can be confidently employed to perform the proposed simulation analysis.
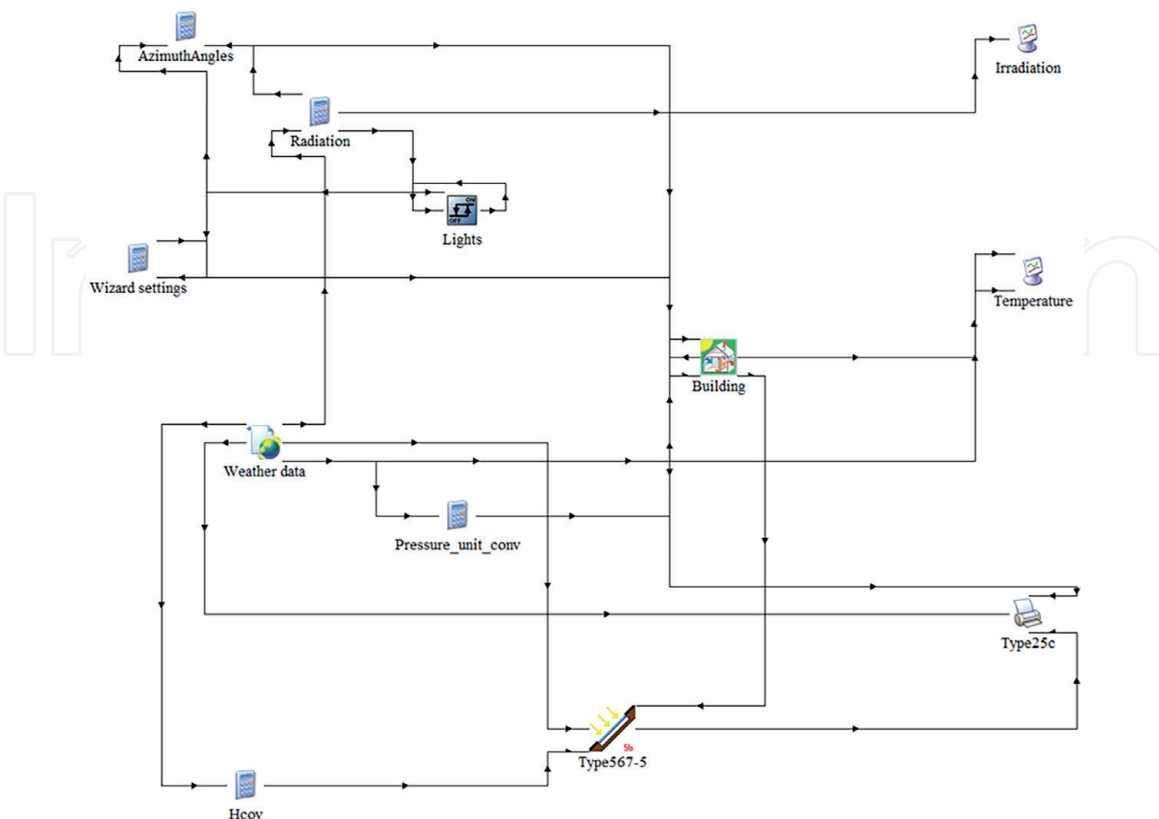

Figure 15.
Schematic diagram of the BIPV-DSF model in TRNSYS.

System components/types	Functions
Azimuth Angles	Determining solar azimuth angle
Radiation	Calculating solar radiation
Lights (Type2d)	Generating ON/OFF control functions
Wizard settings	Adjusting building orientation
Weather data (Type15–3)	Reading weather data at regular time intervals from the external weather file
H_{cov}	The convective heat transfer coefficient from the PV panel surface to ambient air
Pressure_unit_conv	Converting the default pressure unit in the Type15–3 from "atm" into "pa"
Building (Type56-TRNFlow)	Containing numerical information of building geometry, load profiles, construction, window glazing properties, airflow input and output and thermal behaviour of the building
Type567–5	The model of the PV panel
Irradiation (Type65d)	Displaying irradiation related variables while the simulation is progressing
Temperature (Type65d)	Displaying temperature related variables while the simulation is progressing
Type25c	Outputting the selected system variables at specified time intervals

Table 1.
Description of system components and types of the BIPV-DSF model.

6. Conclusions

This chapter presents a comprehensive method of numerical simulation modelling of a novel façade system – BIPV-DSF – in buildings. The proposed simulation modelling is carried out by using a graphically based design tool – TRNSYS and its relevant plugins (TRNFlow and TRNSYS 3D), and the performance of the BIPV-DSF is predicted accordingly.

It is demonstrated the applicability of the TRNSYS programme and its plugins in predicting the performance (for example, indoor thermal comfort and energy consumption) of the buildings incorporate the ventilated BIPV-DSF. The chapter also shows the applicability of TRNSYS in predicting the electric power produced by the semi-transparent PV panels, which serve as the external window glazing in the BIPV-DSF.

However, the BIPV-DSF model in TRNSYS should be further validated in order to reduce the discrepancies in-between the simulated and the actual building/façade behaviours, and therefore ensure the proposed BIPV-DSF model is created accurately and reliably. At this point, future work is supposed to calibrate the BIPV-DSF model against the real building/façade settings, hence it is possible to check validity and accuracy of the simulation results as well as to eliminate the random errors.

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