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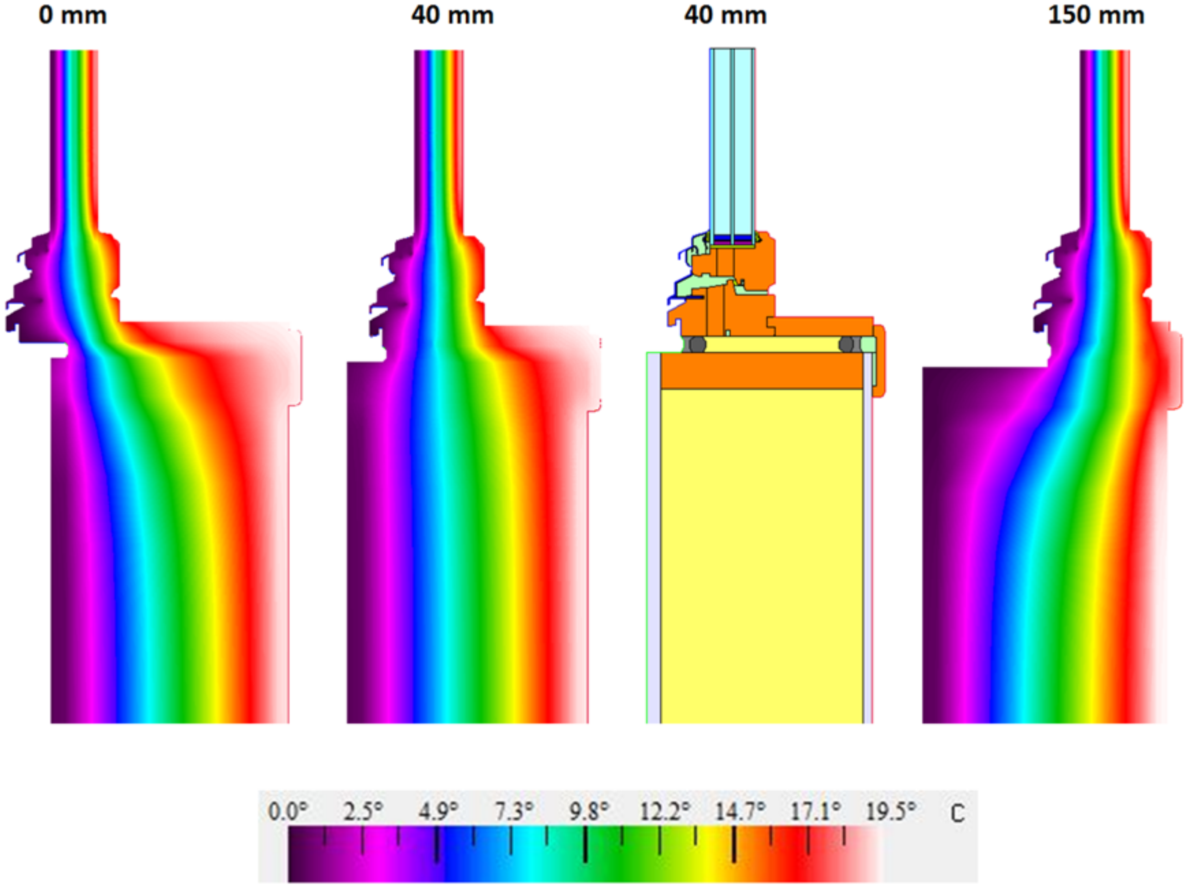

Thermal modeling and investigation of the most energy-efficient window position.

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ABSTRACT

The energy consumption in buildings contributes substantially to the worldwide energy use and greenhouse gas emissions. One of the crucial elements defining energy consumption is the building envelope, which in modern designs includes growing share of fenestration. Due to recent improvements of windows and walls, the thermal bridging effects occurring on their connections, become more significant. Window-to-wall connections appear to be especially important and can contribute up to 40% of the total heat loss caused by thermal bridges in building envelope. Thus, this study is investigating thermal properties of window-to-wall connections. The main scope of the work is to determine the most optimal window position in the window opening regarding minimizing thermal bridging effects. Five different wall constructions are investigated along with two windows with different U-values. The thermal simulation results show that the window position has a crucial impact on the amount of energy loss through the thermal bridges. For each wall type, the optimal position is found, resulting from detailed analysis of sill, head, and jambs construction details. For some cases placing the window in the optimal position reduces linear thermal transmittance (LTT) over 50%. Among considered positions, the temperatures on the internal surface of the assemblies are weakly influenced by the window position. Example calculations show that significant share of energy losses from the fenestration presence is caused by thermal bridge occurring on window-to-wall.

