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DEPARTMENT OF THE BUILT ENVIRONMENT
AALBORG UNIVERSITY

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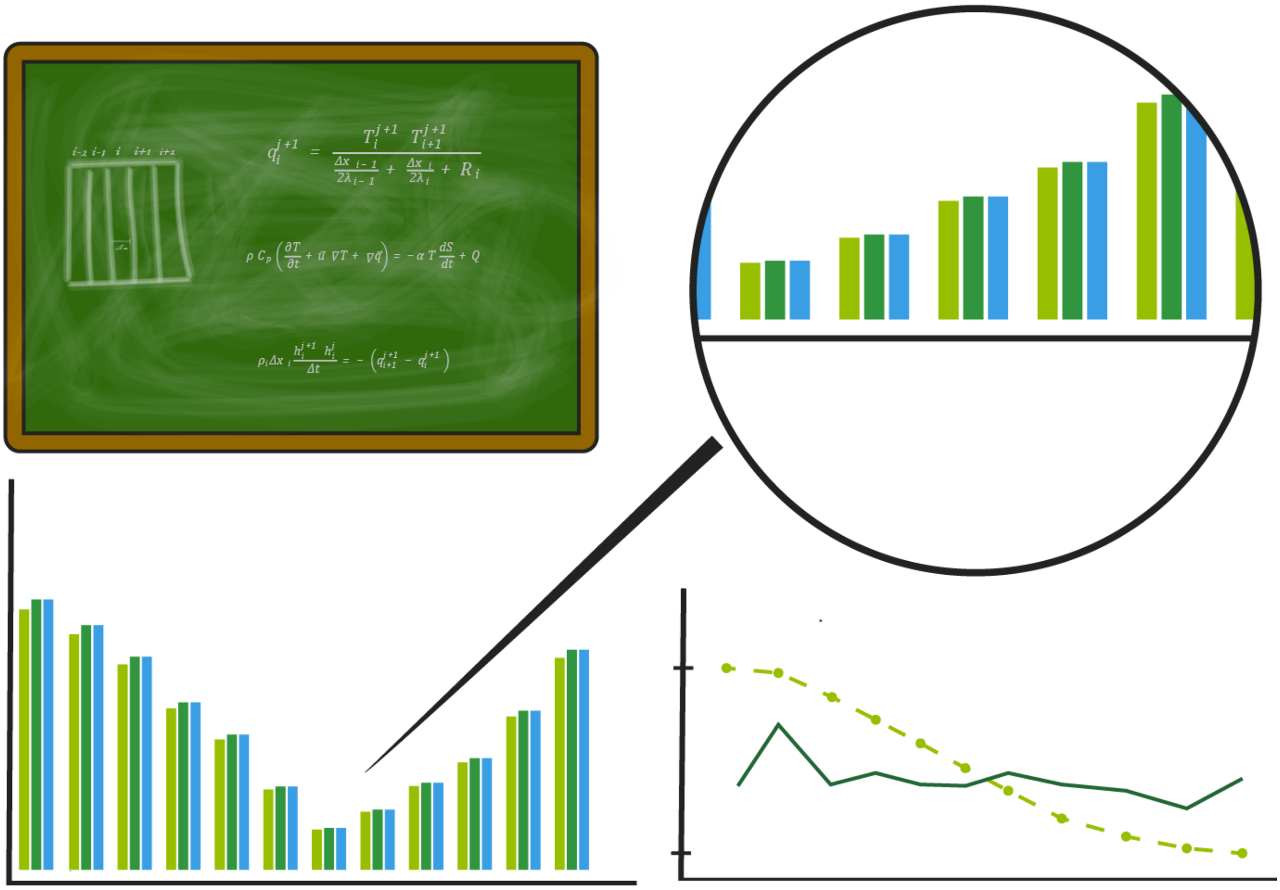

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by

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1. Foreword

The aim of this technical report is to present the results of a validation of transmission loss modelling in BSim against COMSOL Multiphysics as a reference, and to show the background for an analysis of the effects of thermal inertia conducted with BSim and Be18.

2. Summary

In this technical report, key aspects of numerical models in BSim and COMSOL Multiphysics are described along with weather data from the Design Reference Year (DRY). Based on this background, 1-dimensional heat transfer is calculated using BSim and COMSOL Multiphysics, to validate the validity of the results from the BSim model. This is done in three steps: steady-state calculation similar to the one performed in the software Be18, a dynamic calculation without solar radiation and a dynamic calculation with solar radiation. The results are compared to the calculation of transmission losses described in the standard DS418. Finally, a numerical study of a single-family house is performed, where BSim and the software Be18 are compared.

The steady-state calculation showed similar results between BSim and COMSOL Multiphysics, with a slight deviation caused by a round-off error in BSim. A manual calculation based on the method described in the standard DS418 showed identical results to the COMSOL Multiphysics calculation. Furthermore, the temperature profiles computed from BSim and COMSOL Multiphysics showed great similarities, with a maximum temperature deviation of $0.05\ ^\circ\mathrm{C}$.

The dynamic calculation without solar radiation, performed on 300 mm insulation material, showed high similarities between BSim and COMSOL Multiphysics, while the manual calculation from DS418 deviates significantly from these results. This is due to the lack of inclusion of thermal mass in the simple calculation in DS418. This deviation reduces when a calculation transmission loss is performed on a construction element with 30 mm insulation.

The dynamic calculation with solar radiation, was performed for multiple days and insulation thickness, and showed good comparability between BSim and COMSOL Multiphysics. The highest deviation occurred for the simulation of a construction element with 30 mm insulation on the 7th of March, which is the winter day in the used weather data with the highest amount of solar radiation.

The results from BSim and COMSOL Multiphysics are in good agreement, therefore validating the correctness of the BSim simulation results.

The description of the study case includes the different systems used, material properties and properties of the windows. The aim of the study was to see if the thermal inertia of the materials contributed to a lower transmission loss when running a dynamic simulation, compared to the steady-state calculation used in Be18. The validation between BSim and Be18 showed similar results for transmission loss, while there is a higher deviation between the models regarding venting and infiltration loss. The result indicates that detailed simulation with dynamic hourly calculations like in BSim, is not essential for obtaining a realistic performance of the building energy consumption for heating. The effects of occupancy or more complex control strategies might affect this conclusion.

3. Description of software and weather data

This section will describe some general information regarding the calculation in BSim and COMSOL, along with a short description of the weather data used in the numerical analysis.

3.1. BSim software

BSim is used to quantify heat transport through a construction element for this study. BSim is software that is used to simulate and analyze the indoor environment in a building. It includes the possibility of exploring the thermal, visual and atmospheric indoor environment. It can consist of hourly environmental values of multiple parameters and their interaction with the construction and installations. BSim uses a quasi-stationary calculation method. It uses Fourier's law to stationary calculate the 1-dimensional heat transport through each material, accounting for the gain or loss in enthalpy of the material itself for multiple time steps. Since the heat transport is considered stationary, Fourier's law can be simplified by using central difference approximation, see equation **(1)**. The quasi-stationary calculation is done until convergence is reached. The equation for calculating heat transport is shown in **(1)**.

$$q_i^{j+1} = -\frac{T_i^{j+1} - \Delta T_{i+1}^{j+1}}{\frac{\Delta x_{i-1}}{2\,\lambda_{i-1}} + \frac{\Delta x_i}{2\,\lambda_i} + R_i} \tag{1}$$

q	Heatflux	$[\mathrm{W/m^2}]$
T	Temperature	$[\mathrm{K}]$
x	Width of control volume	$[\mathrm{m}]$
λ	Heat conductivity of material	$[\mathrm{W/(m\,K)}]$
R	Resistance between control volumes	$[\mathrm{(K\,m^2)/W}]$
i	Index for position in layer	$[-]$
j	Index for time	$[-]$

When applying the quasi-stationary calculation method, it is necessary to discretize each construction element's layers into control volumes in which the temperature is calculated for each node, illustrated in **Figure 1**.

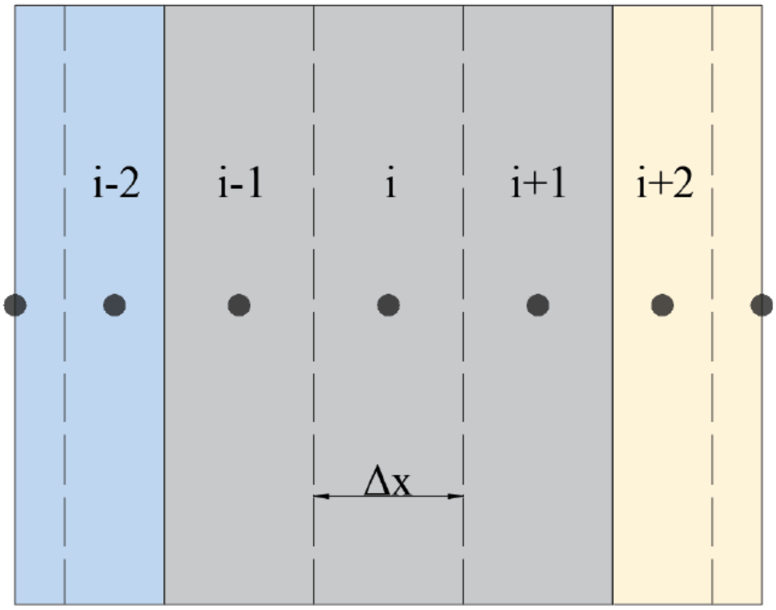


Figure 1. *BSim calculation method by the use of Fourier's law.*

When accounting for the enthalpy in the material, BSim uses equation **(2)**, which makes BSim account for the thermal storage properties of materials. An increase in the enthalpy will increase the temperature in the given node.

$$\rho_i \, \Delta x_i \frac{h_i^{j+1} - h_i^{j}}{\Delta t} = -\left(q_{i+1}^{j+1} - q_i^{j+1}\right) \tag{2}$$

ρ_i	Density of material	$[\mathrm{kg/m^3}]$
h_i	Specific enthalpy for the control volume	$[\mathrm{J/kg}]$
Δt	Size of time step	$[\mathrm{s}]$

By knowing the model's boundary conditions, the external and indoor temperature, and radiation on the external and internal surfaces, the heat transport of a construction element can be calculated with high accuracy. The accuracy depends on the discretization of the material and the size of the time step. Therefore, it is crucial to do a time-step analysis to check for convergence.

When BSim calculates the transmission loss, it bases the transmission loss for the construction element on the heat flux from the thermal zone to the node in the first control volume from the inside. Therefore, it is possible to have a case where the outdoor temperature is above the indoor temperature, but the construction element still experiences a transmission loss.

Before BSim starts the quasi-stationary calculation, it makes sure that the material has reached a steady-state condition close to the first step size of the quasi-stationary simulation. It is done by doing preliminary model calculations for up to 50 days or when stabilization is achieved. The BSim model is considered steady-state when the temperature in the 14th hours compared to the previous day is deviating less than 0.1 °C. Additionally, it starts with a temperature inside the materials of 10 °C.

It must be mentioned that the majority of the output parameters in BSim are based on the latest value every hour. [1]

3.2. COMSOL Multiphysics software

COMSOL Multiphysics is a software that is used to simulate and design in all fields of engineering. It is capable simulating single-physics problems and also combined physics in multiphysics problems. The geometries can be drawn in 1D, 2D and 3D and solve the problems as a steady-state or time dependent problem. The equations in COMSOL Multiphysics are solved using the Finite Element Method. [2]

In this case, where the transmission loss through a construction is considered, the physic heat transfer in solids is used. Moreover, the physic surface-to-surface radiation is used to take the radiation from the ambient into account. The differential equation COMSOL solves for the heat transfer in solids is shown in equation **(3)**.

$$\rho \, C_p \left(\frac{\partial T}{\partial t} + \vec{u} \, \nabla T + \nabla \vec{q}\right) = \alpha \, T \frac{dS}{dt} + Q \tag{3}$$

ρ	Density of material	$[\mathrm{kg/m^3}]$
C_p	Specific heat capacity	$[\mathrm{J/(kg\,K)}]$
T	Absolute temperature	$[\mathrm{K}]$
$\vec{u}$	Velocity vector	$[\mathrm{m/s}]$
$\vec{q}$	Heat flux vector	$[\mathrm{W/m^2}]$
α	Coefficient of thermal expansion	$[\mathrm{kg/m^3}]$
S	Second Piola-Kirchhoff stress tensor	$[Pa]$
Q	Additional heat sources	$[\mathrm{W/m^3}]$

In steady-state conditions the time derivatives are eliminated. The first term after the equal sign is the thermoelastic damping and it accounts for thermoelastic effects in solids.

