BIM-based building physics modelling of ventilated façade systems

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Abstract

In this study, a BIM-based building physics modelling of a ventilated façade of a multistorey residential building was made to obtain the thermal performance of the construction. The workflow is performed in an open BIM environment using Archicad to create the model and Comsol Multiphysics for performing the numerical simulations. After creating a suitable workflow and performing the finite element simulations, we determined the thermal impact of the supporting brackets and the dowels securing the thermal insulation, respectively. We also calculated the thermal performance using simplified methods according to standards to evaluate the BIM-based results.

Introduction

The construction industry is one of the least digitized industries and one of the most significant sources of human output. However, thanks to the 4th industrial revolution, building information modelling (BIM) in the construction industry over the last decade is becoming more widespread, which is essential to bridge the gaps between digitization and construction sites. Nowadays, professionals use mostly CAD software for the design process of ventilated façade systems. Hence, the development of complex details is rarely carried out on a BIM basis. The energy performance design of these structures is most often done only by simplified methods or, in rare cases, by separate numerical modelling of the details. Whole building energy performance models also usually neglect the effect of thermal bridges or use simplifications in the simulation procedures. Thus, the complex behaviour of the entire ventilated façade system is not modelled, so the optimal design of the fastening system is not conceivable unless a building physics model (BPM) is made of the entire structure.

Ventilated façade cladding systems have received considerable attention in recent years [1], because in addition to their favourable thermal properties, they also have a few other beneficial properties, which is why they are used in renovation projects and new office buildings. They are designed to protect and keep dry the walls and thermal insulation of the building and reduce the thermal stress and thermal movement of the walls, thus ensuring a longer life of the building, and to avoid cracks due to the movement of the building by fixing the façade envelope with brackets. They have very favourable sound insulation properties thanks to the "mass-spring-mass" construction principle and are made with dry technology, so they can be constructed all year round and require little maintenance. In the air gap, the air flows from the bottom to the top due to the horn effect, and to ensure this effect, a minimum air gap of 4 cm is typically required, but this depends on, among other things, the height of the building and the width of the supporting wall. Because of the chimney effect, great attention needs to be paid to fire protection, as fire can spread much more easily in these ventilation gaps due to the upward air flow, so it is important that non-combustible insulation is chosen.

The design process for assembled, rear ventilated façade cladding systems is still almost exclusively carried out in the industry using CAD software, with complex details rarely being developed on a BIM basis. The building physics design of these details and of the façade design itself is most often carried out using standard based simplified methods and by using thermal bridge catalogues or, less frequently, by separate numerical modelling of the details, thus not modelling the combined behaviour of the whole ventilated façade cladding system. Detailed calculations can be carried out within the framework of numerical modelling [2-4], as there is currently no calculation method in standards regarding the effects of the supporting brackets. The traditional method for energy simulations is to numerically input architectural data or to build a two-dimensional model using the integrated user interface of the software, but this process is effort intensive. With the introduction of BIM, 3D modelling is becoming more prominent, thus the time required to model architectural geometries can be reduced. The possibilities offered by BIM allow the integration of building energy and building physics calculations and modelling directly into the architectural design process. Building physics modelling, in contrast to building energetics, is typically used for micro-level studies: 3D analysis of complex building constructions. The next step is therefore to harmonise BIM with BPM for more accurate and optimised modelling of façade cladding systems, which interoperability can lead to improvements in reducing costs and design times. In this paper, we demonstrate a BIM to BPM workflow on Open BIM basis to calculate the total thermal transmittance of a wall construction with ventilated façade system.

