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Abstract. The accurate energy performance assessment of building elements remains an active research topic. Studies have indicated that the thermal mass of building envelopes could influence heat losses in dynamic conditions and lead to significant difference in performance compared to steady-state conditions. This article aims to identify the relevance of using dynamic simulations instead of steady-state calculations for the energy performance assessment of building elements in Denmark. A numerical sensitivity analysis is performed on various parameters. The Monte-Carlo approach is used to perform numerous BSim simulations, which are then compared to standard steady-state calculations. The varied parameters include solar absorptance, ventilation in cavities, insulation material, insulation thickness, and orientation. Preliminary results indicate that dynamic conditions can significantly alter the wall heat losses, by up to 20% when compared to steady-state conditions. However, when aggregated, the differences average out to only 4% lower heat losses. When focusing on the thermal inertia of insulation materials, denser insulation materials only slightly delay the heat loss in the building element, but this effect is nullified over longer periods. The sensitivity analysis indicates that the most influential parameter is the solar absorptance, while the type of material is close in significance to the other parameters. The specific heat capacities and density of the insulation layer does not have a significant influence compared to its thermal conductivity. Thus, insulation materials with higher thermal mass do not seem to significantly improve the thermal performance of a building envelope.

1. Introduction

Buildings account for 40% of the total energy demand in the world. The building sector is thus a clear key target to reach the current sustainability goals [1]. The reduction of buildings' energy demand and CO_2 emissions is a focus of the energy policies following the Paris Agreement [2].

In Denmark, one way to reduce energy use in this rather cold climate is to decrease space heating needs. In 1961, the Danish Building Regulation introduced the first requirement for thermal insulation and is tightening it up regularly over time. The assessment of a building's energy requirement relies on a theoretical calculation of its energy balance. The procedure is often simplified with, e.g., the outdoor boundary conditions reduced to monthly averages and does not include aspects such as wind exposure and solar irradiance on the construction elements. This method is adequate for compliance verification and comparing buildings, but it may not reflect the actual energy performance of a given building.

The deviation between the estimated energy performance of a building and the actual performance is emphasized in the study [4]. It attributes the higher energy needs to the fact that poor workmanship is not often accounted for nor modeled in the design process. In 25 new dwellings in the UK, the measured heat loss coefficient was almost 60% higher than the predicted one.

Another reason for deviation in energy performance for a building may be an incomplete assessment of the material properties when it comes to its interaction with real-life weather conditions. This perspective is referred to as the “effective U-value.” The effective U-value is a way of correcting the steady-state measured material properties, reflecting the actual performance of a construction element in dynamic conditions. The study [5] from Newcastle in Australia emphasizes that the steady-state thermal resistance (R-value) is insufficient to describe the energy performance of a construction element alone. It concluded that the thermal mass is a crucial parameter in the overall energy performance of a house and is the reason for the deviation between steady-state measured U-value and effective U-value. The study [6] states that many metrics exist, but only describe single variables and not the overall performance. This is due to complex interactions between different variables, such as what happens when solar radiation hits the surface of a building or interior heat loads. [7] further corroborates this, saying that thermal mass, which is not included in some simple steady-state calculations, can be used as a passive strategy to reduce energy use.

Therefore, when performing steady-state calculations using simplified methods, such as simply calculating a heat balance based on the U-value of the construction elements, the thermal performance can deviate significantly from dynamic conditions in real-life situations.

This article aims to identify the relevance of using dynamic simulations instead of steady-state calculations for the energy performance assessment of building elements in Denmark and to quantify the sensitivity of input parameters using a global sensitivity analysis. Dynamic and steady-state calculations are performed on a single construction element using the Monte-Carlo approach, on a simplified single-zone case, and, finally, on an entire single-family house. The results from the dynamic and steady-state calculations are compared for all cases. A sensitivity analysis is then performed to assess the importance of different input parameters in the calculation.

This work also takes a specific look at the case of wood fiber insulation material. Some wood wool producers claim that the additional thermal mass of this specific insulation material compared to other insulation materials can significantly reduce heat losses when assessing the performance with realistic dynamics boundary conditions instead of steady-state simplified ones.