Keywords: thermal bridge, window-to-wall connection, window position, window opening, linear thermal transmittance, window U-value, window energy loss.

1. INTRODUCTION

Saving energy and reducing carbon emissions are currently seen as a worldwide trend. The buildings energy usage accounts for over 40% of the worlds primary energy use and approximately 24% of greenhouse gas emissions. This includes direct use of fossil fuels on-site and indirect use of energy in the form of electricity, district heating, district cooling and the embodied energy in construction materials [1]. Thus, there is a strong need for reducing the energy consumption in buildings. One of the crucial elements affecting building energy consumption is the thermal performance of building envelope. In modern enclosure designs, a trend of increasing size of fenestration products is noticed. On the one hand, it contributes to a better living standard by providing more daylight and useful heat gains, but on the other hand, a higher share of glazed surfaces may also cause higher heat losses or non-desirable heat gains.

In recent years due to stricter building codes and further development of low-energy houses, building envelopes have been substantially improved. Despite that, thermal bridges still occur on component connection due to their various geometrical shapes or different thermal conductivities. Thermal bridges are causing higher local heat transfer (in comparison to surrounding structure) thus they significant for the enclosure thermal performance. Higher thermal resistances of walls, fenestration, roof and slab constructions causing the thermal bridging effects to become even more pronounced, due to higher share in energy losses [2]. Currently, the thermal transmittance of fenestration products is still significantly higher than for walls. Among other thermal bridges, the window-to-wall connection appears to be especially important. The study conducted by Gustavsen et al. [3] shows that for a typical 160 m^2 Norwegian dwelling, the window-to-wall interface is responsible for about 40% of the total heat loss caused by thermal bridges. Fairly simple improvements to the connection details for the same case resulted in 17% reduction of heat losses. Similar outcomes are reported in the international calculation standard ISO 14683 [4] which describes an evaluation method for thermal bridges. Calculation for relatively low-performing generic buildings indicates that thermal bridges are responsible for 36% of the total energy loss through the building envelope, of which 38% is due to the window-to-wall connection. This demonstrates that the heat loss through the window-to-wall connection is an important issue in an energy context and should hence not be underestimated.

Methodology for assessing thermal bridges is well established and described in the international calculation standard ISO 14683. The document also includes universal values of linear thermal transmittance (LTT) for typical geometric structures occurring in building envelopes, including window-to-wall connections (refer to ISO14683, Table A2) [4]. Six different simplified wall types are considered along with three window positions. Typical values of LTT are reported for each case. The standard indicates preferable window positions in the window openings, however, reported values tend to be much higher than those typical for new construction. Detailed calculations for individual cases of window-to-wall connections can be conducted according to ISO 10211 [5] where calculation algorithms are described.

The topic of window-to-wall connection has been studied in the literature. Maref et al. investigated the influence of air leakage on condensation risk [6], [7]. Lacasse et al. presented solutions reducing water intrusion which could lead to premature failure of the building envelope [8].

First found studies associated with the thermal performance of window-to-wall connections, were conducted in 2007. In various reports and guidelines, the location of windows in a wall opening is referred as an important parameter for minimizing effects of thermal bridges. SINTEF Building Research Project Report no. 25 [3], which focuses on losses caused by thermal bridges, gives an example of the relationship between the window position and the linear thermal transmittance for a wood-framed wall including a 250 mm wide insulation layer. This study shows that installing the window sill 35 mm towards the inside of the wall (measuring from the wind barrier) is the most favorable regarding reducing thermal bridging. The results have also shown that the commonly seen practice of aligning window frame with external cladding results in a 6 to 11 times higher value of LTT.