Materials and Methods

Construction of the ventilated façade system

During the research, a thermal analysis of a ventilated façade cladding of a 3-storey, flat-roofed office building was carried out (see Fig. 1.). The load-bearing walls of the chosen building are made of hollow ceramic masonry blocks based on Wienerberger PTH 30 N+F, on which 1-1 cm internal and external airtight plaster, 15 cm fibrous mineral wool insulation, and façade cladding were applied. The U-value of the wall without thermal bridging is $U_w = 0.175$ W/m^{2}K. The vertical supporting frame is to be fixed with fixed or sliding points, for which small and large brackets were used. The brackets shall be fixed to the masonry with self-tapping screws of the same system. The vertical support frame is made of Hilti MFT-L-based profiles (see Fig. 2), which are placed between the points where the insulation boards are joined in the façade layout, to reduce the number of insulation boards to be cut, thus reducing the effect of thermal bridges. The horizontal support frame is made up of Hilti MFP-HT 200-based hanger profiles, to which the façade cladding panels are fixed. It is important to note that the external cladding has been neglected in the modelling because the aim of the research is to investigate the thermal impact of the fixing elements piercing the thermal insulation, for which it is sufficient to consider the elements in direct contact with the supporting elements, such as the supporting masonry wall, plaster, thermal insulation, brackets, and dowels. The straight order flat roof ($U_r = 0.151$ W/m^{2}K) includes 25 cm thermal insulation below the waterproofing and above the vapour barrier on a 20 cm reinforced concrete slab. The basement slab was constructed having 25 cm thermal insulation below the 20 cm reinforced concrete slab and 7 cm estrich have $U_b = 0.148$ W/m^{2}K. The windows and doors are triple glazed with low-e coatings with plastic spacers and thermal insulating reinforced plastic frames with the $U_{wd} = 0.8$ W/m^{2}K.

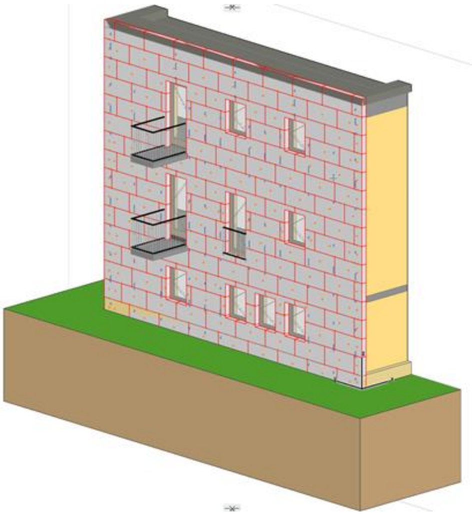

Fig. 1: BIM model of the façade of the office building, modelled in Archicad 25

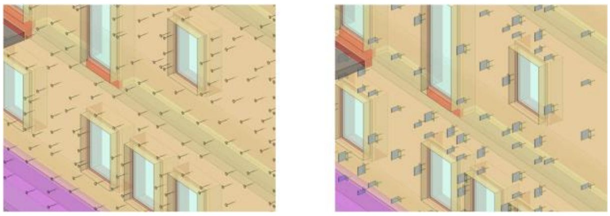

Fig. 2: Design of dowels (left) and brackets (right) in the building physics model in Comsol Multiphysics

The designed ventilated façade's external surface area was 106.28 m^2 and the internal surface area was 70.06 m^2. The adjoining flat roof and basement wall was modelled with 4.73 m^2 internal surfaces, while windows and doors were 13.10 m^2. After the design of the façade, we obtained the quantities of the used dowels (444), fixed brackets (69), sliding brackets (107) and mechanical fasteners of the brackets (283). Therefore, we obtained that 6.34/m^2 dowels for the thermal insulation, 0.98/m^2 fixed brackets and 1.53/m^2 sliding brackets were applied (see Fig. 2).

BIM to BPM workflow

The BIM to BPM workflow is developed using [5]. The geometrical model was created in Archicad 25 with the highest possible precision (10^{-4} m) and had to be imported in IFC format to be used for subsequent building physics simulations. The IFC then converted into a STEP file using Rhino 7 with the GeometryGym plugin (see Fig. 3). In this case, all non-geometrical data is deleted from the model, but the necessary precision of the solid body model for meshing (10^{-8} m) can be provided, which is much higher requirement than BIM systems can produce nowadays. The STEP file can be imported into the numerical thermal modelling environment, which was Comsol Multiphysics 5.6, based on the calculation methodology described in ISO 10211:2017 [6].