The theory and the equation to solve for surface-to-surface radiation uses the assumption that the surface is opaque, which means that no radiation is transmitted through the body. The opaque assumption is a valid assumption for most solids. In all the discretized points on the surface that is exposed to radiation will have incoming irradiation, *G*, and outgoing radiosity, *J*. The radiosity is calculated as given in equation **(4)**.

$$J = \rho_d \, G + \varepsilon \, e_b(T) \tag{4}$$

J	Radiosity	$[\mathrm{W/m^2}]$
ρ_d	Diffuse reflectivity	$[-]$
G	Irradiation	$[\mathrm{W/m^2}]$
ε	Emissivity	$[-]$
$e_b(T)$	Stefan Boltzmann Law	$[\mathrm{W/m^2}]$
T	Surface temperature	$[\mathrm{K}]$

Stefan Boltzmann law can be seen in equation **(5)**.

$$e_b(T) = n^2 \, \sigma \, T^4 \tag{5}$$

n	Refractive index	$[-]$
ρ_d	Stefan Boltzmann constant	$[\mathrm{W/(m^2\ K^4)}]$

The net inward radiative heat flux is the difference between the irradiation and the radiosity, and is calculated using equation **(6)**.

$$q = (1 - \rho_s) \, G - J \tag{6}$$

q	Net inward heat flux	$[\mathrm{W/m^2}]$
ρ_s	Specular reflectivity	$[-]$

By combining equation **(4)** and **(6)**, radiosity, *J*, can be eliminated and the inward radiative heat flux, *q*, can be expressed as a function of the irradiance, *G*, and the surface temperature, *T*:

$$q = \big(1 - (\rho_d + \rho s)\big) \, G - \varepsilon \, e_b(T) \tag{7}$$

With the assumption of the body being opaque, it also behaves as a grey body which means that the absorptivity and the emissivity are equal, and therefore the reflectivity follows the relation shown in equation **(8)**:

$$\alpha = \varepsilon = 1 - (\rho_s + \rho_d) \tag{8}$$

From this relation equation, **(7),** can be simplified to equation **(9)**:

$$q = \varepsilon \, \big(G - e_b(T)\big) \tag{9}$$

Equation **(9)** will then be used as boundary condition when COMSOL is solving equation **(3)**. [3]

3.3. DRY weather data

The numerical study uses DRY-weather data as boundary conditions for the outdoor weather parameters. DRY stands for Design Reference Year and contains hourly mean values of weather parameters. The values are gathered from weather stations in Denmark based on the period from 2001 to 2010. DRY weather contains mean values of the weather parameters, making it a typical weather data set. [4] The outdoor parameters included in the DRY-weather data set are listed in **Table 1**. The following subsections provides information about the parameters in the DRY weather data.

Table 1. *The parameters included in the DRY weather data, with data sampled between 2001 and 2010.*

Parameter in DRY weather data	Unit
Outdoor temperature	$[°C]$
Cloud cover	$[-]$
Atmospheric pressure	$[Pa]$
Diffuse radiation	$[W/m^2]$
Direct radiation	$[W/m^2]$
Absolute humidity level	$[kg/kg]$
Relative humidity	$[\%]$
Sky temperature	$[°C]$
Solar altitude angle	$[°]$
Solar azimuth angle	$[°]$
Wind direction	$[°]$
Wind speed	$[m/s]$

3.3.1. Outdoor temperature

Table 2. *The outdoor temperature based on hourly DRY weather data.*

Month	Maximum $[°C]$	Minimum $[°C]$	Mean $[°C]$
January	4.9	-7.8	0.7
February	6.7	-10.3	0.4
March	13.1	-15.0	-0.7
April	19.7	-0.4	7.1
May	22.6	4.0	11.5
June	25.8	4.2	14.2
July	27.5	8.8	17.8
August	27.7	8.2	17.9
September	27.3	4.5	14.5
November	15.9	1.0	9.8
October	11.7	-7.8	3.4
December	6.9	-14.8	0.7

3.3.2. Wind direction and speed

The wind direction and speed are measured in the height of 10 meters above the ground level. The wind direction, along with its frequency and the magnitude of the wind speed, is illustrated in **Figure 2**.

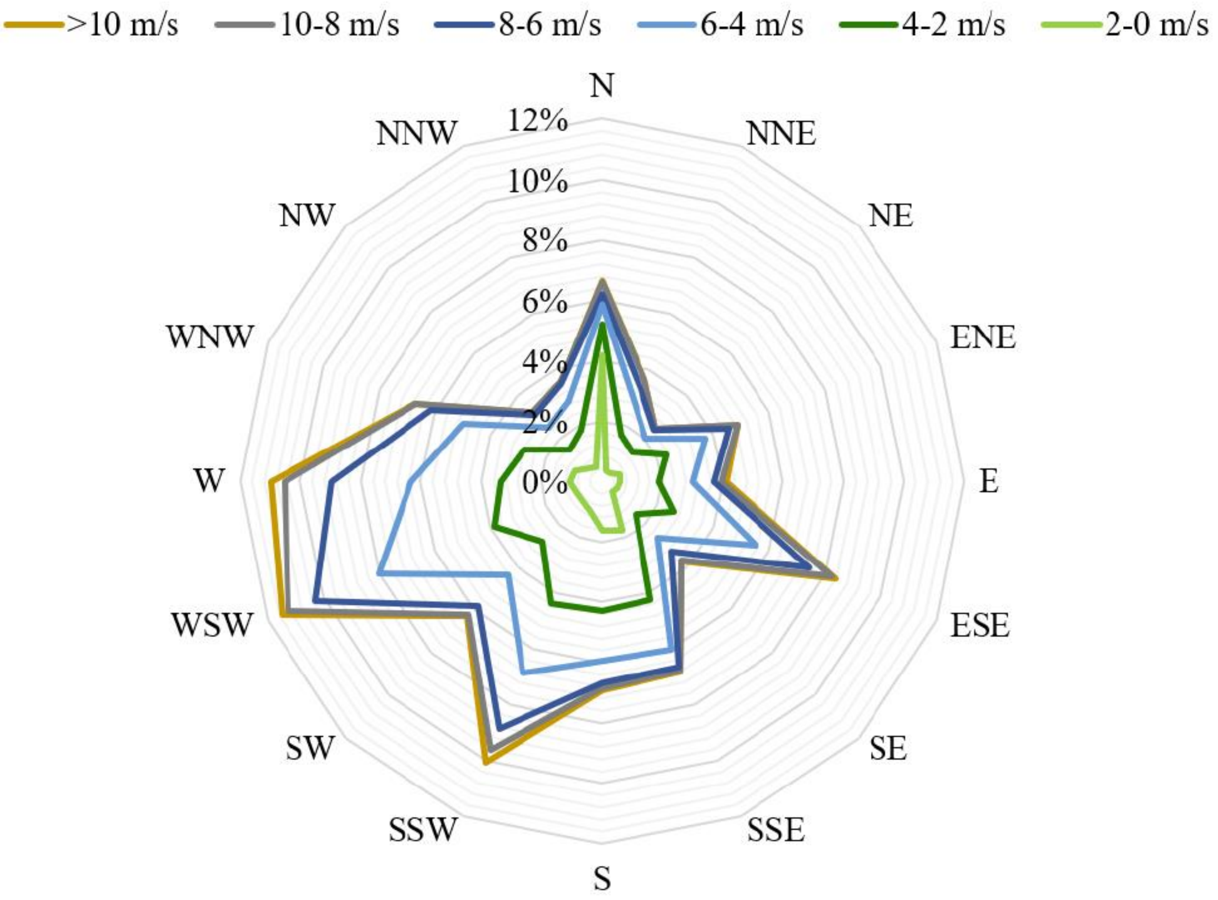


Figure 2. *The frequency of wind direction and the magnitude of wind speed based on DRY weather data.*

3.3.3. Solar irradiation

Solar irradiation denotes the amount of power per unit area of solar radiation that hits a given surface. Solar irradiation consists of direct, diffuse, and reflected solar radiation. Solar irradiation is highly dependent on the orientation and the slope of the surface. The maximum hourly value of direct and diffuse solar irradiance as a function of the orientation and the slope is illustrated in **Figure 3**. The average direct and diffuse solar irradiation as a function of the orientation and the slope is illustrated in **Figure 4**.

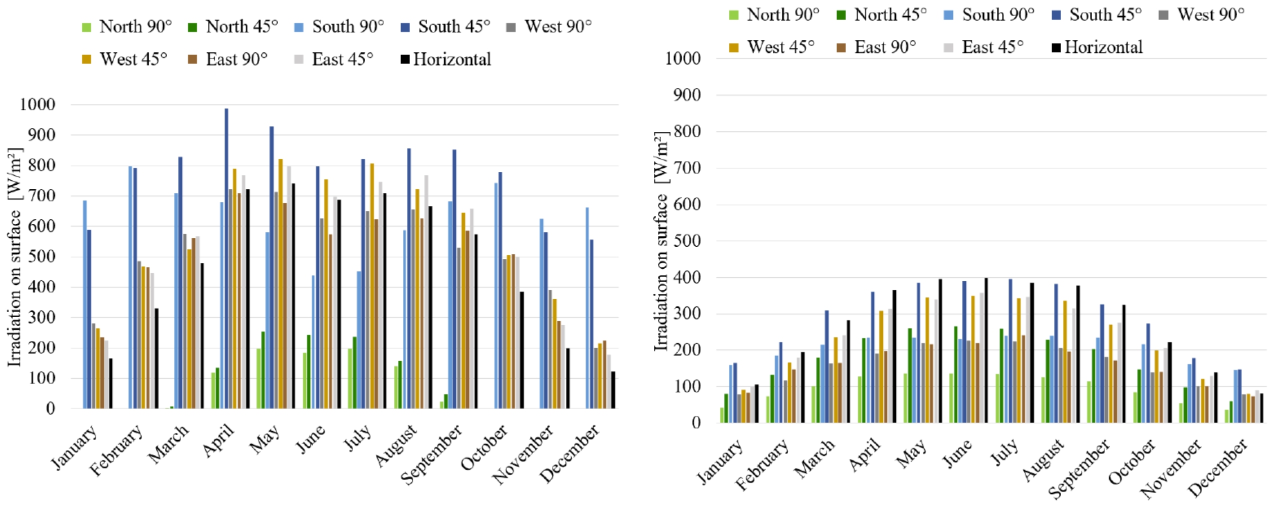


Figure 3. *Maximum hourly solar irradiation during a year based on DRY weather data. Left) Direct solar irradiation right) diffuse solar irradiation.*

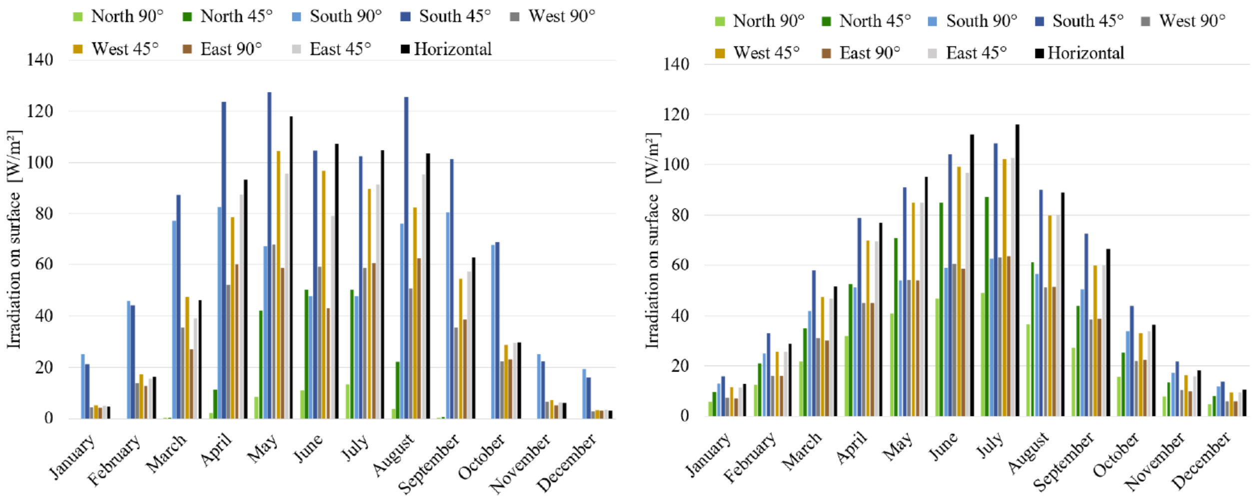


Figure 4. *Average hourly solar irradiation in one day for a year, based on DRY weather data. Left) Direct solar irradiation right) diffuse solar irradiation.*

4. Description of the investigated construction element

The construction element studied in the numerical investigation consists of an external layer of cladding, a cavity, wind protection material, insulation material, a vapor barrier, and a 2-layer of plaster, illustrated in **Figure 5**.