Cappelletti et al. [9] investigated the influence of window installation details for clay block walls. The study simulated the heat flow through wooden windows installed in two different wall constructions (a brick wall insulated from the outside, and a brick wall with an insulated cavity) at three positions: outside, intermediate and inside for each wall design. For each case, the linear thermal transmittance based on external dimensions was calculated according to ISO 10211. It was found that the window position, installation details and the framing of the window aperture in the wall had a significant impact on the LTT, which differed up to 70% between presented cases. Also, the study proposed a methodology to combine the heat transfer via thermal bridging into the window U-value rating.

Our previous studies conducted by Decheva [10], Misiopecki et al. [11], [12] were focused on determining and lowering LTT values for various window-to-wall connection cases. However, these studies only considered the connection of window sill with the wall, while jambs and heads were not considered. The study confirmed results reported in other studies, i.e., that window positions have a significant effect on the thermal performance of window-to-wall connections.

This study expands work performed earlier and focuses on finding the most efficient window positions, regarding minimizing thermal bridging effects in window openings. The following five different walls are investigated: wooden-framed wall with various thicknesses, wall retrofitted with VIPs, concrete wall insulated from the outside, inside and insulated from both sides. Along with window sills, connections of window jambs and heads are included in the process of finding the optimal window position. Smaller distance steps are used for more detailed analysis. Each case is simulated with two window frames with different U-values to determine the influence of window performance on the optimal position. Additionally, temperatures on the internal surfaces are tracked in order to assess the sensitivity of condensation risk due to a particular window position. The study aims to present LTT values for highly insulating window-to-wall connection assemblies and show the quantitative importance of the assembly details on its thermal performance.

The study does not investigate the air leakage or water drainage abilities of the modeled solutions. Further research is required in this field to assess proposed positions for applicability in buildings.

2. METHODOLOGY AND SIMULATION DESCRIPTION

2.1 Theory

Fenestration products interact with other building envelope components. Windows normally have much lower insulating performance than walls, which creates a thermal bridge on the components connection. Recent improvements of walls and windows insulating properties caused the thermal bridge effect to be more significant, due to its relatively higher contribution to energy losses from the building envelope. Thus, it is important to find the most efficient window positions for most popular wall constructions which are used in modern construction.

2.2 Window/frame geometries

Thermal simulations are performed using a representative highly performing window product. The studied window has a wooden frame covered with aluminum on the outside surface. Moreover, the frame can accommodate polyurethane foam acting as a thermal break which improves the thermal performance. Both geometries are considered, (i.e., with and without the thermal break) to investigate the influence of window insulating properties on the optimal position in the opening. Moreover, the monolithic frame is used along with 2P IGU (double pane insulated glazing unit) incorporating one Low-E coating and argon as a filling gas, which results in a whole product U-value of 1.57 W/(m^{2}K). Thermally broken frame along with 3P IGU (three panes insulated glazing unit) incorporating two Low-E coatings and krypton as filling gas, provided a higher performance with U-value of 0.64 W/(m^{2}K). Both windows' U-values are assessed according to the standard ISO 10077-1 [13]. U-values are calculated for products with dimensions of 1.23 m x 1.48 m. Material properties assigned to geometries are obtained from ISO 10077-2 [14]. For the simulations, a simplified version of a high performing, market available spacer is used. Figure 1 presents the window sketch and geometry prepared in THERM software.

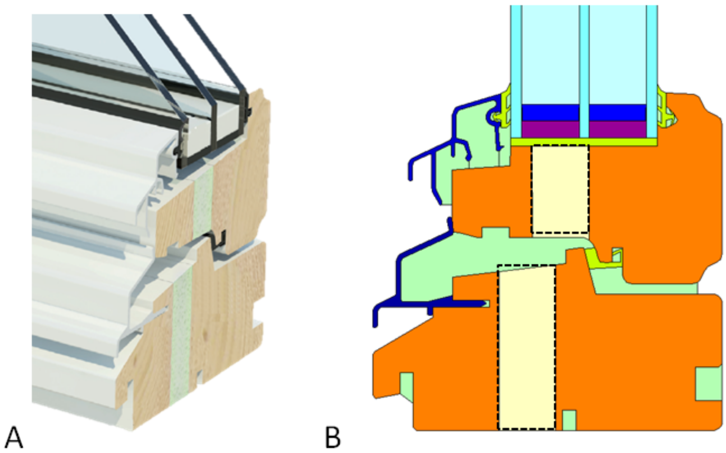

Figure 1 - A: Cross-section drawing of a window used in the study (NorDan 2010), B: Geometry used for thermal modeling using 3P IGU. The area marked with dotted lines indicates polyurethane foam.