Fig. 3: Workflow of the used BIM to BPM process

The following workflow was developed to handle BIM to BPM modelling:

1. Geometry modelling in Archicad using layers or colors to provide material groupability during FEM. During IFC conversion and export, export an exploded BREP geometry, parametric extractions cannot be used properly. We can save the whole building or parts of it.
2. IFC to STEP conversion in Rhino using GeometryGym plugin, the model should be checked and repaired as necessary if the tolerance does not meet the required level.
3. Export the checked and repaired 3D model to a STEP file. STEP files turned out to be the most robust to be used in numerical modelling.
4. STEP import to COMSOL, form union generating solid domains (requires 10^{-6} m tolerance) then automatic geometry and material sorting based on

colors or layers. If form union can't performed, the model has to be repaired again.

5. Meshing is advised to run right after importing the geometry, since it requires the highest tolerance and has the highest amount of failure possibility when the geometry comes from BIM systems with lower precision.
6. After meshing is done, material properties (thermal conductivity) needs to be assigned to individual or grouped domains. Source of material properties could be ISO 10456 [7].
7. Assign boundary conditions to internal and external surfaces. Source could be ISO 6946 [8].
8. Define probes to obtain the required results after the simulations. Probes can be assigned to domains, surfaces, lines or points. Minimum, maximum, average or integral temperature and heat fluxes also can be obtained.
9. Perform the numerical simulatons, then visualise it or export the results from probes to further evaluation.
10. Postprocessing of the results could be performed in COMSOL or in external softwares (e.g. EXCEL).

Simplifications of the BIM based thermal modelling

The workflow is complex, with many pitfalls: it was necessary to simplify and limit both the geometric and the building physics models to reduce the number of errors. The following simplifications and limitations were used during the modelling, shown in Fig. 4:

1. Adequacy of space boundaries
2. Validity of boundary conditions
3. Computational simplifications
4. Use of standards and its simplifications
5. Geometric simplifications
6. Perfectly executed structures
7. FEA compatible model assumed to be airtight
8. Steady-state physics
9. Only heat conduction occurs
10. Planar internal surfaces used for U-value calculation
11. Materials modelled using simple geometry and equivalent thermal conductivity
12. Construction inaccuracies are neglected

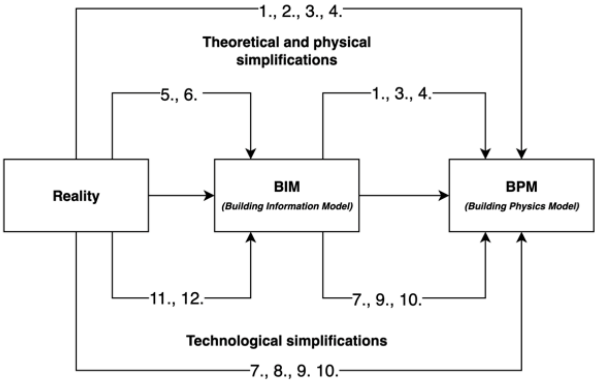

Fig. 4: Simplifications used in the BIM-based modelling

Numerical modelling methodology

In the numerical simulations, to calculate the resulting thermal transmittances, firstly, the adjoining building envelope elements' thermal transmittance shall be calculated. We calculated the U-value of the wall, flat roof and the basement slab ignoring the thermal bridges according to ISO 6946 [8], as well as obtained the U-value of the windows and doors. We modelled the ventilated façade with four cases to be able to model the individual effects of the fastening system: Case 1) without dowels and brackets; Case 2) including dowels and without brackets; Case 3) including brackets and without dowels; Case 4) including dowels and brackets.

The numerical model is set using the geometry from the BIM model for each case. The partial differential equation of steady-state heat conduction is solved in Comsol Multiphyiscs 5.6 according to the following equation:

$$\nabla \mathbf{q} = \nabla(\lambda_{eff}\nabla T) = 0 \tag{1}$$

The boundary conditions are set using Eq. 2 and Eq. 3:

$$-\mathbf{n}\cdot\mathbf{q} = d_z\left(h_{ci} + \varepsilon\cdot 4\cdot\sigma\cdot {T_{m,i}}^3\right) \tag{2}$$

$$-\mathbf{n}\cdot\mathbf{q} = d_z\left(h_{ce} + \varepsilon\cdot 4\cdot\sigma\cdot {T_{m,e}}^3\right) \tag{3}$$