2. Materials and methods

The numerical study aims to clarify whether the transmission loss through a construction element depends on parameters other than the thermal resistance or the thermal conductivity and the size hereof. The numerical study is performed in three steps: analysis of a single construction element, a collection of construction elements constituting a simplified single-zone case, and a single-family house based on the standard, DS 418. These different steps are explained in the following.

To perform the numerical study on a single construction element, a cubical room is modeled with a lightweight construction element (see Figure 1). The analysis does not include air infiltration through the construction element, thermal bridges, moisture transport, material properties as a function of temperature and moisture, or 2D effects such as internal convection in the insulation layer. The simulation options in BSim comprise the systems’ regulation in every time step, calculation of sun position every 30 minutes, calculation of longwave radiation exchange between the exterior surfaces and the sky, along with the Perez model for the solar radiation distribution. A validation of the BSim simulations has been performed using COMSOL Multiphysics as a reference (details can be found in [8]).

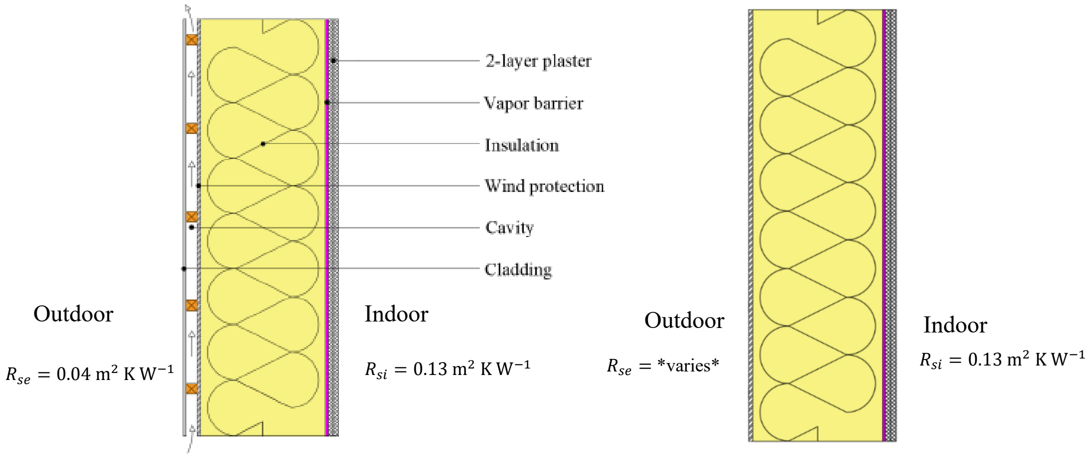

Figure 1. The BSim model and the construction element used for the numerical study. Left) Original construction element. Right) Modelled construction element. The corresponding values for the surface resistances are denoted on both the indoor (R_{si}) and exterior (R_{se}) side of each construction element.

After the study of single construction elements, the construction elements are integrated into four different types of simplified single-zone cases (see Figure 2) to investigate the effect of the dynamic calculation method compared to steady-state calculations. The simplified single-zone cases have the dimensions: (a) 1x1 m with a flat roof, (b) 1x2 m with a flat roof, (c) 1x1 m with an inclined roof, and (d) 1x2 m with an inclined roof.

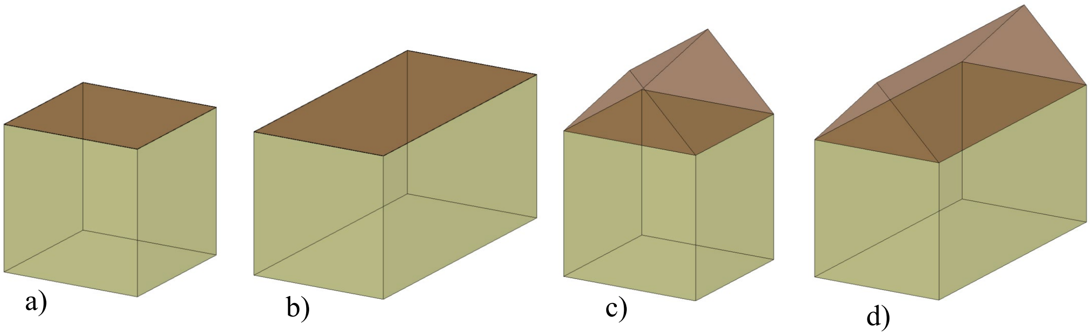

Figure 2. a) 1x1 m with flat roof b) 1x2 m with flat roof c) 1x1 m with inclined roof d) 1x2 m with inclined roof.

