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COMPARISON OF THERMAL BRIDGE CALCULATION METHODS

Balázs Nagy*, Martin Marosvölgyi, Zsuzsa Szalay

Budapest University of Technology and Economics, Faculty of Civil Engineering, Department of Construction Materials and Technologies, 3 Műegyetem rakpart, H-1111 Budapest, Hungary

* corresponding author: nagy.balazs@emk.bme.hu

Abstract. We need to consider linear heat losses due to thermal bridges for the accurate calculation of building heat losses. Our research examined a whole building, and different thermal bridge calculation methods were compared. The following techniques were included in the study: a simplified method according to the Hungarian energy performance regulation where the effect of thermal bridges can be taken into account by multiplication factors applicable to thermal transmittances; a simplified thermal bridge catalogue of ISO 14683; a recent national thermal bridge catalogue; two-dimensional thermal modelling as well as a conjugated heat and moisture (HAM) simulation considering steady-state and dynamic conditions. Overall, we created eight different numerical modelling approaches depending on the type of simulation and boundary condition. The modelling and simulations were carried out using multiphysics software based on the finite element method according to ISO 10211 and EN 15026. All the relevant details of the building were analysed to get a complete picture. Based on the results, we analysed each method's relative proportions of surface and linear heat losses. The evaluation showed that the Hungarian simplified method generated the lowest heat losses for thermal bridges, while ISO 14683 produced the highest results, with the numerically simulated results in the middle. The overall heat losses varied by 30 %, depending on the thermal bridge calculation method. Linear heat losses were between 12 % to 32 % of the surface heat losses. Our study helps to choose the adequate method to perform thermal bridge simulations.

Keywords: Thermal bridges, building constructions, heat and moisture transfer, numerical modelling.

1. Introduction

As a result of trends and stricter legislations in recent years, our buildings today are built with a significant amount of thermal insulation compared to the past. Buildings can be designed with different building constructions, but poorly designed details are implemented in many cases. Linear thermal bridges are responsible for a significant percentage of energy losses in buildings, even with a consciously designed thermal insulation, but this percentage increases further with inappropriate joint constructions. A better understanding of thermal bridges is essential for calculating the energy demand of buildings.

Several studies worldwide have been carried out that compare the calculation of linear heat losses and their share in the total energy balance of buildings. In most studies, there are significant differences between the methods used [1, 2]. This study aimed to compare these methods to investigate the thermal bridge effect using a nearly zero-energy residential building as a case study, which is considered typical for the Hungarian market. We compared the Hungarian simplified method according to the domestic energy performance regulation [3], the simplified thermal bridge catalogue according to MSZ EN ISO 14683:2017 [4], the results of a detailed national thermal bridge catalogue, and the results of complex two-dimensional heat and moisture transfer simulations with steady-state and dynamic environmental conditions.

For each thermally relevant building construction joint, the temperature factor at the internal surface (f_{Rsi}), the average thermal transmittance (U), the linear thermal transmittance due to the thermal bridging effect (Ψ), as well as the transmission heat transfer coefficient of the entire building (H_{tr}) is analysed. The minimum internal surface temperatures ($T_{s,min}$) were also determined for the numerical finite element method-based models.

2. Methodology

The examined building, built with an approximate gross floor area of $80\,\mathrm{m}^2$, with a pitched roof and partially a flat roof, provides comfort for 3–4 people and has a flat roof used as a large terrace. The house is simple, 21[st]-century, and modelled using building information modelling (BIM) software ArchiCAD 25 to create the envelope and details for energy performance and thermal bridge calculations. The used construction materials are typical for Central Europe. The building comprises ceramic hollow brick walls with a 15 cm thick expanded polystyrene external thermal insulation composite system (ETICS) achieving $U = 0.167\,\mathrm{W/m^2K}$. In comparison, the flat roof slab is monolithic reinforced concrete with 25 cm extruded polystyrene insulation having $U = 0.138\,\mathrm{W/m^2K}$. The pitched roof includes 30 cm mineral wool insulation between the rafters and has a vapour barrier layer behind the interior gypsum