where in Eq. 2, h_{ci} is the internal convective surface heat transfer coefficient (2.5 W/(m^2·K)), ε is the longwave emissivity of the surface (0.9), σ is the Stefan-Boltzmann constant ($5.67\cdot10^{-8}$ W/(m^2·K^4)) and T_{mi} is the mean thermodynamic temperature of the internal surface and its surroundings set to 293.15 K according to MSZ 24140 [9]. In Eq. 3, $h_{ce} = 4 + 4\cdot v$, where v is the wind speed in [m/s] set to 4 m/s according to [8] and T_{me} is the mean thermodynamic temperature of the external surface and its surroundings in Kelvin set to 268.15 K according to [9].

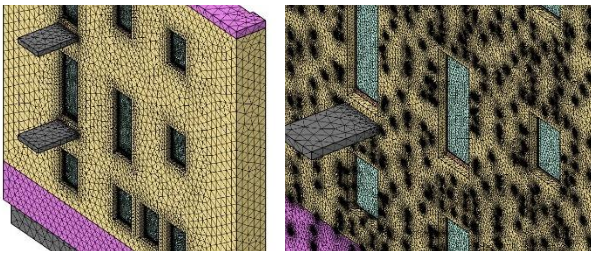

Fig. 5: Finite element mesh of Case 1 (left) excluding the fastening system and Case 4 including both dowels and brackets (right)

Fig. 5. shows the finite element mesh, that is created using simplex elements (tetrahedrons), and the mesh statistics are summarized in Table 1 for all cases. The meshing and simulations were performed by a workstation including AMD Ryzen Threadripper 2950X CPU, 128 GB RAM, Nvidia Quadro RTX 4000 GPU and 2 TB SSD.

Table 1: Mesh statistics of the numerical modelling cases

Model	Elements	Nodes	Meshing time
Case 1	285,912	556	5.71 s
Case 2	7,882,536	21,784	277.91 s
Case 3	8,132,999	21,022	222.03 s
Case 4	7,058,738	42,306	1,198.81 s

To obtain the thermal performance of the façade from the numerical modelling, the total heat flux from the internal surfaces of the construction were collected. The total thermal transmittance of the façade shall include the effect of the fastening system (dowels and brackets) as well as the effect of the linear thermal bridges. Latter can be calculated if we perform modelling without the fastening system and subtract all envelope elements' heat transfer coefficient from the numerically obtained total heat transfer coefficient of the façade. Therefore, we obtained Q_1 total heat flux [W] from the model containing the linear thermal bridges as well as the heat loss through the flat roof ($A_r U_r$), basement slab ($A_b U_b$), walls ($A_w U_w$), and windows and doors ($A_{wd} U_{wd}$). If we subtract the heat loss of the adjoining building elements from the total heat loss (obtained by dividing the heat flux with the temperature difference ΔT of 25 K) and normalize it with the internal wall surface (A_w), we can get a correction term $\Delta U_{TB,sim}$ including only the effect of linear thermal bridges due to the adjoining building envelope elements:

$$\Delta U_{TB,sim} = (\frac{Q_1}{\Delta T} - A_r U_r - A_b U_b - A_w U_w - A_{wd} U_{wd})/A_w \quad (4)$$

We also obtained correction terms representing the point thermal bridge effect of the mechanical fasteners, the dowels ($\Delta U_{f,sim}$), brackets ($\Delta U_{b,sim}$) and the whole fastening system ($\Delta U_{fs,sim}$) from the four different cases simulated using the following equations:

$$\Delta U_{f,sim} = (Q_2 - Q_1)/(A \cdot \Delta T) \quad (5)$$

$$\Delta U_{b,sim} = (Q_3 - Q_1)/(A \cdot \Delta T) \quad (6)$$

$$\Delta U_{fs,sim} = (Q_4 - Q_1)/(A \cdot \Delta T) \quad (7)$$

In the notation you can observe that Q1 is calculated from Case 1, Q2 from Case 2, etc. Therefore, the total thermal transmittance including the effect of linear thermal bridges as well as the fastening system can be calculated using the following equations regarding of different modelling cases:

$$U_{w,tot,sim,1} = U_w + \Delta U_{f,sim} + \Delta U_{b,sim} + \Delta U_{TB,sim} \quad (8)$$

$$U_{w,tot,sim,2} = U_w + \Delta U_{fs,sim} + \Delta U_{TB,sim} \quad (9)$$

$$U_{w,tot,sim,3} = (\frac{Q_4}{\Delta T} - A_r U_r - A_b U_b - A_{wd} U_{wd})/A_w \quad (10)$$