Finally, a parameter variation on a single-family house comprising the studied construction elements is performed (see Figure 3). The difference between the single-family house, and the simplified single-zone cases, is that the single-family house has internal walls, which add more thermal mass. Furthermore, the single-family house does not have fixed internal temperatures, as opposed to the single construction element and the simplified single-zone case study, to see if the effects of the thermal mass are more pronounced when the internal temperature can vary. The building also has windows, which adds a solar load that possibly activates the thermal mass. More information on the parameter variation can be found in [8].

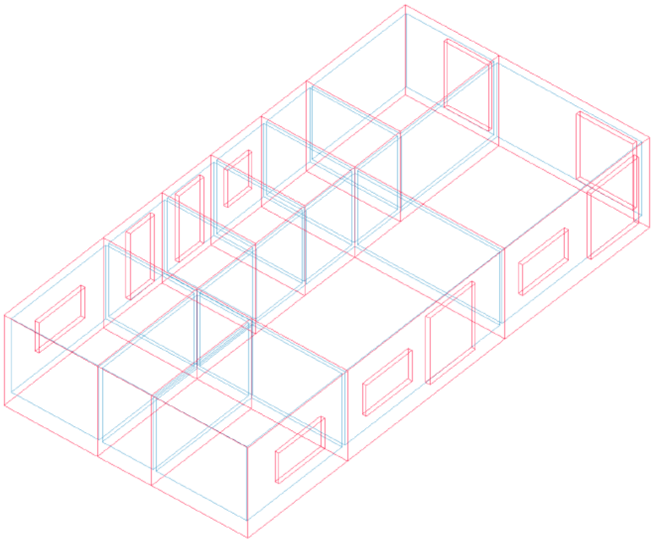

Figure 3. Single-family house based on dimensions from DS 418.

The numerical study analyzes lightweight construction elements made of three types of insulation material (see Table 1).

Table 1. Material properties of the insulation materials used in the analysis [9].

Insulation Material	Thermal conductivity $[\mathrm{W\ m^{-1}K^{-1}}]$	Density $[\mathrm{kg\ m^{-3}}]$	Specific heat capacity $[\mathrm{J\ kg^{-1}K^{-1}}]$
Wood fiber	0.033	43	1950
Glass wool	0.030	32	884
Stone wool	0.033	40	845

The first part of the numerical study investigates the differences in transmission loss between a quasi-stationary simulation and a standard DS 418 steady-state calculation for different parameters and boundary conditions. This calculation procedure is shown below.

$$\Phi_t = U\ A\ (\theta_i - \theta_e)$$

Φ_t	Transmission loss	$[W]$
U	Thermal transmission coefficient	$[\mathrm{W\ m^{-2}\ K^{-1}}]$
A	Area of construction element facing the exterior	$[\mathrm{m^2}]$
θ_i	Dimensioning indoor temperature	[°C]
θ_e	Dimensioning exterior temperature	[°C]

The quasi-stationary simulations are carried out with BSim (1-dimensional heat transfer simulations). The steady-state calculation is based on DS 418: a simplified calculation, which does not include the effects of thermal mass. For elements with high thermal mass, there is a latency response for the heat loss to occur, which is not considered in the DS 418 calculation. According to DS 418, when dealing with a ventilated cavity in the construction element, the thermal properties of the cladding layer are disregarded. Moreover, the external thermal resistance is set to be equal to the internal thermal resistance to compensate for the addition of the convective resistance [9]. Therefore, contrary to the original study case, the modeled wall does not include cladding (see Figure 1).

To highlight the difference between a quasi-stationary calculation and a steady-state calculation, multiple input parameters are varied in the numerical study. The calculation from DS 418 is used as a reference baseline. A Monte Carlo (all-at-a-time) approach is adopted to explore the input parameter variations (see Table 2). The parametric analysis is performed on the three types of study cases: the single construction element, the simplified single-zone cases, and the entire single-family house.

Table 2. Parameters varied for the construction element in the numerical study. Discrete steps are separated by a semicolon.