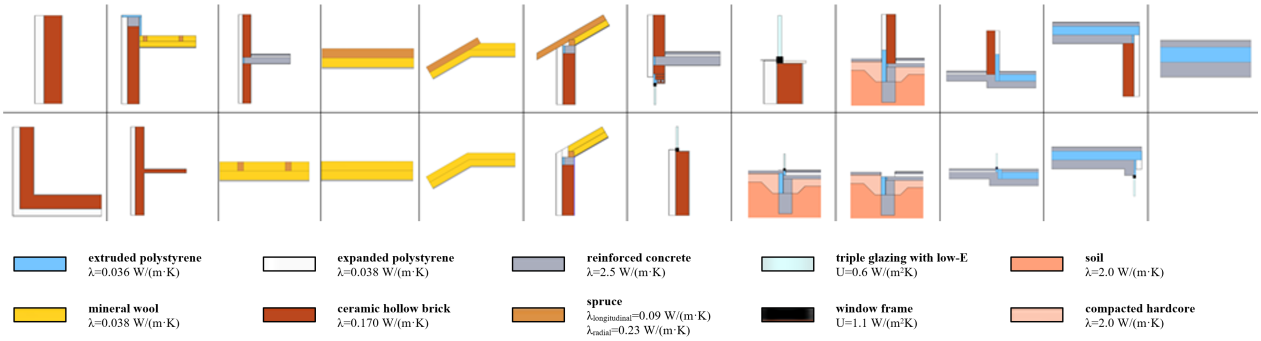

Figure 1. Analysed building construction joints of the examined building.

board interior finish, and its thermal transmittance is $U = 0.138\,\mathrm{W/m^2K}$. In the slab-on-ground, 10 cm load-bearing extruded polystyrene thermal insulation was installed above the bituminous waterproofing on the reinforced concrete base plate. The U-value of the designed layers is $U = 0.225\,\mathrm{W/m^2K}$; however, since the footing contains perimeter insulation, the U value of the ground contact floor can be reduced to $0.191\,\mathrm{W/m^2K}$.

In the research, the heat transfer coefficient of the building is calculated using different calculation methods and was compared together. Firstly, the simplified calculation procedure was carried out. The transmission heat losses were determined based on the specific length of thermal bridges according to Hungarian building energy performance regulation TNM decree 7/2006. [3]. The specific length shall be calculated by dividing the length of the specific joint (e.g., wall corner) by the area of the connecting surfaces (e.g., façade walls). Then based on the result, the thermal bridging of the joint is classified as slight, moderate, or large. According to the category, the U value of the envelope element should be multiplied by a correction factor included in tabulated form in the legislation. Additionally, the heat loss of ground contact structures was determined according to ISO 13370:2017 [5].

In the case of the detailed calculation, the linear thermal transmittances of the thermal bridges can be obtained from the standard ISO 14683:2017, which can be used as a simple thermal bridge catalogue. For this purpose, we need to know the type and length of the thermal bridge and its material composition. If the detail can be found in the standard, the value of the linear thermal transmittance is obtained from its tables, which is then multiplied with the length of the thermal bridge to determine the transmission heat loss. The disadvantage of this standard is that it only covers eight different types of thermal bridges and is less varied in terms of insulation material, thickness, use of construction materials and structural design. The building constructions presented in this standard do not comply with Hungary's current energy performance requirements.

The heat transfer coefficient of the building was also determined with a new Hungarian thermal bridge catalogue containing linear thermal bridges generated by mainly domestic products and building constructions [6]. In contrast to the ISO 14683:2017 [5] standard, this is a much more detailed catalogue. In total, the thermal bridge catalogue contains about 21 thousand linear thermal transmittance values for the most typical building detail designs, with a particular focus on building materials from domestic product manufacturers (more than 50 different masonry blocks with different building construction designs, several types of slab constructions, etc.). Building materials used to create the catalogue were modelled based on performance data published by manufacturers or distributors.