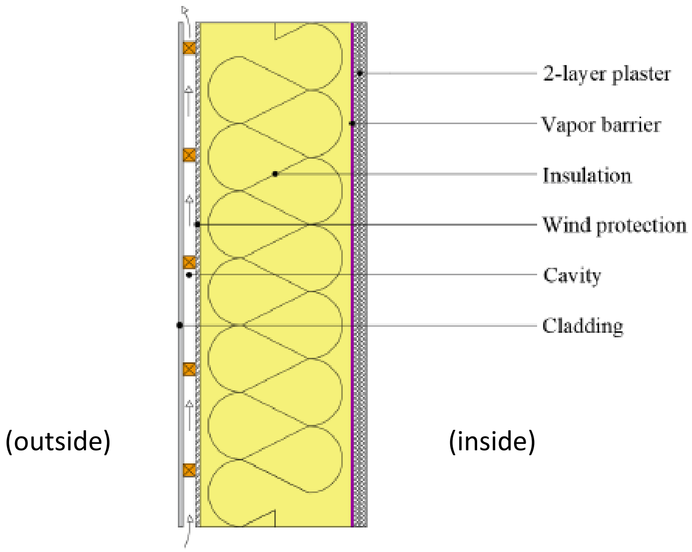


Figure 5. *The construction element used in the numerical study.*

Only the insulation material in the construction element is varied to investigate its influence on heat transfer. The properties for all the materials have been gathered from measurement in the guarded hot plate and can be seen in **Table 3**. [5] In reality, the material properties vary as a function of the temperature and the moisture content. However, in BSim it is not possible to implement this information, so they are assumed to be constant. The calculation principle of the U-value for the construction element containing the three different insulation materials is illustrated in **Figure 6** for a horizontal heat transfer. In accordance with [6], it distinguishes between horizontal and vertical heat transfer when the slope of the construction element is below and above 30°, respectively.

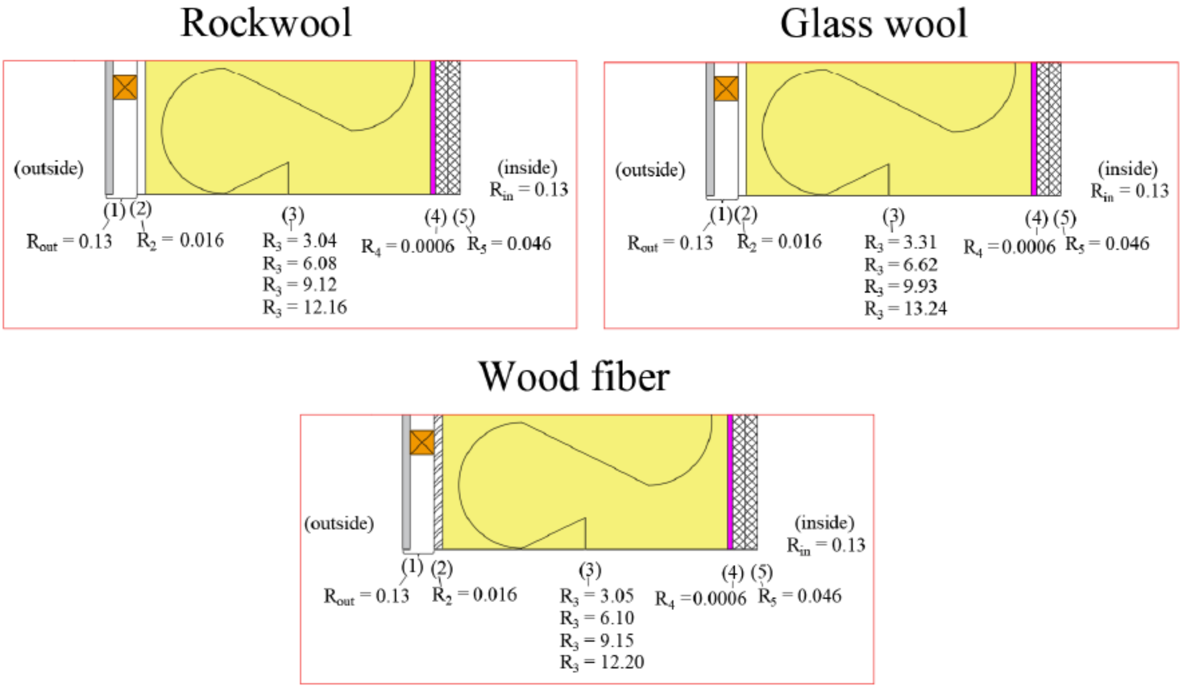


Figure 6. *The calculation principle of the U-value for the construction element.*

According to [6], when having a cavity in the construction element, the procedure of calculating the heat transport is to disregard the materials on the outer side of the cavity and instead adjust the external thermal resistance to become equal to the internal thermal resistance.

Table 3. *Properties of the construction element. *The thermal resistance corresponding to the internal thermal resistance is used. **Disregarded in the simulation. [5]*

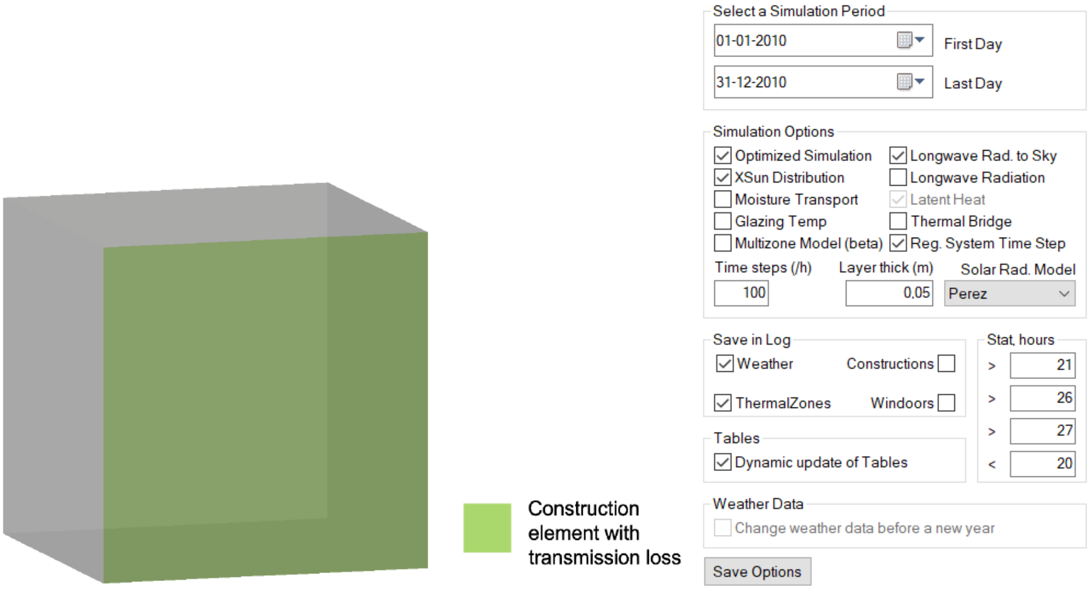
Material	**Thickness of layer** $[\mathrm{m}]$	**Density** $[\mathrm{kg/m^3}]$	**Specific heat capacity** $[\mathrm{J/(kg\ K)}]$	**Heat conductivity** $[\mathrm{W/(m\ K)}]$	**Thermal resistance** $[\mathrm{(m^2\ K)/W}]$
Internal thermal resistance	-	-	-	-	0.13
2-layer plaster	0.026	1350	1000	0.56	0.046
Vapor barrier	0.0002	920	2200	0.33	0.0006
Insulation (wood fiber)	0.1; 0.2; 0.3; 0.4	43.18	1950	0.328	Varies
Insulation (glass wool)	0.1; 0.2; 0.3; 0.4	32	884	0.3022	Varies
Insulation (rockwool)	0.1; 0.2; 0.3; 0.4	40.55	845	0.3289	Varies
Wind protection plaster	0.009	1350	1000	0.56	0.13
*Cavity	-	-	-	-	0.13
**External cladding	0.008	400	1000	0.2	0.04

5. Numerical study of construction element

This section describes how the construction is modelled in BSim and COMSOL Multiphysics.

5.1. BSim model setup

The BSim model setup for the first part of the numerical study consists of a cube where one surface is used to simulate the transmission loss through a construction element, as illustrated in **Figure 7**. The surrounding surfaces of the model are facing the thermal zone, meaning that no transmission loss will occur. Only transmission loss directly through the surface is included, meaning no thermal bridges are included. The simulation options are shown in **Figure 7**, to the right.



Select a Simulation Period
01-01-2010 First Day
31-12-2010 Last Day

Simulation Options
☑ Optimized Simulation ☑ Longwave Rad. to Sky
☑ XSun Distribution ☐ Longwave Radiation
☐ Moisture Transport ☑ Latent Heat
☐ Glazing Temp ☐ Thermal Bridge
☐ Multizone Model (beta) ☑ Reg. System Time Step
Time steps (/h) 100
Layer thick (m) 0,05
Solar Rad. Model Perez

Save in Log
☑ Weather ☐ Constructions
☑ ThermalZones ☐ Windoors

Stat. hours
> 21
> 26
> 27
< 20

Tables
☑ Dynamic update of Tables

Weather Data
☐ Change weather data before a new year

Figure 7. *Left) The BSim model used for the numerical study. Right) Simulation options in BSim.*

The cube is equipped with a thermal zone keeping approximately 20.0 °C inside to represent an identical calculation procedure as DS 418. A temperature of 20.0 °C is maintained inside with a heating and cooling system. The heating and cooling system settings can be seen in **Table 4**. With the following setpoint for the heating and cooling system, it is possible to keep an indoor temperature between 20.0 °C – 20.6 °C.

Table 4. *Set point for the heating and cooling system in the model. *The temperature at which the system reaches its minimum power.*

Parameter	Heating system	Cooling system
Maximum power [kW]	10.0	-10.01
Setpoint [°C]	20.0	20.01
Design Temperature [°C]	12.0	30.0
Minimum power [kW]	10	-10.0
Tempeture for minimum power* [°C]	30	10.0
Operation time	Always	Always

The surrounding construction is made of a material that influences the heat transfer as little as possible. It is impossible to build a single construction element in BSim, and it is impossible to make a material with no properties. The calculation time in BSim strongly depends on the material properties of the constructions in the model. The amount of time step can be described by equation **(10)** where the material with the most critical value of Δt_{max} is used as the threshold.

$$\Delta t_{max} \leq \left(1.25 \frac{\rho\, c_p}{\lambda}\, (\Delta x)^2\right) \tag{10}$$

Δt_{max}	Maximum amount of time steps required	$[-]$
ρ	Density of material	$[\mathrm{kg/m^3}]$
c_p	Specific heat capacity of the material	$[\mathrm{J/(kg\ K)}]$
λ	Thermal conductivity of the material	$[\mathrm{W/(m\ K)}]$
$\Delta\mathrm{x}$	Thickness of control volume	$[\mathrm{m}]$

For this reason, it is chosen to have surrounding constructions that are not thin and have low thermal conductivity to reduce the calculation time. In this way, the thermal storage of the surrounding constructions is also minimized due to low values of density and specific heat capacity. The properties of the surrounding constructions are shown in **Table 5**.