Parameter	Unit	Continuous	Discrete
Insulation material	$[-]$	-	Wood fiber; glass wool; Stone wool
Insulation thickness	[mm]	-	100; 200; 300; 400
Orientation	[°]	$0-359$	
Slope	[°]		0; 45; 90
Ventilation of cavity (External thermal resistance)	$[\mathrm{m^2\,K\,W^{-1}}]$	$0.04-0.14$	-
Solar absorptance of external surfaces	$[-]$	-	0.0; 0.1; 0.2; 0.3; 0.4; 0.5

The discrepancies between the methods are assessed with the correction factor *b*: the ratio between the transmission loss estimated by BSim and the one calculated with the DS 418. The correction factor is determined as the relationship between the average of the total transmission loss in September up to and including April, for all simulations performed in the parameter variation:

$$b = \frac{\Phi_{BSim}}{\Phi_{DS418}}$$

b	Correction factor of the transmission loss	$[-]$
Φ_{BSim}	Total of transmission loss for the Bsim simulation in September-April	$[\mathrm{W\,m^{-2}}]$
Φ_{DS418}	Total of transmission loss for the DS 418 simulation in September-April	$[\mathrm{W\,m^{-2}}]$

3. Results and discussion

3.1. Results for parameter variation of single construction elements

The results of the transmission loss calculations for a single construction element are presented in Figure 4.

The parameter variation shows that the slope, solar absorptance, and variation in external thermal resistance have a large impact on the transmission loss, which is not included in the steady-state calculation from DS 418. A low wind-exposed, black-colored construction with a slope perpendicular to the sun can thus present a transmission loss that is 20% lower than the reference DS 418 calculation when oriented to the South. Conversely, it can result in a 4% higher transmission loss when facing North.