Besides simplified calculations and using a different kinds of thermal bridge catalogues, numerical modelling was also deployed to calculate the linear thermal transmittances of the examined building. The geometry for the numerical finite element analyses was modelled according to ISO 10211:2017 [7], neglecting details that are not thermally relevant (e.g., roof tiles, roof battens, counter battens, etc.). The model, which includes the central element, is bounded by cut-off planes. The geometric dimensions used to create the model are more extensive than those specified in the standard. The distance between the cut-off plane and the central element is at least three times the structural thickness, or at least 1 metre. Where possible, a 1.5 m distance was taken from the central element. A total of 4 surfaces and 15 linear thermal transmittance values were determined using numerical modelling. Together with the reference tests, numerical finite element analyses were run on 23 different geometries (see Figure 1).

However, not only steady-state numerical models were created. Seven different studies were considered for each construction joint: three steady-state and four dynamic-state.

Two different thermal models were investigated and a conjugated heat and moisture transfer model in a steady state. In the thermal models, the design is assumed to be completely dry (0 % relative humidity) in the first condition, while in the second condition, relative humidity of 50 % is assumed. Former is test-

Building envelope components	U-values (with thermal bridge effect) [W/m2K]	Surface heat transfer coefficient [W/K]	Linear heat transfer coefficient [W/K]	Total heat transfer coefficient [W/K]
External wall	0.218	23.78	7.13	30.92
Flat roof	0.152	4.08	0.41	4.49
Pitched roof	0.159	3.50	0.52	4.02
Ceiling of pitched roof	0.152	6.04	0.61	6.65
Ground contact floor	0.191	12.35	-	12.35
Windows and doors	Frame:1.1 Glazing: 0.6	15.46	-	15.46
Total		65.21	8.67	74.18

Table 1. Heat transfer coefficients based on simplified calculation according to [3, 5].

ing the case when building materials are modelled based on performance data published by manufacturers, who usually publish dry test results only to show the lowest possible thermal conductivity of their products. At the same time, 50 % relative humidity is assumed to be closer to real application cases; however, out of the three steady-state numerical finite element analyses, the conjugated heat and moisture (HAM) analysis is considered to be the most accurate method because it takes more physical processes into account. In steady-state conditions, the methodology described in ISO 10211:2017 [7] was used to calculate the Φ linear thermal transmittance using the L_{2D} thermal coupling coefficient taken from the numerical modelling. In steady-state conditions, the environmental conditions (outdoor and indoor air temperature and relative humidity) were statistically assumed based on the heating season in Budapest. The surface resistance values were set by ISO 6946:2017 [8].

For dynamic-state thermal models, the evaluation of the results is almost identical to the method used for the steady-state analyses. However, in the case of the dynamic study, an hourly-based simulation was conducted for 4 369 hours (length of the standard heating period between 15^{th} October and 15^{th} April in Hungary according to the previously mentioned legislation) and then averaged. However, the definition of thermal transmittance refers to steady-state conditions. Therefore, it is essential to consider before the evaluation at least the temperature difference between the different building elements at the thermal coupling coefficient from the numerical investigations. When there is only a slight difference between the internal and external temperature, the magnitude of the heat flux density decreases, but it is important to note that this decrease is not directly proportional. These excursions can be filtered out by choosing the correct minimum temperature difference. Our study chose a 10 K temperature difference to analyse the dynamic results. Four different dynamic models were created; two used dry constructions, and two used 50 % relative humidity, like the steady-state models; however, each condition was tested with solar radiation and without solar radiation, respectively. The boundary conditions were set using weather data for the dynamic study were determined according to [9]. Boundary conditions also depend on temperature, relative humidity, long and short-wave radiation, wind speed, which vary every hour. The modelled period was two years in total, of which only the heating period of the second year was considered during the evaluation. Both steady-state and dynamic numerical simulations were carried out using COMSOL Multiphysics.

3. Results and discussion

3.1. Simplified calculation according to Hungarian Regulation

Table 1 shows the heat losses based on the simplified calculation. The additional heat loss due to thermal bridges may contain significant inaccuracies, as this calculation does not consider the design of the joints. The correction factors were determined when the Regulation was adopted in 2006, based on the typical designs used at that time, which have undergone significant changes in the last decade for new buildings. The surface heat transfer coefficient of the ground contact floor was calculated using [5].