Later (in Table 2.) we refer to these 3 calculation methods as Sim,1 (described in Eq. (8): adding the correction factors calculated from Case1 and Case2 to the U_w baseline), Sim,2 (described in Eq. (9): adding the correction factor from the full numerical model) and Sim,3 (described in Eq. (10): using the numerical model as the source of total heat loss). Case 1 is used to determine the linear thermal bridges, as that model doesn't include any point thermal bridging. Case 2-4 are the basis to compare point thermal bridges originating from various building subsystems.

Simplified calculation for comparison

The total thermal transmittance was also calculated using simplified methods, that are often used during design. The geometry data is taken from the BIM model for the calculations. The correction term for thermal bridges are obtained based on the Hungarian regulation [10]. During energy performance certification of buildings, the simplified method for considering thermal bridges is to evaluate the length of thermal bridges (adjoining building elements with the wall), including the wall corners, window installation, flat roof, intermediate slab and basement slab. The total length is 98.65 m in the modelled building, which divided by the internal surface are of the wall gives 1.41 m/m^2 specific quantity, therefore the thermal bridging coefficient for insulated walls are $\chi = 0.3$ meaining we have to increase the corrected U-value of the wall (which includes the effect of the dowels and brackets) by 30% due to thermal bridges. If we the subtract the U-value of the wall from the increased value, the thermal bridging correction term is found:

$$\Delta U_{TB,simp} = U_{w,corr} * (1 + \chi) - U_{w,corr} \quad (11)$$

The correction term $\Delta U_{f,simp}$ regarding of the dowels can be calculated using ISO 6946 [8], while for obtaining correction terms of the brackets, we used the Hilti thermal bridge catalogue [11], from which we included both fixed ($\chi_{fixed} = 0.0534\ W/K$) and sliding ($\chi_{fixed} = 0.0336\ W/K$) brackets fixed on masonry:

$$\Delta U_{b,simp} = n_{fixed} * \chi_{fixed} + n_{sliding} * \chi_{sliding} \quad (12)$$

Therefore, the calculation of the façade's total thermal transmittance using simplified methods is the following:

$$U_{w,tot,simp} = (U_w + \Delta U_{TB,simp} + \Delta U_{f,simp} + \Delta U_{b,simp} \quad (13)$$

Results

Numerical modelling

After the numerical thermal modelling was performed, the results were visualised in 2D horizontal and vertical sections. The temperature distribution in the modelled façade is given Fig. 6-9 including all cases. Fig. 6. shows Case 1, where the fastening system (dowels and brackets) were neglected, therefore the point thermal bridges are not included. However, it is visible that the adjoining building envelope elements create linear thermal bridges next to the perimeters of the slabs, windows, and doors. Nevertheless, temperature factor of the internal surfaces was above 0.8 everywhere in the construction, therefore hygrothermal problems in the structure are not expected.