Table 5. *Properties of the construction elements facing the thermal zone in BSim.*

Thickness [m]	**Density** $[\mathrm{kg/m^3}]$	**Specific heat capacity** $[\mathrm{J/(kg\ K)}]$	**Thermal conductivity** $[\mathrm{W/(m\ K)}]$
0.5	200	200	0.05

A time step analysis is conducted to verify that the results do not depend upon the number of time steps. The time step analysis is based on the sum of the transmission loss during a year with DRY-weather data and a wall element facing south, with an insulation thickness of 100 mm, see **Table 6**. A wall element with a thickness of 100 mm is chosen since it will have the highest transmission loss among the investigated wall elements and therefore deviates more during the dynamic simulation. From the time step analysis, it is decided to run the model with the time steps of 80.

Table 6. *A time step analysis of the BSim model. The total transmission loss is the sum of transmission loss for one year.*

Time step [m]	**Total transmission loss** [kWh]	**Deviation** [%]
5	290.91	-
10	281.37	3.28
20	274.3	2.51
40	270.61	1.35
80	268.45	0.80
160	267.32	0.42
320	267.22	0.04
640	267.01	0.08

5.2. COMSOL model setup

In the following sections, the COMSOL model setup is described. The COMSOL model is used to validate the BSim model.

5.2.1. Mesh dependency analysis

COMSOL suggests meshes which are adjusted to the physics that are used in the model. It suggests nine meshes with different resolutions from extremely coarse to extremely fine. Before COMSOL is used to verify the BSim model, a mesh dependency analysis is performed on a steady-state case, so the results are independent of the mesh resolution. The nine suggested meshes are compared, and the coarsest mesh, which gives results that do not deviate from a more refined mesh, will be used to validate the BSim model. The coarser the mesh is, the less computational time is required. The conditions during the mesh dependence test are used according to the weather data from DRY from the 1st of January in hour 12 and with a construction facing south.

The conditions and results from the mesh dependence test when heat flux is the measured parameter are shown in **Table 7** and **Table 8**, respectively. The heat flux is measured on the surface, which is facing the indoor. This is the same place heat flux is measured in BSim. [1]

Table 7. *Boundary condition for the mesh dependence analysis in COMSOL.*

Boundary condition	Value
Indoor temperature	20 °C
External temperature	-0.4 °C
Direct irradiation	454.1 W/m^2
Diffuse irradiation	167.3 W/m^2
Surface emissivity	0.1
Surface solar absorptance	0.1
Ambient emissitivty	0.9
Ambient solar absorptance	0.8

Table 8. *Results for the mesh dependence analysis in COMSOL.*

Mesh resolution	Number of elements $[-]$	Heat flux $[\mathrm{W/m^2}]$	Deviation from previous mesh $[\%]$
Extremely course	2192	1.39	0
Extra course	2638	1.39	0
Coarser	3207	1.39	0
Coarse	3348	1.39	0
Normal	3624	1.39	0
Fine	3748	1.39	0
Finer	4050	1.39	0
Extra fine	4474	1.39	0
Extremely fine	6354	1.39	0

From **Table 8**, it can be concluded that the extremely coarse mesh resolution can be used since the results do not change when the mesh is refined. The mesh resolution is shown in **Figure 8**.

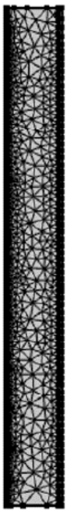


Figure 8. *The extremely course mesh resolution from COMSOL.*

5.2.2. Time step analysis

In the dynamic validation, the numerical model in COMSOL needs to have the amount of time steps defined. The same analysis as the mesh dependence test has been performed on the time steps, so the results are independent of the number of time steps. The time step analysis will be made for all the hours on the 1st of January of DRY with the external temperature, direct irradiation, and diffuse irradiation as boundary conditions. First, the amount of time steps has been chosen to be one, and the amount of time steps has been doubled until the maximum deviation between the two results is less than 0.1%. The results from the time step analysis are shown in **Figure 9** and **Table 9**.

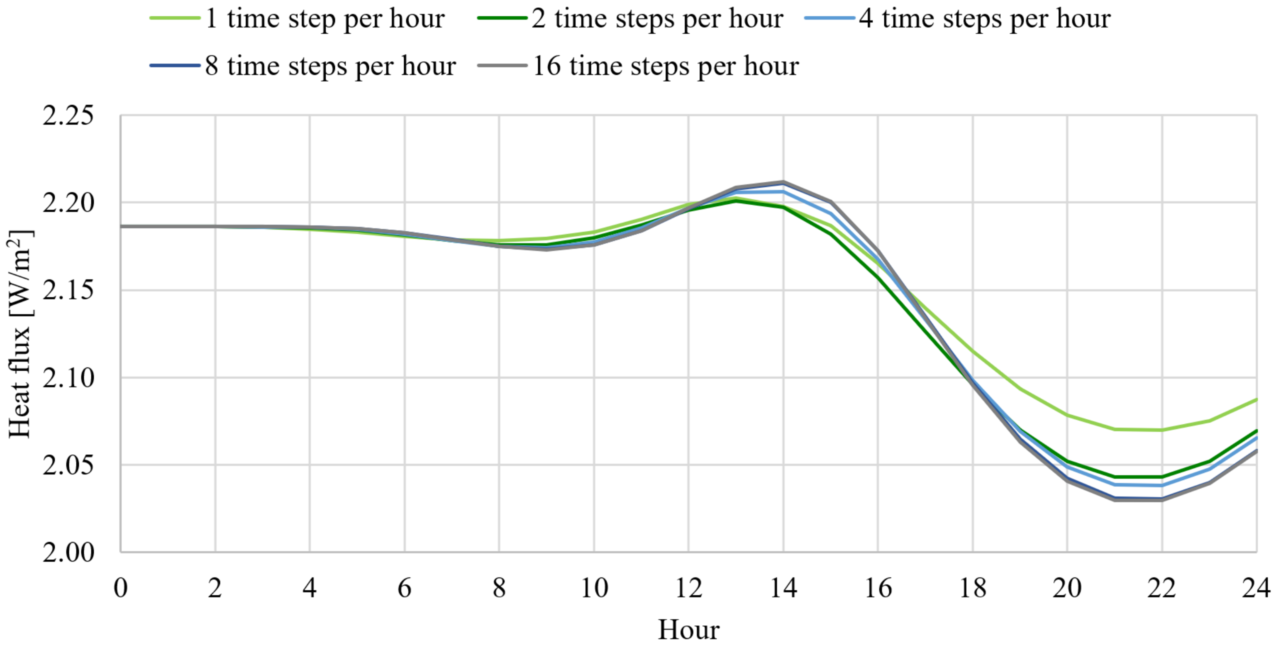


Figure 9. *Heat flux in all the hours on the 1st of January with different time steps.*

Table 9. *Maximum deviation from the previous simulation with lower time step.*

Time step	**1/h**	**2/h**	**4/h**	**8/h**	**16/h**
Maximum deviation [%]	-	1.32	0.54	0.38	0.07

From **Table 9**, it can be concluded that the results from having 8 or 16 time steps per hour do not deviate with more than 0.07%, and therefore 8 time steps per hour will be used for the validation of the BSim model. Furthermore, it is visible from **Figure 9** that the results from the simulation with 8 and 16 time steps per hour are almost identical.

5.3. Initialization period analysis

In BSim, it simulates the 1st of January repeatedly until the temperature in the thermal zone for two following days does not deviate with more than 0.1 °C [1]. The same approach is applied to COMSOL, where the heat flux will be used as the measured parameter and with the previously determined time step and mesh. The results from the initialization period analysis are shown in **Figure 10**.

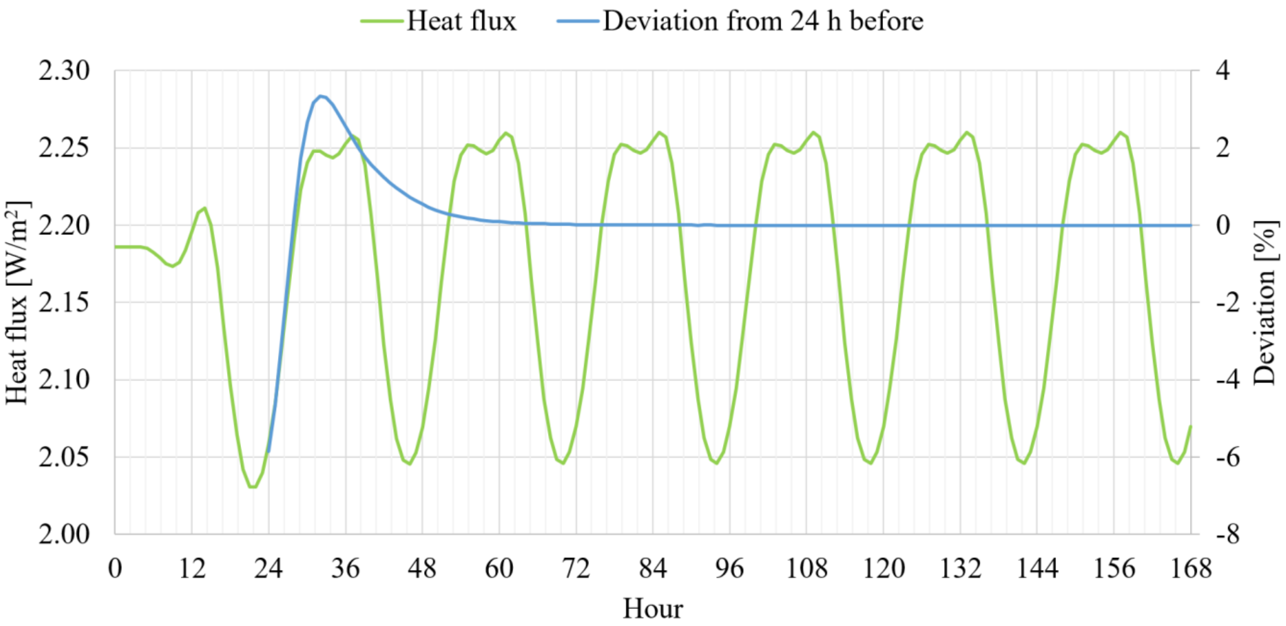
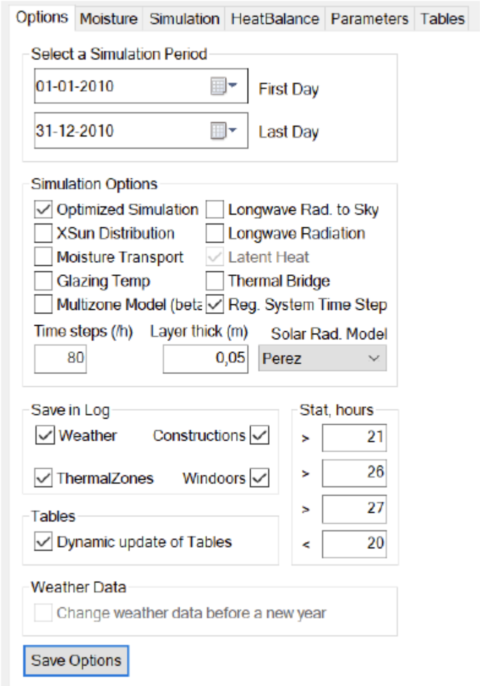


Figure 10. *Heat flux for the 1st of January with the same weather and percentage deviation from hourly heat flux from the same hour the previous day.*

One can observe in Figure 10 that the deviation is 0 after 72 h (3 days). This means that there is no deviation between the 3rd and the 2nd day. It is thus chosen to take 2 days as the initialization time for the model

6. Validation of the BSim model

To ensure that the BSim model is reliable, steady-state and dynamic validations of the BSim model are performed. The validation is based on the transmission loss and is validated by the DS 418 standard calculation [6] and the numerical simulation software COMSOL Multiphysics. All validations take are based on a 90° angle of the construction element containing wood fiber insulation. In BSim, it is possible to calculate the longwave radiation exchange between the internal surfaces and the longwave radiation exchange between the building and the sky but including this will require more complex modelling in COMSOL Multiphysics. For this reason, this feature is turned off during the validation. The setting of the BSim software during the validation can be found in **Figure 11**.