3.2. Thermal bridge catalogues

When using a thermal bridge catalogue, the surface heat transfer coefficient of the building envelope (external wall, flat roof, pitched roof, ground contact floor) is still calculated according to the simplified procedure (total: 65.21 W/K). Still, the thermal bridge heat losses are now considered with the values determined from the catalogues (Table 2). If a detail was not included in the thermal bridge catalogue, it was not considered in the calculation. The linear heat transfer coefficients clearly show that the standard ISO 14683:2017 [4] gives significantly higher values than the newer and more extensive thermal bridge catalogue published in 2020 [6]. This is mainly the reason for the differences. The ISO 14683:2017 was published in 1999 and was last updated in 2017, but neither were the values for existing designs revised nor was the standard extended to include more current details. The standard especially seemed incorrect for wall and ground contact floor joint values since it was more than ten times greater than the value

Thermal bridges	Length [m]	Linear thermal transmittance [W/(m·K)] MSZ EN ISO 14683	Thermal bridge catalogue	Linear heat transfer coefficient [W/K] MSZ EN ISO 14683	Thermal bridge catalogue
Wall corner	18.60	0.15	0.05	2.79	0.93
Wall – slab joint	20.90	0.10	0.07	2.09	1.46
Window lintel – slab joint	16.75	-	0.19	-	3.18
Wall – window joint	55.15	0.00	0.02	0.00	1.10
Wall – ground floor joint	34.80	0.75	0.06	26.10	2.09
Wall – flat roof joint	20.20	-	0.10	-	2.02
Total			30.98	10.79	

Table 2. Heat transfer coefficients based on thermal bridge catalogues [4, 6].

Model	Surface heat transfer coefficient [W/K]	Linear heat transfer coefficient [W/K]	Total heat transfer coefficient [W/K]
Thermal with 0 % RH	59.92	13.81	73.73
Thermal with 50 % RH	70.22	18.93	89.15
HAM	65.18	18.05	83.23

Table 3. Heat transfer coefficients based on steady-state numerical analyses .

from the Hungarian thermal bridge catalogue. This value generated a massive difference between the two catalogues' linear heat transfer coefficient results.

3.3. Numerical finite element analyses

The evaluation of the numerical modelling results allows us to determine the heat transfer coefficient of each envelope element (external wall, flat roof, pitched roof, ground contact floor) from the average heat flux density and the difference between the internal and external air temperature (Table 3). Out of the examined cases, the thermal model at 0 % RH gives a nearly 12 % lower value than the HAM analysis, while the joints calculated at 50 % RH provide a 7 % higher value. It is essential to know that most material or building element producer gives their materials' thermal performance data at 0 % RH since the thermal conductivity of their products could be much lower without moisture content. Most thermal calculations and thermal bridge catalogues use data right from the material producers. Although there is always moisture in constructions, therefore, HAM model is supposed to be closer to the average of the real-life behaviour than a thermal model without moisture content.

After the 10 K temperature difference data filtering, four different studies were evaluated in dynamic conditions:

(1.) with solar radiation included and with dry conditions,

(2.) with solar radiation included and 50 % relative humidity,

(3.) without solar radiation and dry conditions,

(4.) without solar radiation and 50 % relative humidity.

Among the four studied dynamic simulations, the highest heat transfer coefficient was obtained for the model with 50 % relative humidity, including the solar radiation in the analysis. In contrast, the lowest was obtained with dry conditions and without considering solar radiation (see Table 4). This could be explained by solar radiation heating up the construction, and warmer materials are less insulating, while the evaporation of the moisture was neglected in the thermal models. The overall difference comparing case (2.) to case (3.) is close to 30 %. However, if we compare case (1.) to case (3.) or case (2.) to case (4.) the difference is only 3.5–5.5 % (the cases including solar radiation were higher due to the reason mentioned above), showing that the effect of moisture in the construction is much more dominant than the effect of the solar radiation. The dynamic analysis method has the highest number of physical processes considered, and the calculation method requires the longest time of all the analysis methods presented. The speciality of this calculation method is that it requires a large computational power, which is even more pronounced than for the conjugated thermal and moisture models.