2.3 Selected walls

Five different walls constructions are chosen for the simulations. Additionally, wooden-framed walls and wall retrofitted with VIPs are considered, with 3 and 2 different thicknesses of the insulation layer, respectively. To simplify the calculations, the same insulation material is used for each case, with a thermal conductivity of 0.035 W/(mK). Simulated walls are listed and shortly described in Table 1. Cross-section drawings of walls are presented in Figure 2. External cladding which is typical for walls A and C is not physically modeled, due to simulation simplification. Instead, an approach from ISO 6946 [15] is used to account cladding by using a modified boundary conditions on the most outside surfaces of the model geometry.

Table 1 – Description of walls selected for the investigation.

Label	Wall name	Construction	U-value (W/(m^{2}K))
A	Wooden-framed wall – 198 mm	Cladding* - Gypsum Board (GB) – insulation layer - GB	0.21
	Wooden-framed wall – 296 mm	Cladding* - GB – insulation layer - GB	0.15
	Wooden-framed wall – 396 mm	Cladding* - GB – insulation layer - GB	0.11
B	Concrete wall insulated from the inside	Plaster - Concrete wall (210 mm) – insulation layer (198 mm) - GB	0.14
C	Concrete wall insulated from the outside	Cladding* - GB - Insulation layer (248 mm) - Concrete wall (160 mm)	0.12
D	Concrete wall insulated from outside and inside	Plaster – Insulation boards (50 mm) – concrete (150 mm) – insulation layer – (148 mm)	0.17
E	Wooden-framed wall (148 mm) retrofitted with VIP	Expanded polystyrene (EPS) (25 mm) – VIP (25 mm) – EPS (25 mm) – GB – insulation layer (148 mm) - GB	0.06
	Wooden-framed wall (198 mm) retrofitted with VIP	EPS (25 mm) – VIP (25 mm) – EPS (25 mm) – GB – insulation layer (198 mm) - GB	0.05

*Cladding has not been physically modeled.

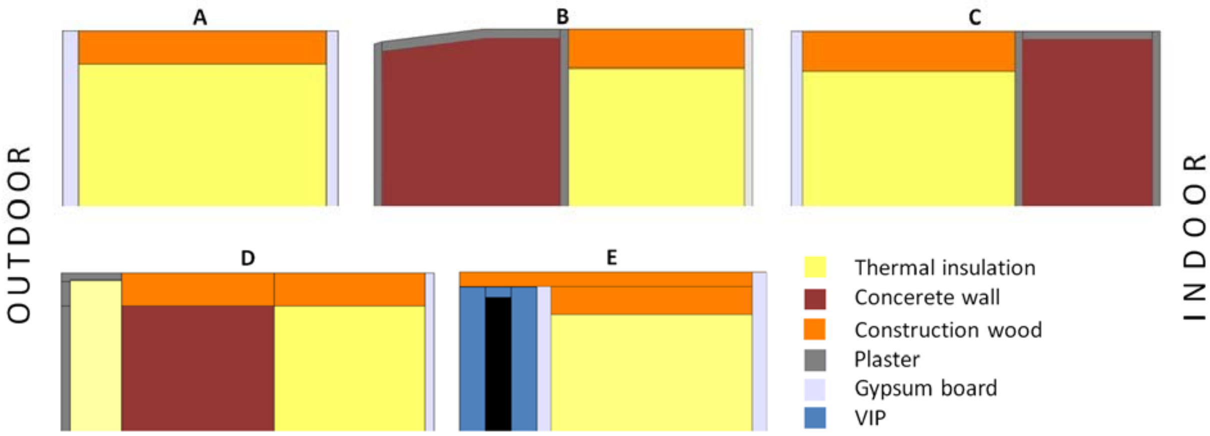

Figure 2 – Cross-section sketches of walls used in the study. For each wall, the sill is presented. (A) - Wooden-framed wall, (B) - concrete wall insulated from the inside, (C) - concrete wall insulated from the outside, (D) - concrete wall insulated from outside and inside, (E) - and wooden-framed wall (198 mm) retrofitted with VIP.