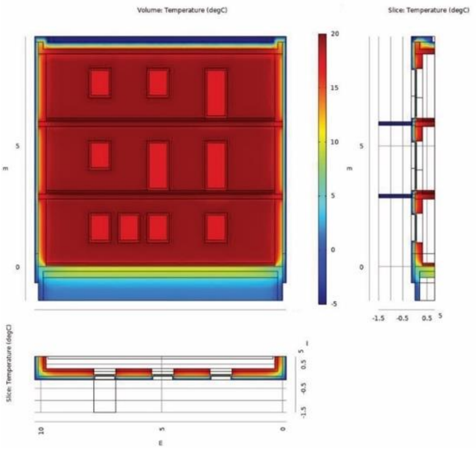

Fig. 6: Temperature distribution of Case 1

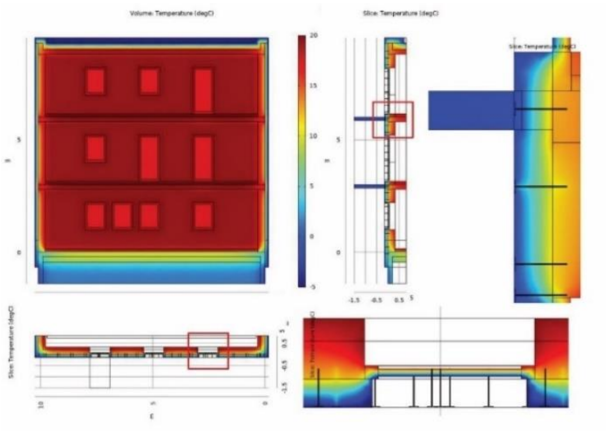

Fig. 7: Temperature distribution of Case 2

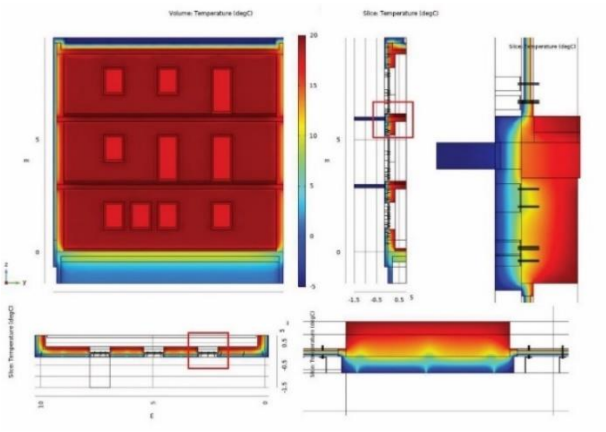

Fig. 8: Temperature distribution of Case 3

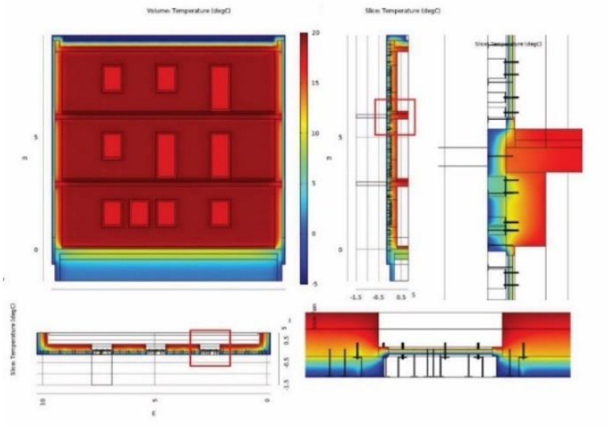

Fig. 9: Temperature distribution of Case 4

For the cases where mechanical fasteners were included, details were also evaluated (see Fig. 7-9). It is observable that dowels and brackets caused point thermal bridges change the temperature distribution around them, mostly in the thermal insulation and slightly in the masonry blocks. Although the temperature distribution and heat flow magnitude only change nearby the mechanical fasteners. Therefore, the fastening systems has only minor, almost negligible effects on the internal surface temperatures, which are still resulted above the 0.8 temperature factor.

Thermal transmittances

The simulated total thermal transmittances are calculated using Eq. 8-10. The total thermal transmittance was also calculated using simplified methods using Eq. 13. The results of the BIM-based simulated and simplified results were summarized in Table 2.

Table 2: Total thermal transmittances and their components

Refer to Eq. 8-10.	**Simulated results**			**Simplified calculation (W/m^2K)**
	Sim,1 (W/m^2K)	**Sim,2 (W/m^2K)**	**Sim,3 (W/m^2K)**	
U_w	0.1754	0.1754	-	0.1754
ΔU_f	0.0124	-	-	0.0151
ΔU_b	0.0325	-	-	0.1047
ΔU_{fs}	-	0.0420	-	-
$U_{w,corr}$	0.2203	0.2174	-	0.2952
ΔU_{TB}	0.134	0.134	-	0.0886
$U_{w,tot}$	0.3543	0.3514	0.3514	0.3838