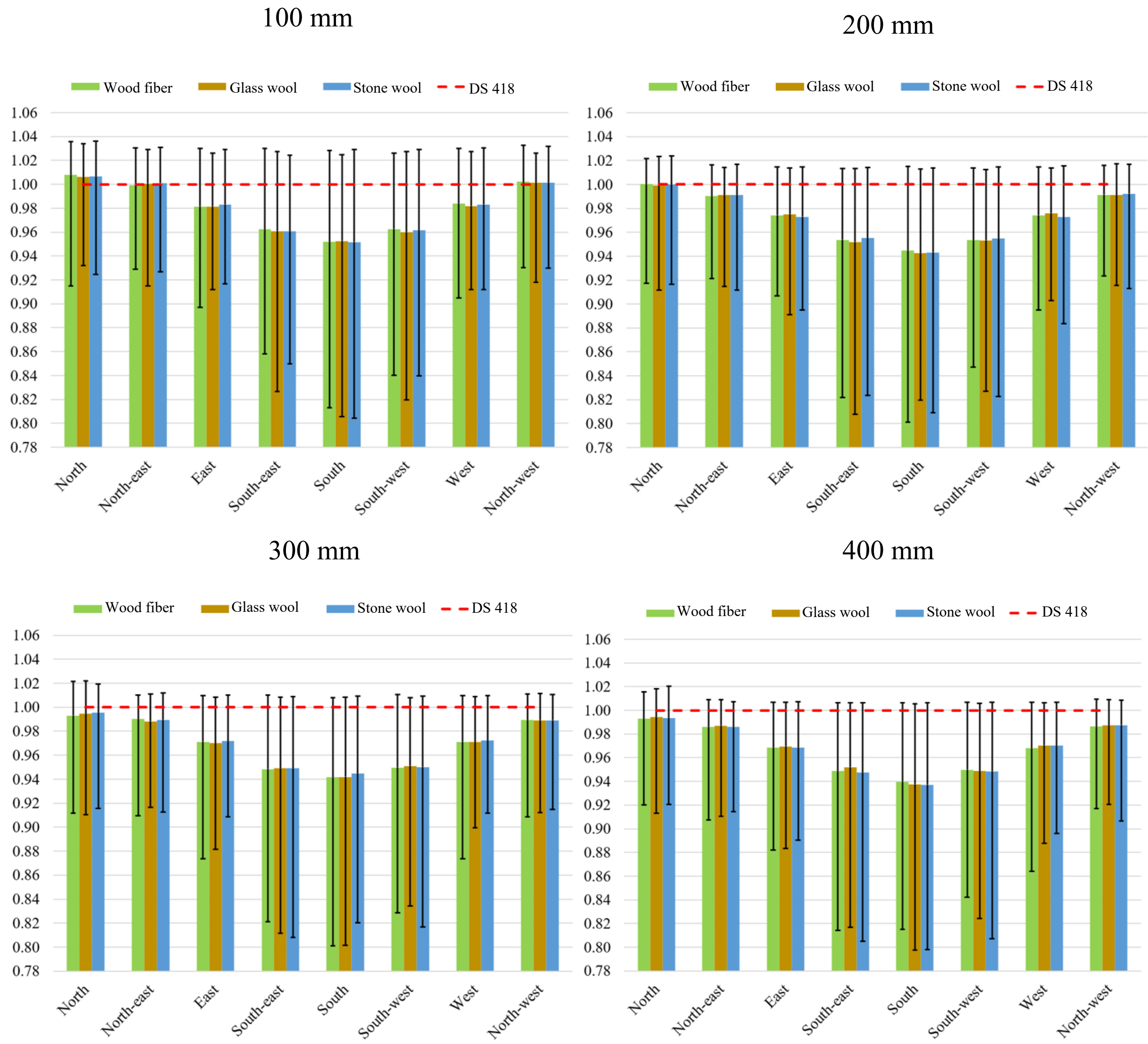

Figure 4. The ratio of transmission loss from September to April, for elements with different insulation thicknesses. The error bars indicate the variation caused by the slope, solar absorptance and the external thermal resistance. The X-axes have their origin set to 0.78.

3.2. *Results for parameter variation of a simplified single-zone case*

As the results shown in Figure 4 are only valid for a single construction element, four different simplified single-zone cases are modeled (see Figure 2) and the same Monte Carlo analysis is performed. Insulation thicknesses are not differentiated in this analysis, as the deviation across the insulation thicknesses is insignificant. The results for these simplified single-zone cases are shown in Figure 5, with the corresponding simplified single-zone cases below the figure. The figure shows the difference between the respective *b*-factors and the DS 418 calculation.

As evident by the results in Figure 5, when the heat loss for a collection of construction elements is aggregated, the deviations of dynamic simulations compared to steady-state calculations diminish. This is due to the fact, that the extreme scenarios illustrated by Figure 4, are only for a single surface under ideal circumstances. The other surfaces of a building will not be subject to the same favorable circumstances, meaning that the total transmission loss will not deviate as much from the DS 418 calculation when the transmission loss from all surfaces of a simplified single-zone case is aggregated.

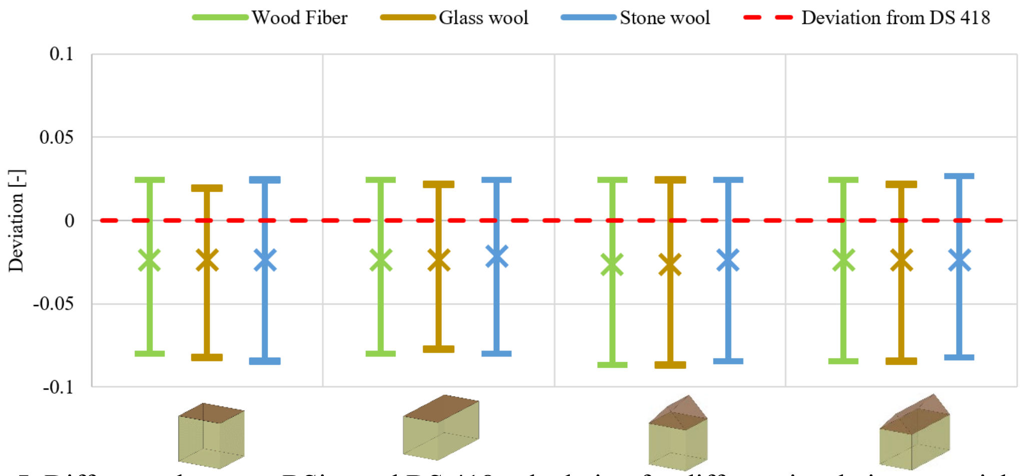

Figure 5. Difference between BSim and DS 418 calculation for different insulation materials and simplified single-zone cases, see the indication below the figure. The dotted red line indicates perfect correspondence between BSim and the DS 418 calculation, the crosses indicate the mean value and the bars indicate the minimum and maximum values. The variation is caused by solar absorptance and variation in external thermal resistance.