2.4 Numerical simulations

Thermal simulations are carried out using the computation program THERM 7.0 which uses the finite element method to solve two-dimensional heat conduction governing equation (1) in steady state.

$$\left(k_{11}\frac{\delta^2 T}{\delta x^2} + k_{22}\frac{\delta^2 T}{\delta y^2}\right) + Q(x,y) = 0 \qquad (1)$$

where, (k_{11}) and (k_{22}) are conductivities in the x and y directions, respectively, (Q) - known internal heat generation per volume unit. Convection boundary conditions are defined by following equation (2):

$$q_c = \mathrm{h_c}\ (\mathrm{T,x,y,z}) * (\mathrm{T}-T_c) \qquad (2)$$

where, (q_c) is convective heat flux, (h_c) is the convective heat transfer coefficient in the location on the boundary (x,y,z), (T) – temperature and, (T_c) - reference temperature for convective transfer.

THERM utilizes CONRAD [16] calculation routine which treats all layers (including air cavities) as solids with assigned effective thermal conductivity. Effective conductivity is a sum of gas conductivity and convection, radiation mechanisms effects occurring in the air cavity. Convective heat transfer is estimated through the use of constant film coefficients which are adjusted/assigned depending on cavity geometry, surface temperature, surface emissivity and the heat flow direction. Film coefficients built-in software are acquired from experimental studies or advanced computational simulations [17], [18]. For more information, please refer to the technical documentation describing THERM algorithms [19].

Radiation is accounted with the view-factor-based method. The view factor is a fraction of energy emitted or reflected from the surface which directly impinges another surface, where is absorbed, reflected or transmitted. The view factor is defined by the following equation (3):

$$F_{k-j} = \frac{1}{A_k} \iint_{A_k A_j} \frac{cos\theta_k cos\theta_k}{\Pi S^2} \, \mathrm{d}A_k dA_j \qquad (2)$$

where, S is the distance from a point on surface A_j to a point on surface A_k, θ_j and θ_k are angles measured between the line S and the normal to the surface as shown in Figure 3.

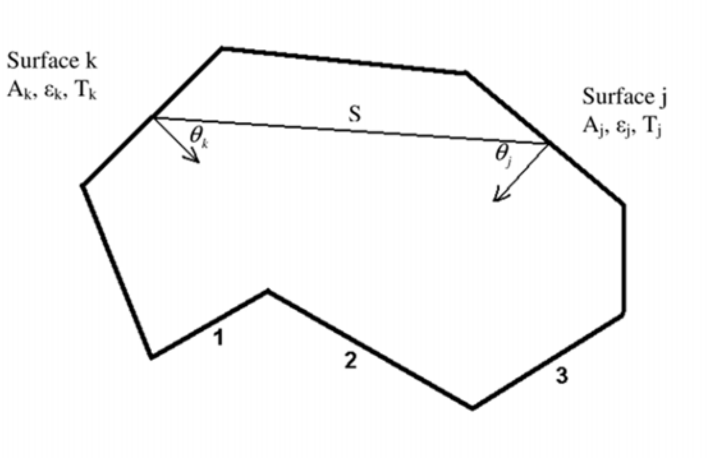

Figure 3 - Nomenclature for enclosure radiation [19]

The software completing a simulation round checks up solutions for convergence and refines the mesh in required areas based on an error-estimation algorithm. The energy error norm for all simulations is kept around 6% which yields U-value uncertainty of less than 1% based on THERM documentation [19], [20]. The software is used to prepare geometry and conduct heat transfer simulations in two-dimensions.