Select a Simulation Period
01-01-2010 First Day
31-12-2010 Last Day

Simulation Options
☑ Optimized Simulation
☐ XSun Distribution
☐ Moisture Transport
☐ Glazing Temp
☐ Multizone Model (beta
☐ Longwave Rad. to Sky
☐ Longwave Radiation
☑ Latent Heat
☐ Thermal Bridge
☑ Reg. System Time Step
Time steps (/h) 80
Layer thick (m) 0,05
Solar Rad. Model Perez

Save in Log
☑ Weather
☑ Constructions
☑ ThermalZones
☑ Windoors

Tables
☑ Dynamic update of Tables

Stat, hours
> 21
> 26
> 27
< 20

Weather Data
☐ Change weather data before a new year

***Figure 11.** The setting for BSim during the validation.*

6.1. Steady-state validation

Firstly, a steady-state validation is made. Here DRY-weather data for the BSim model has been created with a constant external temperature within each month, see **Table 2**. The validation is made for the construction element equipped with 300 mm of wood fiber insulation simulated for one year. **Figure 12** illustrates the deviation between BSim and the two other calculation approaches, which gives a similar result. The slight deviation in the result is due to the resolution that BSim uses, which has an accuracy of 1 W. Since the transmission loss is low, BSim makes some round-off errors, creating this deviation. It can especially be found during the summer months when the transmission loss is almost non-existing.

To further verify the transmission loss in the construction element with 300 mm of wood fiber insulation, the temperature profile for January has been compared for BSim and COMSOL in **Figure 13**. From the figure, it is observed that the deviation in the temperature is less than 0.05 °C.

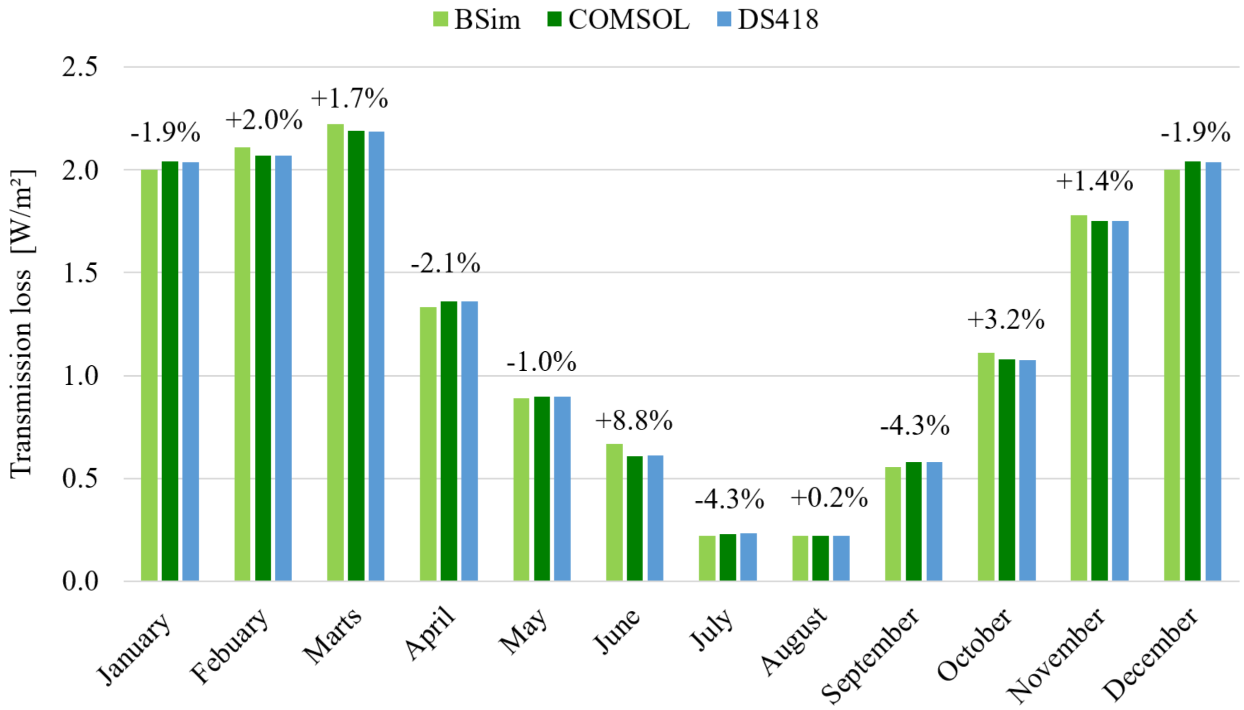


Figure 12. *The transmission loss for a construction element equipped with 300 mm wood fiber insulation. The numbers on top of the bars indicate the deviation between BSim and DS 418.*

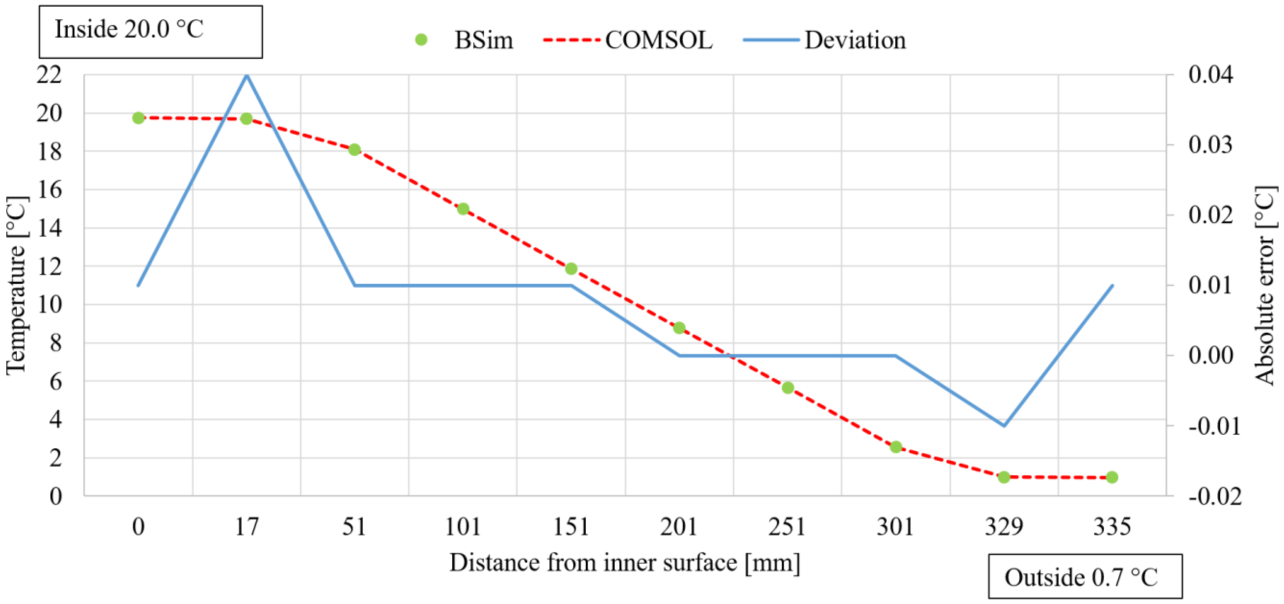


Figure 13. *The temperature profile for January, for a construction element equipped with 300 mm wood fiber insulation.*

6.2. Dynamic validation

Two comparisons of the vertical construction element are made to validate the quasi-stationary calculation method of BSim. The first validation is without solar radiation, where only the outdoor temperature influences the transmission loss. The second validation includes solar radiation. An initialization period of 50 days is added to the DRY-weather file. This feature repeats the outdoor conditions for the model 50 times and therefore increases the accuracy of period-wise stationary conditions in the construction element.

6.2.1. Validation 1: No solar radiation

The first comparison takes offset only in the outdoor temperature. A DRY-weather file has been designed containing hourly outdoor temperature values but with no wind or solar radiation. An identical step-function as the DRY-weather file of the outdoor temperature is inserted in COMSOL to imitate the quasi-stationary calculation approach.

Figure 14 indicates the transmission loss for the construction element with 300 mm of wood fiber insulation for the 1st of January. BSim and COMSOL strongly agree on the transmission loss during the day, whereas the standard DS 418 calculation deviates. The DS 418 varies more due to the lack of inclusion of thermal storage in the calculation for the construction element. Even though DS 418 does not have the same tendency during the day, the sum of transmission loss for the three approaches for the 1st of January is equal, see **Table 10**.

Figure 14. *The transmission loss for the 1st of January using the construction element equipped with 300 mm wood fiber insulation.*

Table 10. *The sum of transmission loss for the 1st of January using the construction element equipped with 300 mm wood fiber insulation.*

BSim [kWh]	**COMSOL** [kWh]	**DS418** [kWh]
0.48	0.48	0.48

Since the transmission loss is low for the construction element equipped with 300 mm of wood fiber insulation, a similar approach is conducted with only 30 mm of wood fiber insulation, see **Figure 15**. The variation in outdoor temperature is clearer in this situation. Again, BSim and COMSOL have a similar tendency in the transmission loss, whereas the DS 418 calculation deviates due to no thermal storage properties. The sum of transmission loss during the day is approximately equal, see **Table 11**.

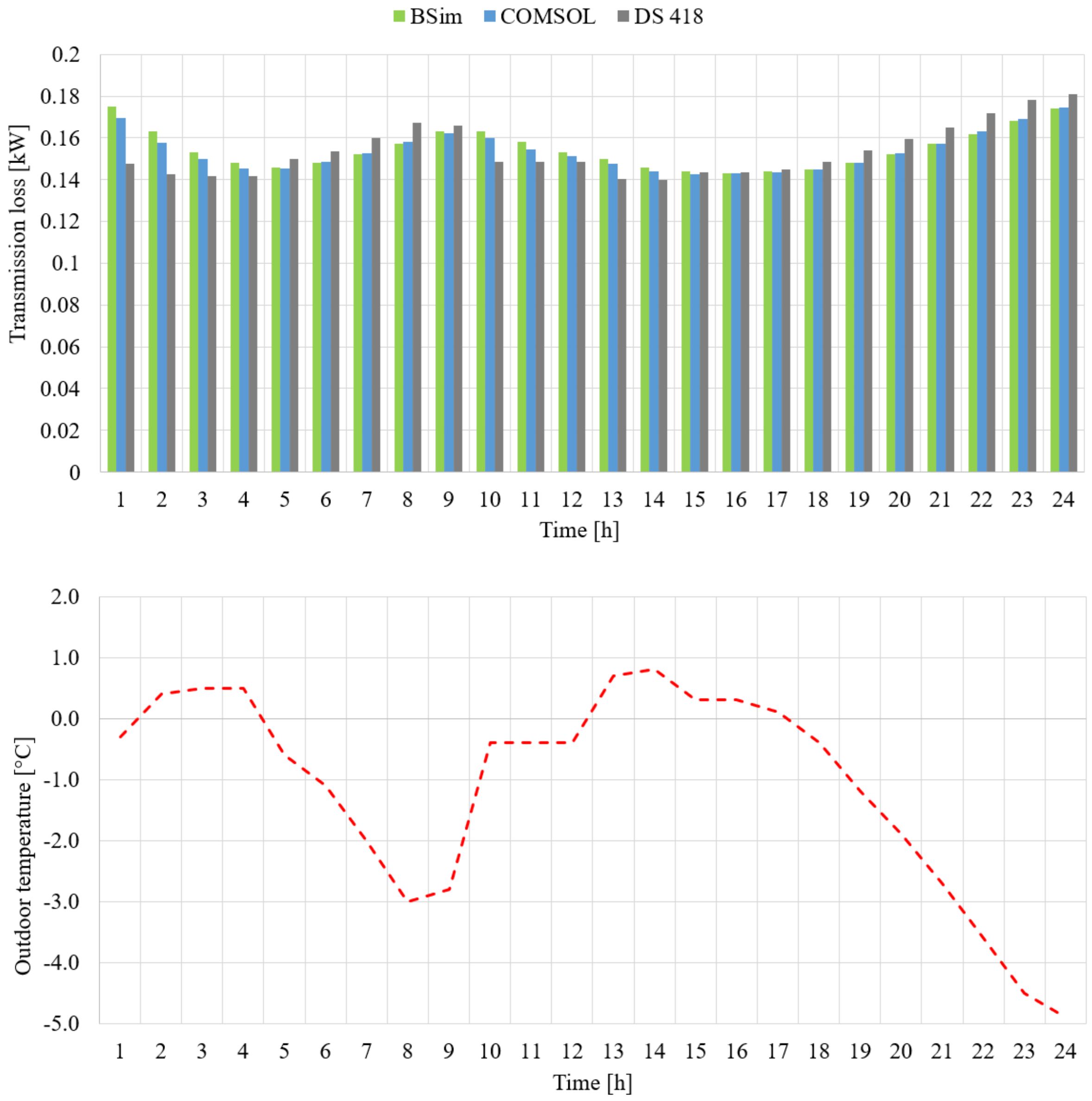


Figure 15. *The transmission loss for the 1st of January using the construction element equipped with 30 mm wood fiber insulation.*

Table 11. *The sum of transmission loss for the 1st of January using the construction element equipped with 30 mm wood fiber insulation.*

BSim [kWh]	**COMSOL** [kWh]	**DS418** [kWh]
3.71	3.69	3.69

6.2.2. Validation 2: With radiation

The same analysis is performed in this section, including solar radiation. The validation is made for the 1st of January. The direct, diffuse, and reflected irradiation from the ground are inserted in COMSOL as a step-function. The orientation is set towards the south to include the impact of the irradiation as much as possible. The insulation thickness is again set to 300 mm and 30 mm. The setting for BSim can be seen in **Figure 11**. It can be observed from **Figure 16** that the two curves have the same tendency with a slight deviation.