3.4. Comparison of the heat transfer coefficient of the building envelope and construction joints

In the following section, we compared the heat transfer coefficients of the building envelope and construction joint designs and the differences between numerical analysis methods. The thermal transmittances of the openings (glazing and frame) were determined using

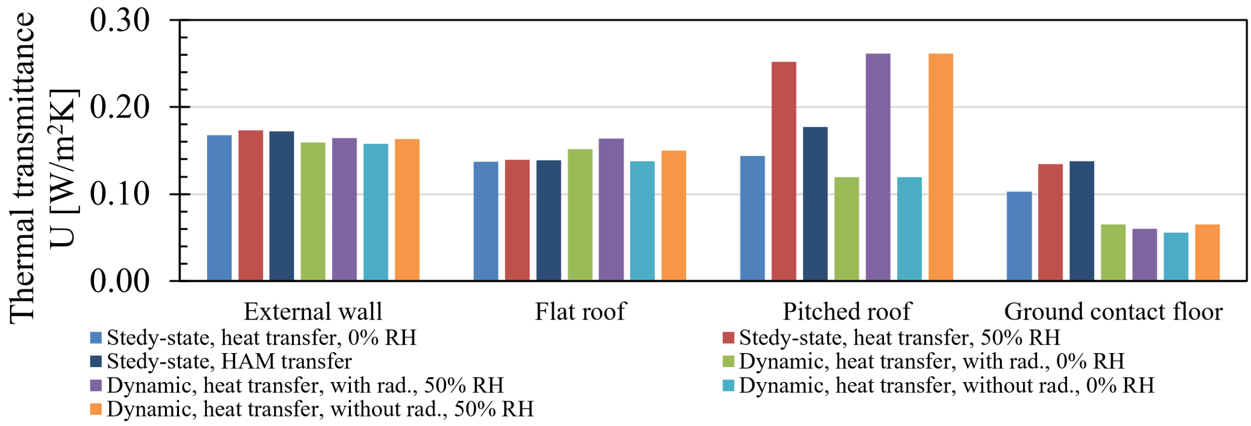

Figure 2. Thermal transmittance of the building envelope under different modelling conditions.

Model	Surface heat transfer coefficient [W/K]	Linear heat transfer coefficient [W/K]	Total heat transfer coefficient [W/K]
0 % RH w. solar radiation	55.01	16.41	71.42
50 % RH w. solar radiation	65.58	23.99	89.57
0 % RH w/o solar radiation	53.74	15.21	68.95
50 % RH w/o solar radiation	65.30	19.64	84.94

Table 4. Heat transfer coefficients based on dynamic thermal simulations.

a manufacturer's catalogue. Therefore, there is no difference for different environmental conditions in our calculations.

Observing the calculated thermal transmittances of the building envelope constructions, Figure 2 clearly shows no significant difference between the analysis methods for the external wall and flat roof constructions. However, the magnitude of the U values of the pitched roof construction is significantly influenced by the internal moisture content and for the corresponding environmental conditions (0 % or 50 % RH). Still, there is no significant difference between the steady-state and dynamic conditions. It is also visible that the steady-state condition gave higher results for the ground contact floor than the dynamic analysis method. This is because we can include the heat storage and the soil under the floor that significantly influence heat transfer in a dynamic state. On this basis, the heat transfer coefficient of the ground contact floor in the simplified case and the steady-state analyses is significantly higher than in the case of the dynamic condition, which is much more realistic.

Figure 3 illustrates four different building construction joints for the numerical models analysed under different modelling conditions (out of 15 different analysed construction joints in total). In the case of the wall corner joints, the Φ value is mainly influenced by the moisture content, like other construction joints with capillary active materials and not connected to the ground (e.g., firewall, openings in walls). For the intermediate slab and wall joint (similarly to the flat roof and external wall, flat roof, and attic wall joint), the dynamic analyses gave higher Φ values, while for the external wall and pitched roof joint, the dynamic analyses gave lower results compared to the steady-state conditions. In the analyses for the horizontal section of the openings and the partition or the external wall connection, both moisture and modelling conditions significantly affected the Φ value. Only the case of the flat roof and external wall joint resulted in almost identical results independently from the moisture or modelling conditions. Considering the different conditions for a single design, it can be concluded that in most cases, there can be a difference of ±50 % between the linear thermal transmittances, which is a significant discrepancy. It is important to emphasise that we are talking about relative situations here; we cannot determine whether the dynamic model without moisture transport or the steady-state model with moisture transport is better than reality. The values for all joints are within ±3 % of the values measured in the temperature factor for the internal surface. It is safe to say that condensation and mould growth is not expected on the internal surface since $f_{Rsi} > 0.8$ was obtained in every case.