According to Table 2, if we simulate and obtain the correction terms of dowels and brackets from individual cases, the correction term of the mechanical fastening system is 7% higher (0.0449 W/m^{2}K) than modelling them together (0.0420 W/m^{2}K). This shows that the effect of thermal bridges can't really be superposed sufficiently, however, the error is now on the safe side and the individual results does not show huge differences, therefore we can claim that they can be used for calculations to spare computational resources. It is noteworthy, that if we handle together Case 1-3, their combined meshing time was only about 42% of Case 4 (see Table 1), as well as the simpler cases required less RAM during simulations due to the lower number of nodes. Modelling the whole façade including the mechanical fastening system (Sim,3) gave equal results to Sim,2, where thermal bridging and the mechanical fastening system came from different cases. It shows that the linear thermal bridges did not change visibly the point thermal bridge effects of the dowels and brackets.

The corrected thermal transmittance of the walls was 0.22 W/m^{2}K according to numerical simulations, which complies with the limit value, $U_{max,wall} = 0.24\ W/m^2K$ of the Hungarian regulation [10]. The correction term responsible to handle the effect of the linear thermal bridges were 0.134 W/m^{2}K according to the numerical simulations, therefore we got $U_{w,tot,sim} = 0.35\ W/m^2K$.

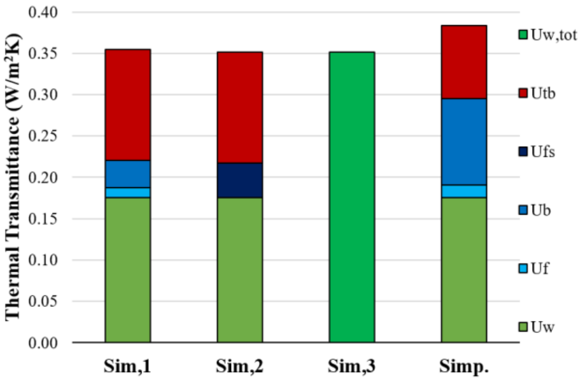

Fig. 10: Components of the total thermal transmittance

Comparing the simplified calculations to the numerical simulation results, the correction term for dowels were 22% smaller using numerical modelling, therefore the simplified calculation according to ISO 6946 [8] is on the safe side and can be used simplified calculations. The correction term for brackets is considered according to a thermal bridge catalogue [11] and gave more than three times larger result than numerical modelling. This could be because in the thermal bridge catalogue, the used hollow masonry blocks were different than ours, the thermal conductivity of the materials does not comply with ISO 10456 [7] and the numerical models representing the brackets were much simpler. Although the correction term for the brackets is on the safe side, we did not recommend using the thermal bridge catalogue's values, especially if the masonry block is much different than what included in the thermal bridge catalogue. The corrected thermal transmittance of the wall, due to the high correction terms of the mechanical fastening system, does not comply with the limits of the Hungarian regulation, the calculated value is about 35% higher, than what we obtained from numerical simulations. This is also visualized in Fig. 10, respectively.

Comparing the correction term of linear thermal bridges, simplified calculation is not on the safe side anymore. Numerical simulation gave 51% higher correction term than the simplified calculation. The methodology and correction factors included in the Hungarian regulation [10] is not changed since 2006, therefore its values are outdated and not able to handle highly insulated building constructions. In these case, detailed calculations or numerical modelling is advised. Comparing the final results, simplified method gave almost 10% higher total thermal transmittance, than numerical simulations.

Conclusion

In this paper, we presented a BIM-based building physics modelling of a ventilated façade system. Firstly, we created a workflow to handle OpenBIM based building physics modelling, that also can be used for any kind of multiphysical modelling. Then we performed numerical thermal simulations considering different cases to obtain the total thermal transmittance of the façade walls, which are either included or excluded the mechanical fastening systems. We also calculated the results using simplified methods based on standards and regulations.

The results showed that numerical modelling gave lower corrected wall thermal transmittance as well as total thermal transmittance than simplified results. However, the effect of the brackets was significantly higher, while the effect of linear thermal bridges was significantly lower, if we compared the numerical modelling results to simplified methods.

The demonstrated BIM-based numerical thermal performance simulation workflow provides essential and gap-filling information for practical, BIM-based facade design and BIM-based building physics modelling.

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