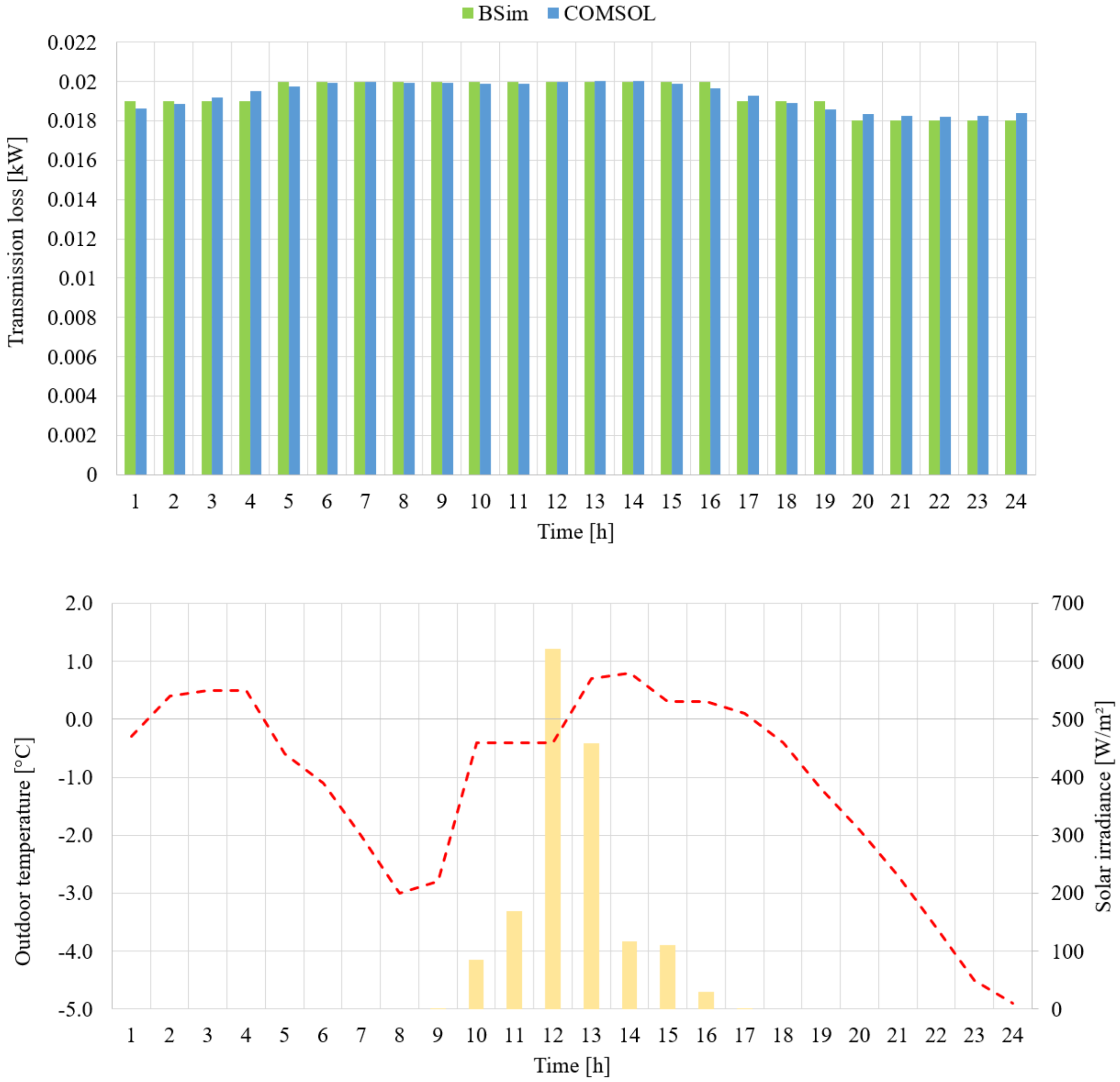


Figure 16. *The transmission loss during the 1st of January using the construction element equipped with 300 mm wood fiber insulation, including radiation.*

Some of the variations in **Figure 16** come from the round-off error, but still, it deviates with less than 1 W. The sum of the transmission loss during the day can be found in **Table 12**. The accumulated transmission loss is compared to the case without solar radiation in the table. Here it is observed that solar radiation has a minor effect on the transmission loss for a construction element with 300 mm insulation the 1st of January.

Table 12. *The sum of transmission loss for the 1st of January using the construction element equipped with 300 mm wood fiber insulation.*

	BSim [kWh]	**COMSOL** [kWh]
With radiation	0.46	0.46
Without radiation	0.48	0.48

Figure 17 shows the validation of the BSim model when the construction element is equipped with 30 mm insulation.

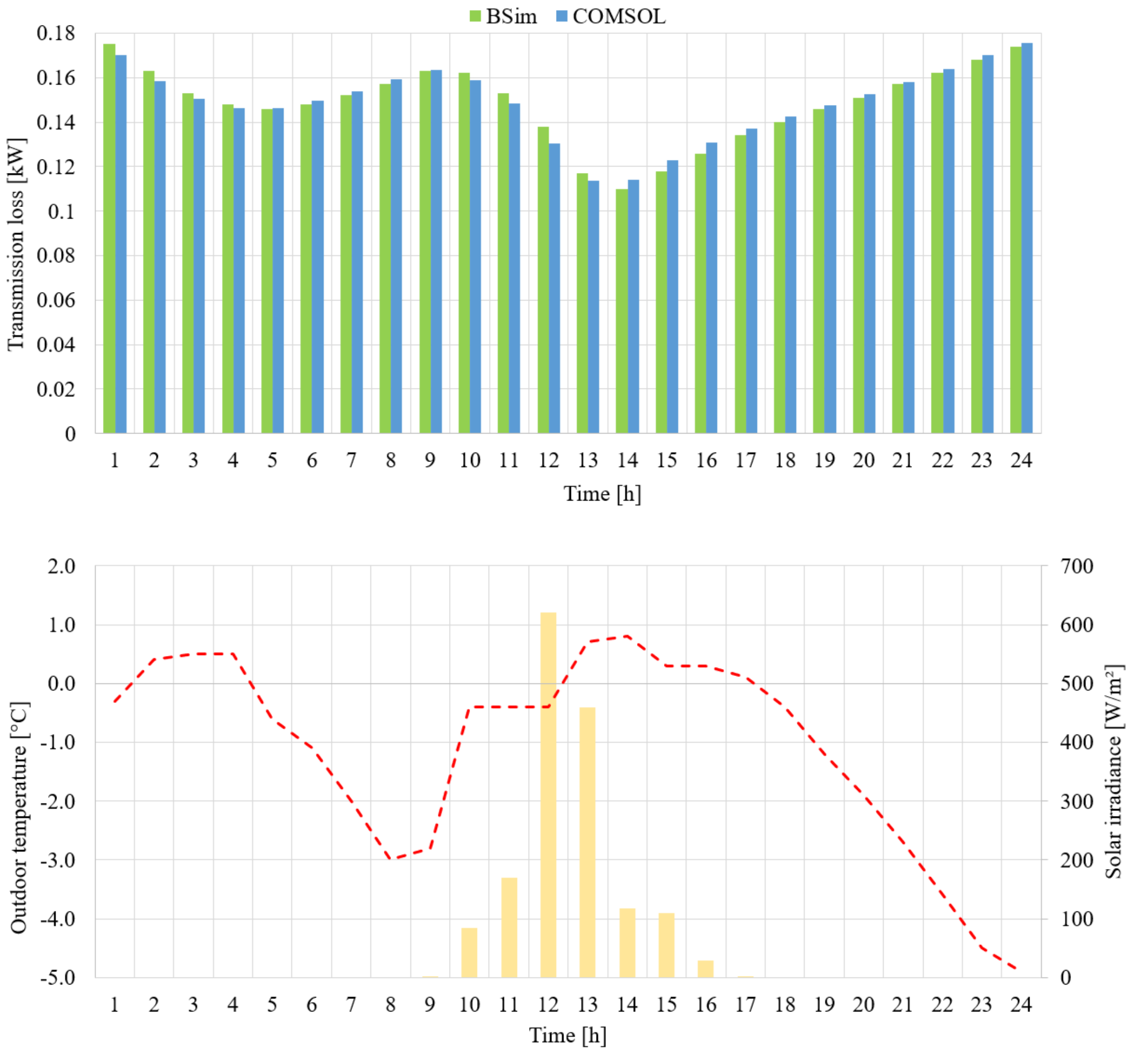


Figure 17. *The transmission loss during the 1st of January using the construction element equipped with 30 mm wood fiber insulation, including radiation.*

In **Figure 17**, a high agreement between BSim and COMSOL is again observed. The highest deviation occurs in the middle of the daytime due to solar radiation exposure. The sum of transmission loss during the day is visible in **Table 13** and is compared to the case without solar radiation.

Table 13. *The sum of transmission loss for the 1st of January using the construction element equipped with 30 mm wood fiber insulation.*

	BSim [kWh]	**COMSOL** [kWh]
With radiation	3.57	3.56
Without radiation	3.71	3.69

The weather data from the 7th of March has also been included in the models and been compared since this day has a large temperature deviation throughout the day from -15 °C to -0.5 °C. In March, the deviation in solar radiation is also larger. This comparison determines if COMSOL and BSim give similar results when the boundary conditions are even more dynamic. From **Figure 18** and **Figure 19** it can be seen that BSim and COMSOL still give similar results.