3.5. Comparison of the difference of heat transfer coefficients depending on the used methods

The results for surface heat transfer coefficients are within approximately ±10 % for all methods, with significant differences in the analysis of the linear heat transfer coefficients, as visible in Figure 4. According to the Hungarian Regulation, the value of the

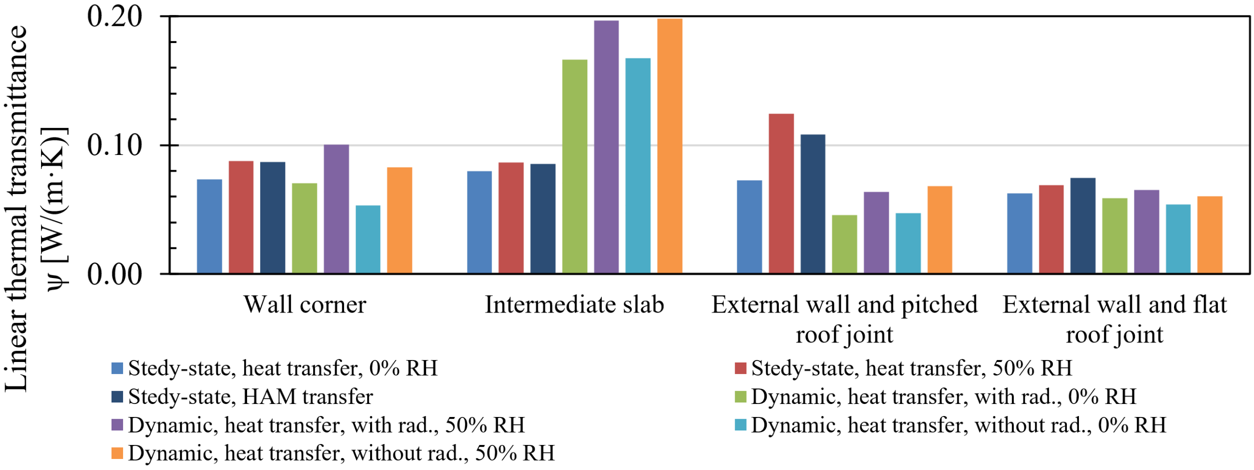

Figure 3. Linear thermal transmittance of construction joints under different modelling conditions.