3.3. *Results of the parameter variation for a single-family house*

The simulations in this parameter variation on a single-family house include modeling of internal walls, windows, and varying indoor temperature, as this is more realistic and account better for the thermal mass of the building. As shown in Figure 6, there is only a marginal difference between the dynamic and steady-state calculation, meaning that the advantage of having a higher thermal mass in the wood fiber insulation is insufficient to make a significant impact on the transmission loss.

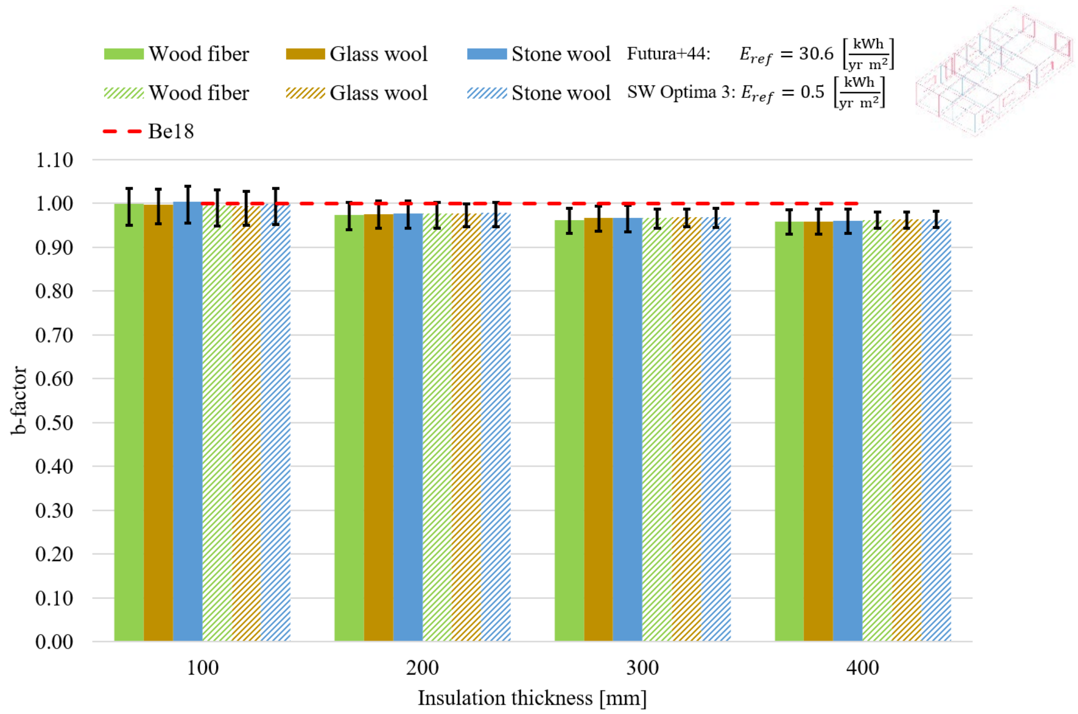

Figure 6. The ratio of transmission loss from September to April between dynamic and steady-state calculation. The fully colored bars consists of models with the window Futura+44, and the checkered bars consists of models with the window SW Optima 3. The dispersion is caused by solar absorptance, orientation of the house and the variation in external thermal resistance.

From this final analysis, it can be concluded that even with the addition of more thermal mass in the building, windows, and the use of solar irradiance in the weather file, the difference in doing a dynamic calculation and having an insulation material with more thermal mass, is insignificant.

3.4. *Sensitivity analysis of parameter variation using the TOM method*

A sensitivity analysis (SA) is performed to clarify the relationship between the contribution the input parameters have on the output and hereof rank the input parameters. The TOM method is used for SA, as it is computationally cheap and independent of the non-linearity and non-additive nature of the model [10]. The SA is performed on the parameter variation on a single construction element. As shown in Figure 7, it demonstrates a similar ranking of the input parameters in all cases. Note that the insulation thickness and insulation material properties are not varied, as only the secondary parameters of the detailed BSim model are investigated. The color of the external cladding (solar absorptance) is the most influential input parameter with a sensitivity of approximately 40% for all thicknesses. This parameter is mainly responsible for causing a deviation when including dynamic conditions. The remaining input parameters are almost equally influential. However, wind exposure is slightly more important for smaller insulation thicknesses, and the material is slightly more important for larger insulation thicknesses.