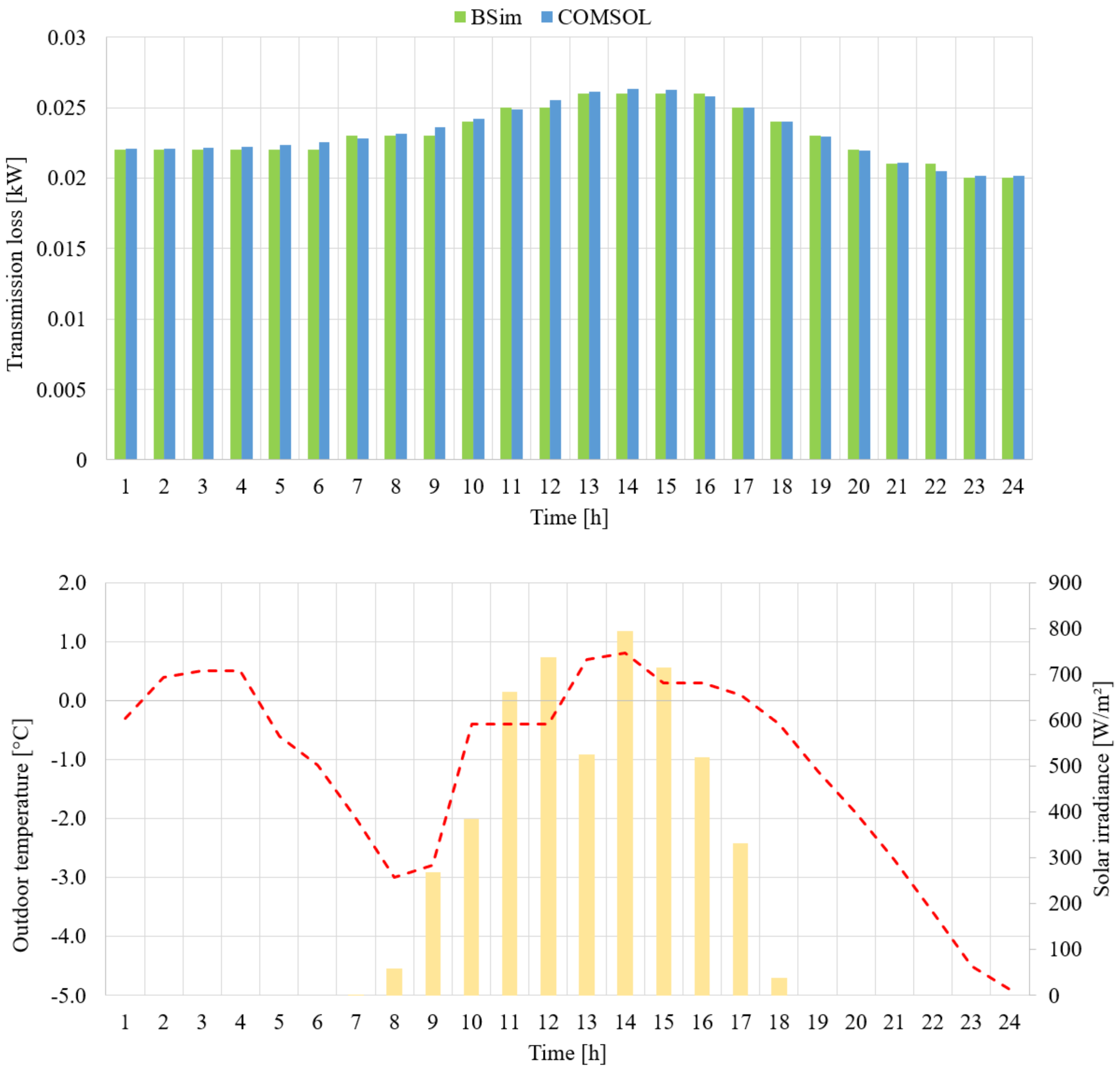


Figure 18. *The transmission loss during the 7th of January using the construction element equipped with 300 mm wood fiber insulation, including radiation.*

Notice in **Figure 18** that the lowest transmission loss occurs during the end of the day. The reason is the thermal mass, which delays heat transport.

Table 14. *The sum of transmission loss for the 7th of March using the construction element equipped with 300 mm wood fiber insulation.*

BSim [kWh]	**COMSOL** [kWh]
0.56	0.56

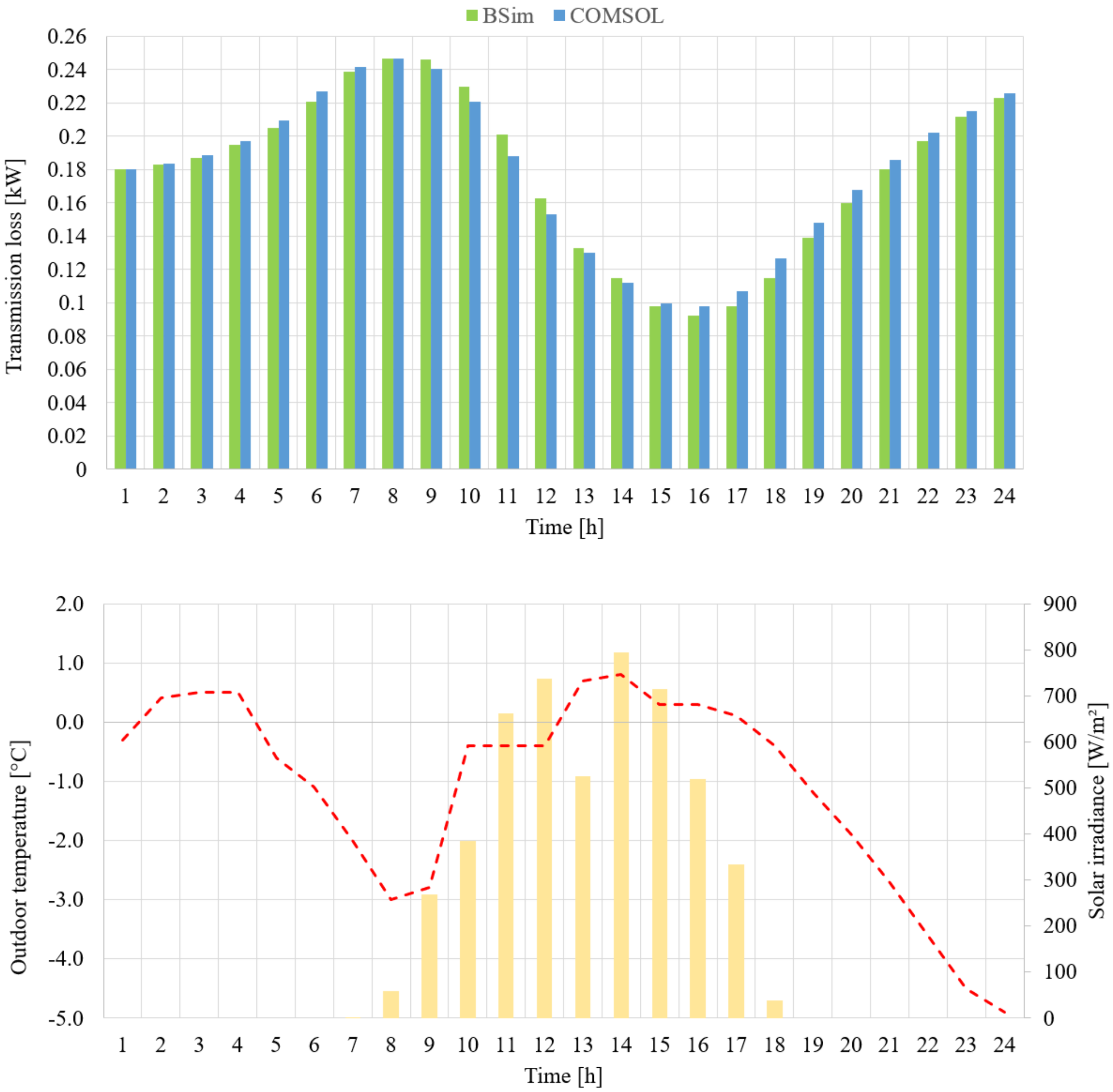


Figure 19. *The transmission loss during the 7th of January using the construction element equipped with 30 mm wood fiber insulation, including radiation.*

Table 15. *The sum of transmission loss for the 7th of March using the construction element equipped with 30 mm wood fiber insulation.*

BSim [kWh]	**COMSOL** [kWh]
4.26	4.30

7. Numerical study of the effective U-value for a single-family house

This section deals with the setup for the numerical study regarding a single-family house. The section includes information about the model setup for BSim and Be18, varied parameters, and validation of the model.

7.1. Be18 software

The Be18 software is used to document the energy consumption for buildings in the Danish building industry. It is a requirement in the Danish building regulation that new and renovated buildings demonstrate the energy consumption by this tool to comply with the energy frame. [7]

The Be18 software accounts for the building envelope properties, the orientation concerning daylight and outdoor conditions, building systems, and the thermal indoor environment (in a simplified manner). The outdoor conditions are based on Design Reference Year (DRY) weather data. The weather data is gathered from weather stations in Denmark in the period from 2001 to 2010 [4].

Be18 uses a simplified calculation method: a monthly average calculation procedure, meaning that within each month, the same boundary conditions are kept constant [8]. This is also known as the quasi-steady-state calculation procedure in accordance with [9]. Each month, the energy balance is calculated based on the gains and losses depending on the building materials, installations, and setpoints.

7.2. BSim and Be18 model setup

The comparison will be made for a whole year containing the outdoor air temperature is given in **Table 2**. The ground temperature is 10 °C for all months.

The single-family house has a heated floor area of 129 m^2 and a building height of 3.2 m, see **Figure 20**.

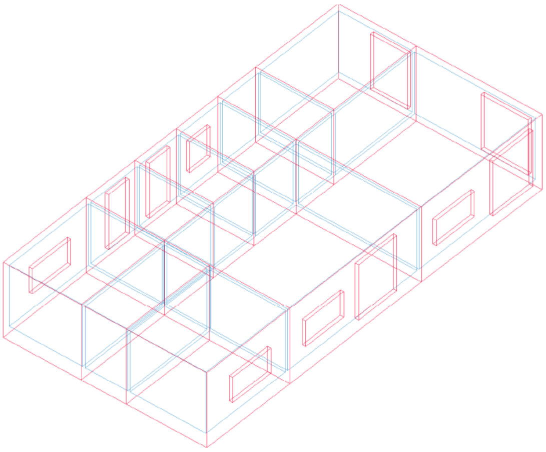


Figure 20. *The BSim model of a single-family house.*

The setpoints of the Be18 model and BSim can be found in **Table 16**. A temperature range between 20 °C – 25 °C is aimed for, and thermal comfort is not in focus. Therefore, the temperature setpoint does not vary during the seasons. The setpoint for cooling is set to 30 °C in Be18 since the building is punished in the energy frame with the amount of energy required to obtain acceptable indoor temperatures. Be18 does not calculate the transport trough the construction element as BSim but bases the gains and losses on correcting the boundary conditions [8].

***Table 16.** Setpoint for the Be18 and BSim software in the analysis.*

Parameter	Setpoint Be18	Setpoint BSim
Heating [°C]	20	20
Venting [°C]	25	25
Venting at night [°C]	25	25
Cooling [°C]	30	$[-]$

It is assumed that the building has natural ventilation with the minimum ventilation rate at $0.3\ \mathrm{l/(s\ m^2)}$, equal to $0.44\ \mathrm{h^{-1}}$, which is the minimum ventilation rate according to the requirement [7]. Therefore, the infiltration rate is set equal to the natural ventilation. Additionally, it is assumed that the occupants can open all the windows if the indoor temperature exceeds 25 °C [7]. All the windows are assumed to be side hinged, which makes the effective opening area for the windows 60% of the total window area. When the occupants open the window during warmer periods, single-sided ventilation is assumed to occur with a ventilation rate at $2.95\ \mathrm{l/(s\ m^2)}$, equal to $4.35\ \mathrm{h^{-1}}$. The venting and infiltration systems can be found in **Table 17** and **Table 18** for Be18 and BSim, respectively. [8] No systems for occupancy or internal heat loads are included in the models.

The parameter variation can be found in **Table 19**. The floor deck is kept constant in all simulations. Additionally, the thickness of the internal walls is also kept constant, whereas only the insulation material is varied along with external walls and the roofs. The two window types used in the simulation complies with the building regulation about an energy balance with an energy balance of $\geq 0\ \mathrm{kWh/(m^2\ yr)}$ [7].