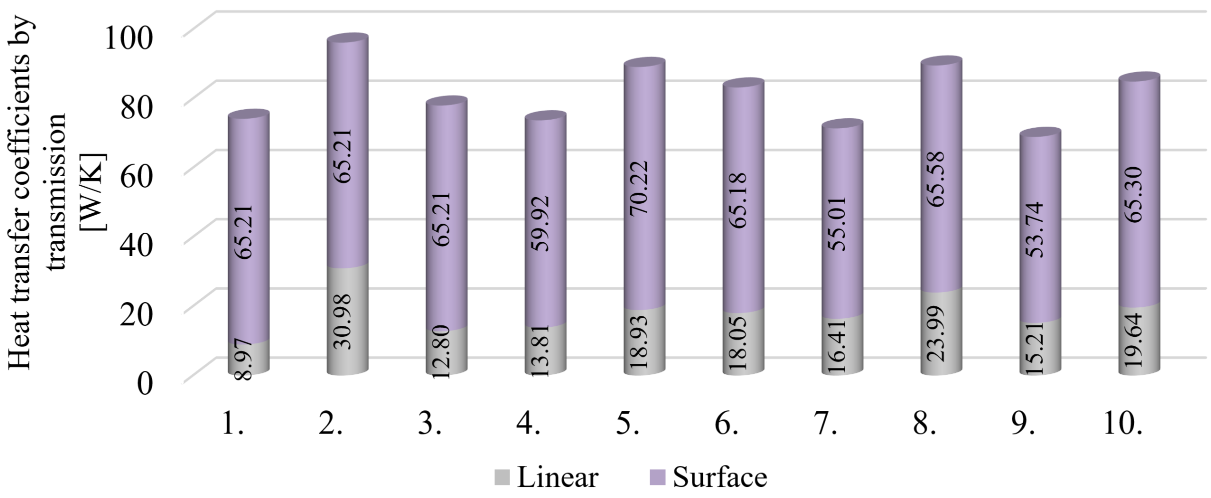

Figure 4. Comparison of heat transfer coefficients: 1) simplified calculation, 2) MSZ EN ISO 14683, 3) Thermal bridge catalogue, 4) steady-state and 0 % RH, 5) steady-state and 50 % RH, 6) steady-state HAM, 7) dynamic, with effect of radiation and 0 % RH, 8) dynamic with solar radiation, 50 % RH, 9) dynamic without solar radiation and 0 % RH, 10) dynamic, without solar radiation and 50 % RH.

linear heat transfer coefficients is the lowest for the simplified method, almost 50 % below the average of the other methods. This is because the correction value only needs to be determined based on the specific surface areas of the building envelope containing thermal bridges. There are different kinds of thermal bridges that cannot be considered. As expected, the highest heat transfer coefficient was obtained using ISO 14683:2017 [4], which exceeded the average of the other methods for the linear heat transfer coefficients by almost 90 %. This is due to the obsolescence and lower level of detail mentioned earlier. The new 2020 Hungarian thermal bridge catalogue gave higher results than the simplified method but significantly lower than the standard. It also can be said that the use of the thermal bridge catalogue was substantially more straightforward and faster compared to all other methods presented.

The results show that including solar radiation increases the result by an average of 5 %, with the additional increase of the heat transfer coefficient occurring mainly at the thermal bridges. At 50 % RH, the thermal performance of the constructions deteriorated by about 20 %. Observing the values for the total heat transfer coefficients of the dynamic conditions, it can be concluded that it gave a lower result than the steady-state models with the same moisture conditions. It can be said that with the use of steady-state modelling, the value of the total heat transfer coefficients is mistaken in favour of safety. Roughly 22 % of the total heat transfer coefficient of the building used for the study comes from thermal bridges. The building can be considered an average new building in Hungary, but the proportion of the surface and linear heat transfer coefficients for other building construction designs may vary.

4. Conclusion

The research aimed to compare the methods used to investigate the thermal bridging effect of buildings, using the example of a newly built residential building, which is considered typical on the Hungarian market. The results of the simplified method according to TNM Decree 7/2006., a thermal bridging catalogue according to ISO 14683:2017, a new Hungarian thermal bridge catalogue, and detailed two-dimensional thermal and HAM simulations in both steady-state and dynamic conditions were compared. The simplified calculation determined the surface heat transfer coefficients with satisfactory accuracy compared to the average of the other methods, but the linear heat transfer coefficient was much lower. This contradicts the general assumption that the simplified method is biased in favour of safety. The simplified method may result in lower heat transfer coefficients for low-energy buildings than the detailed calculations and numerical modelling. The use of the standard ISO 14683 is not recommended in any situation. Due to its obsolescence and lack of variation, it is recommended to update this standard. In the case of the examined building, the Hungarian thermal bridge catalogue provided a much better alternative, which stands out from the other methods for its ease of use and its simplicity and speed of use. At the same time, it approximates the results of the steady-state thermal model with 0 % RH. However, not all building constructions were included in the catalogue. It is not possible to consider every thermal bridge; therefore, this catalogue should be expanded in the future. The 2D steady-state model is excellent for more complex building constructions. Although the model construction takes a similar time regardless of modelling conditions, a steady-state calculation is much faster than solving the dynamic simulation. Nevertheless, with the development of computational technology and software solutions, it may soon become applicable to professional works. However, due to its long calculation time, dynamic thermal analysis and HAM simulations are currently recommended only for research purposes.

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