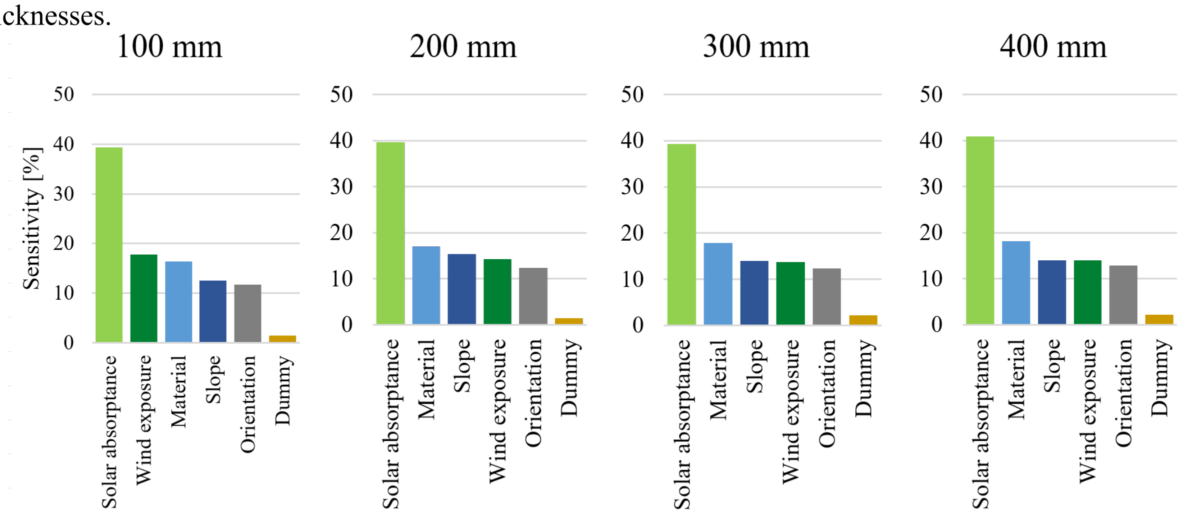

Figure 7. The sensitivity of the input parameters with respect to the transmission loss for elements with the indicated thickness of insulation. The dummy variable constitute a variable with random noise that does not influence the model, and is used as a benchmark for insignificance.

4. Conclusions and suggestions for further work

The numerical study hypothesized that insulation materials with higher thermal mass, such as wood fiber, will perform better with regard to the transmission loss and energy needs for heating in dynamic conditions. This would mean that the dynamic calculation would deviate from the steady-state calculation. The more detailed calculation procedure and the inclusion of multiple inputs, such as the orientation, color, and level of wind exposure for the construction element, do not indicate a significant deviation. The numerical study does not include 2D heat transfer effects, where materials with higher density might be beneficial for reducing heat transport by convection inside the insulation layer, which might be significant in thick vertical wall elements subjected to large temperature differences.

The numerical study on the single-family house concluded that even when a more realistic scenario is used, with the inclusion of thermal mass from internal walls and windows, the deviation between the steady-state and dynamic simulations is not significant, as the thermal mass does not significantly change the transmission loss over long periods of time. In practice, this means that the thermal mass of an insulation material should not be a deciding factor when choosing an insulation material for a construction element.

In the sensitivity analysis, the most significant input parameter was identified as the solar absorptance, while the remaining parameters had a similar sensitivity, with the wind exposure becoming less influential for thicker insulation layers, and the material being more influential for thicker insulation layers.

More work should be done for the accurate dynamic modeling of phenomena such as the internal convection inside insulation layers, which can negatively impact the thermal performance of the construction element. This is currently not implemented in the BSim software (therefore disregarded in this study) but can be accounted for in numerical tools like COMSOL Multiphysics.

Furthermore, moisture transport and construction defects resulting from poor craftmanship in the construction elements are not modeled here. If accurately modelling these factors, the difference between dynamic and steady-state simulations might lead to more significant differences. More accurate modeling of 2D-3D effects and complex dynamic phenomena could help close the performance gap between building performance software and observed heating demand in real buildings.

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