***Table 17.** Description of the system for venting and infiltration in Be18.*

Venting

Description	Percent of time in use
Air change $[\mathrm{l/(s\ m^2)}]$: 2.95	75%

Infiltration

Description	Percent of time in use
Air change $[\mathrm{l/(s\ m^2)}]$: 2.95	75%

***Table 18.** Description of the systems for venting and infiltration in BSim.*

Venting

Description	Regulation	Time
Basic air change $[\mathrm{h^{-1}}]$: 0.44 Max. air change $[\mathrm{h^{-1}}]$: 4.35	$100\% > 25\ ^\circ\mathrm{C}$	Monday-Sunday

Infiltration

Description	Regulation	Time
Air change $[\mathrm{h^{-1}}]$: 0.44	$100\%\ 00{:}00 - 24{:}00$	Monday-Sunday

Table 19. *Parameters varied for the construction element in the numerical study.*

Parameter	Unit	Discrete steps
Insulation material (External- internal walls and roof)	$[-]$	Wood fiber; Glass wool; Rockwool
Insulation thickness (External walls and roof)	$[\mathrm{mm}]$	100; 200; 300; 400
Window	$[-]$	Futura $+44$; SW Optima 3
Orientation	$[\,^\circ\,]$	0; 45; 90; 180; 270; 315
Ventilation of cavity	$[(\mathrm{m}^2\ \mathrm{K})/\mathrm{W}]$	0.04; 0.06; 0.08; 0.10; 0.12; 0.14
Solar absorptance of external surface	$[-]$	0.0; 0.1; 0.2; 0.3; 0.4; 0.5

Information about the structure of floor deck, internal walls and the window used in the simulation are given in **Table 20** - **Table 22**.

Table 20. *Material properties of the materials in the floor deck.*

Material	**Thickness** $[\mathrm{m}]$	**Heat conductivity** $[\mathrm{W}/(\mathrm{m\ K})]$	**Density** $[\mathrm{kg}/\mathrm{m}^3]$	**Specific heat capacity** $[\mathrm{J}/(\mathrm{kg\ K})]$	**Thermal resistance** $[(\mathrm{m}^2\ \mathrm{K})/\mathrm{W}]$
External heat transfer coefficient	–	–	–	–	1.5
Leca fill	0.20	0.21	325	800	0.95
EPS	0.25	0.045	17	750	5.55
Concrete	0.10	2.1	2400	1000	0.05
Stone wool	0.05	0.039	32	800	1.28
Spruce	0.022	0.13	500	1600	0.17
Internal heat transfer coefficient	–	–	–	–	0.17

Table 21. *Material properties for the materials in the internal walls. *Only one type of insulation material is used at a time.*

Material	**Thickness** $[\mathrm{m}]$	**Heat conductivity** $[\mathrm{W}/(\mathrm{m\ K})]$	**Density** $[\mathrm{kg}/\mathrm{m}^3]$	**Specific heat capacity** $[\mathrm{J}/(\mathrm{kg\ K})]$
Plasterboard	0.026	0.25	900	1000
Woodfiber*	0.07	0.0328	43.18	1950
Glass wool*	0.07	0.0302	32	884
Rock wool*	0.07	0.0329	40.55	845
Plasterboard	0.026	0.25	900	1000

Table 22. *The window types and relevant properties. The properties are given for a reference window with the dimensions of 1.23 x 1.48 m. [10]*

Product	**Panel type** $[-]$	E_{ref} $[\mathrm{kWh/(m^2\ yr)}]$	**U-value** $[\mathrm{W/(m^2\ K)}]$	**SHGC** $[-]$	**LT-value** $[-]$	**Glass fraction** $[-]$
Futura +44	Wood/aluminum	30.6	0.78	0.52	0.75	0.83
SW Optima 3	Wood	0.5	0.87	0.40	0.75	0.76

Since the hypothesis is that the thermal mass of the construction is significant for the transmission loss, the effective heat capacity is calculated according to [11]. The simplified standard procedure for calculating the effective heat capacity is to estimate the total amount of the construction contributing to accumulating heat. In the estimation, the effective thermal inertia has been estimated as the heat capacity of the construction element on the first 10 cm of the element facing the indoor environment. Therefore, the rest of the construction is neglected.

The effective heat capacity is then calculated for each construction element and divided by the floor area of the building and added up with the remaining construction elements. Both sides of the internal walls are accounted in the estimate. Windows, doors, and furniture are assumed to contribute with $10\ \mathrm{Wh/(m^2\ K)}$. The equation for the calculation procedure is given in **(11)** [11] and the effective heat capacity for the building equipped with one of the three insulation materials appears in **Table 23**.

$$k_{building} = \rho\ c_p\ d\ \frac{A_{construction}}{A_{building}} \tag{11}$$

$k_{building}$	Effective heat capacity	$[\mathrm{Wh/(m^2\ K)}]$
ρ	Density of material	$[\mathrm{kg/m^3}]$
c_p	Specific heat capacity	$[\mathrm{J/(kg\ K)}]$
d	Thickness of the construction element	$[\mathrm{m}]$
$A_{construction}$	Surface area of the construction element	$[\mathrm{m^2}]$
$A_{building}$	Floor area of the building	$[\mathrm{m^2}]$

Table 23. *The effective heat capacity for the single-family house equipped with different insulation materials.*

$k_{building}$ $[\mathrm{Wh/(m^2\ K)}]$		
Wood fiber	Glass wool	Rock wool
56.5	54.2	54.5

7.3. Validation of models

BSim and Be18 are compared to each other, to validate the results. The sum of transmission loss and loss for infiltration and venting is compared within each month. The two models are made comparable by making the weather data for the BSim model constant within each month, so it corresponds to the weather data used in Be18. The weather data is without solar radiation or wind. The Be18 uses a mean value for solar radiation, which is neglected by setting the solar heat gain coefficient (SHGC) to 0. Additionally, the longwave sky radiation is turned off for the BSim model. Both models are equipped with 100 mm of wood fiber insulation in the external walls and roof construction. The thermal mass of the construction elements is also inserted to represent the building's capacity to dampen the fluctuations in the indoor temperature. The sum of transmission loss and infiltration/venting loss for each month in Be18 and BSim can be seen in **Figure 21** and **Figure 22**, respectively. There is a slight deviation between the two models since they calculate the transmission loss for the floor deck differently. Be18 uses a temperature factor of 0.7 to correct that the floor deck faces the ground, where as BSim calculates the transmission loss the same as other construction elements, while using a different temperature for the ground.

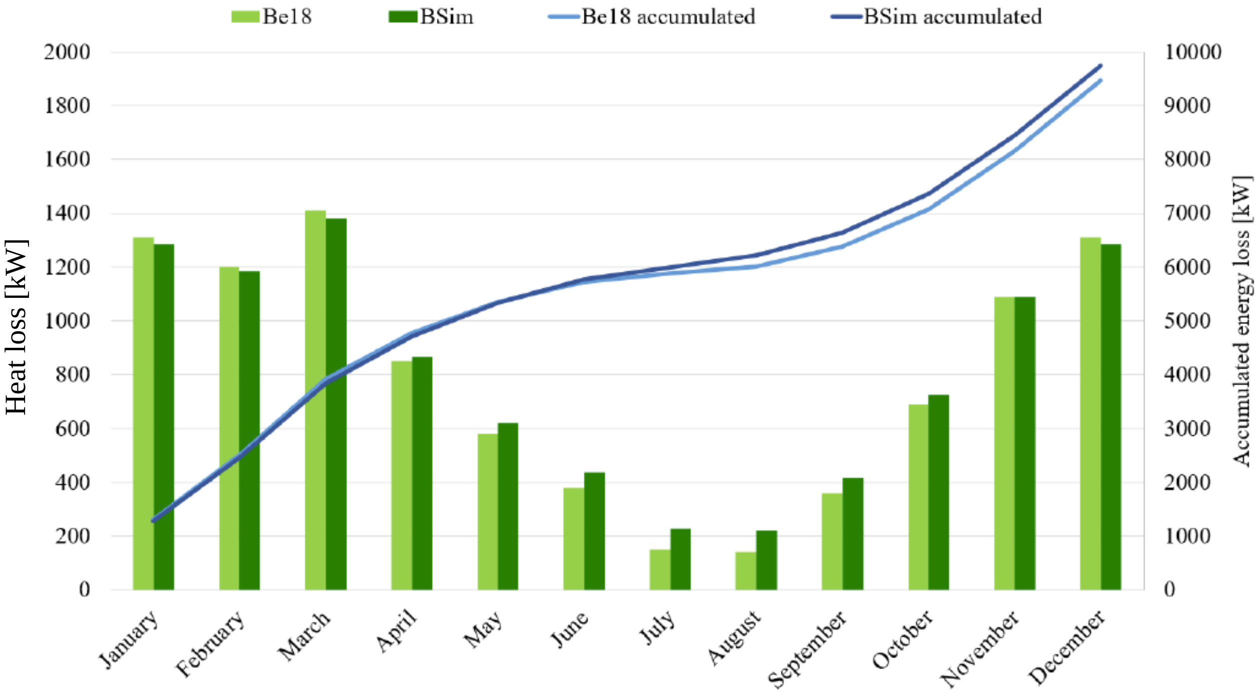


Figure 21. *The transmission loss for the Be18 and BSim model for a single-family house, using identical weather data.*

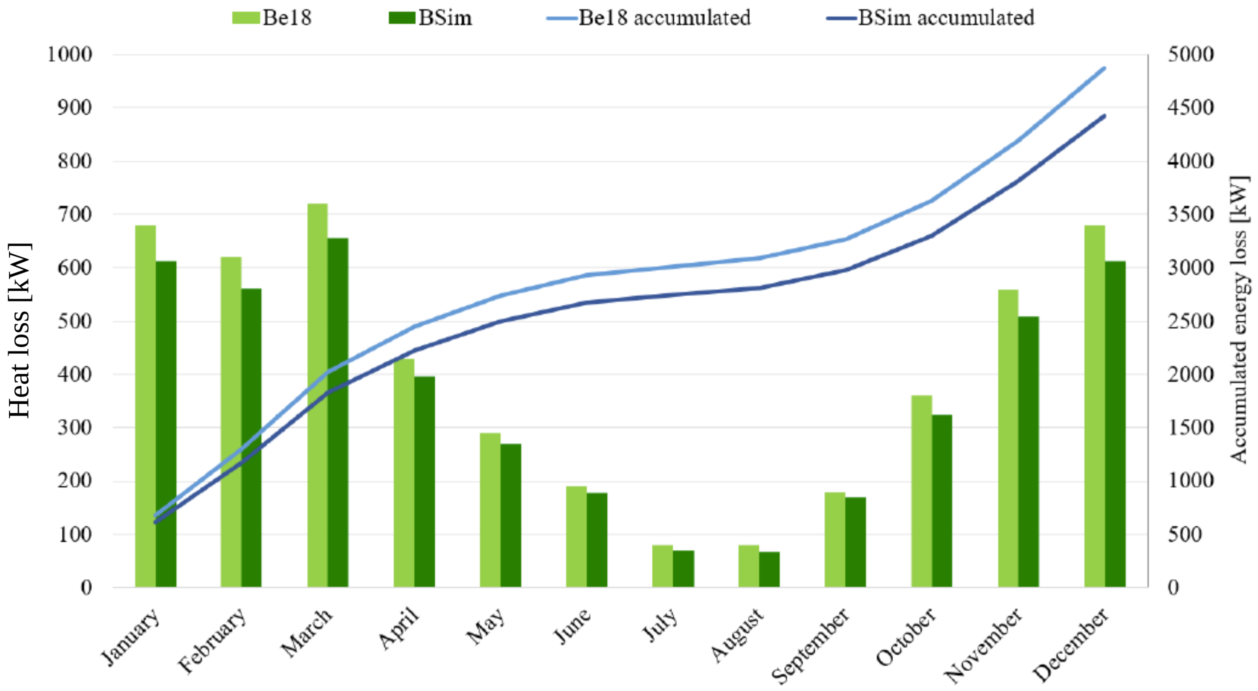


Figure 22. *Infiltration and venting loss for the Be18 and BSim model for a single-family house using identical weather data.*

8. Conclusion

In this technical report, key aspects of numerical models in BSim and COMSOL Multiphysics have been described along with weather data from the Design Reference Year (DRY). 1-dimensional heat transfer has been calculated using both BSim and COMSOL Multiphysics, to validate the validity of the results from the BSim model. This was performed in three steps: steady-state calculation, a dynamic calculation with solar radiation and a dynamic calculation with solar radiation. In all three steps, there is a great similarity between BSim and COMSOL. Therefore, based on the different analyses, the BSim model are considered validated.

The final numerical study, performed on a single-family house, showed a great similarity between the Be18 calculation and the BSim calculation.

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