Window frame geometry is prepared in accordance with ISO 10077-2 standard and overall geometry of window-to-wall connection in accordance with ISO 10211. Boundary conditions for the window-to-wall assembly are set as follows. For windows in accordance with ISO 10077-2, i.e., indoor/outdoor temperature: 293.15/273.15 K and combined convection and radiation coefficient of heat transfer for the indoor/outdoor: 7.692 / 25.0 W/(m^{2}K)m respectively. For walls in accordance with ISO 6946 where values are the same as for windows, except cases of walls A and C for which combined coefficient on the outside side is reduced to 7.692 W/(m^{2}K) due to established approach of external cladding modeling, which is described the earlier paragraph.

Walls are drawn with a height of 1.2 m, and a window is inserted in the various positions. Before the simulations, international standards were reviewed to find exterior flashing slope for effective water drainage. In different sources, i.e., ASTM [21] and SINTEF [22], [23] an agreement on the exterior flashing slope, is not found. It was decided to follow the current SINTEF guidelines of setting the slope of the sill flashing at ratio 5:1 (horizontal : vertical). If required, for a specific sill position an additional wooden piece/shim are added to elevate frame and provide a required slope. Window positions are labeled as a distance from the most outside surface of the wall to the window symmetry axis. In case of walls A and C, the distance is measured excluding exterior cladding, starting from the external surface of gypsum board (where alternatively a wind barrier can be present). An example of geometry and method of indicating window position is shown in Figure 4. The linear thermal transmittance is calculated according to the following equation (4) which is derived from ISO14683:

$$\Psi = L^{2D} - \sum_i U_i \cdot l_i \qquad \left[\frac{W}{mK}\right] \qquad (4)$$

where, (L^{2D}) is the thermal coupling coefficient obtained from a two-dimensional calculation of the component separating the two considered environments, U_i is the thermal transmittance of the (equivalent) one-dimensional component separating the two considered environments, l_i is the length within the two-dimensional geometrical model over which the value of U_i applies (refer to Figure 4).

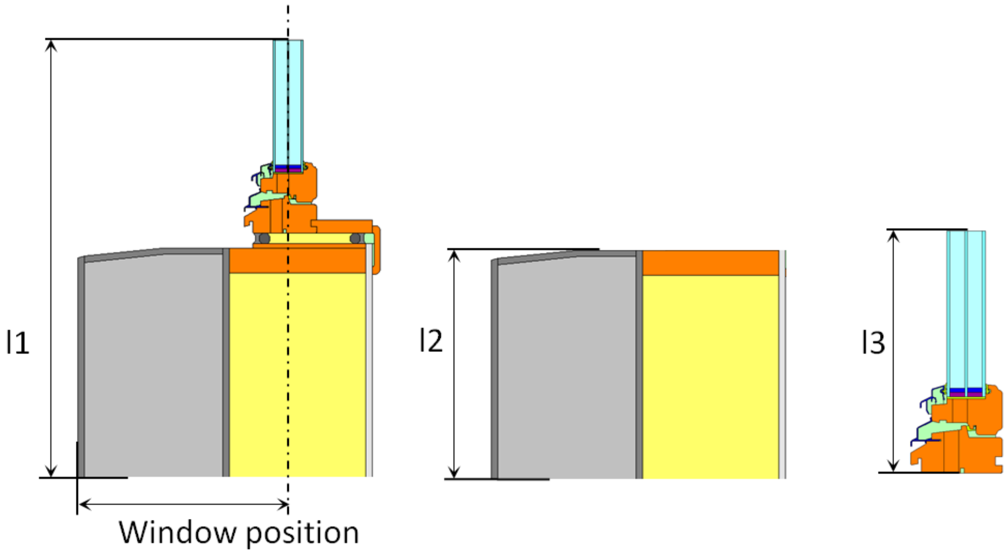

Figure 4 - Sketch of example geometry modeled in the study (the model is not to scale).

The geometry of external flashing is not included in the simulation. Pre-simulations indicated that it has minor influence both on LTT values and temperature distribution. For the sake of simplification, air barriers, tapes, and foils normally used around window openings are not included due to their small thickness and limited thermal resistance. All insulation layers are modeled as continuous. For each wall, a set of simulations are conducted with several window positions in the wall. Each position is evaluated for sill, head, and jambs (refer to Figure 5).

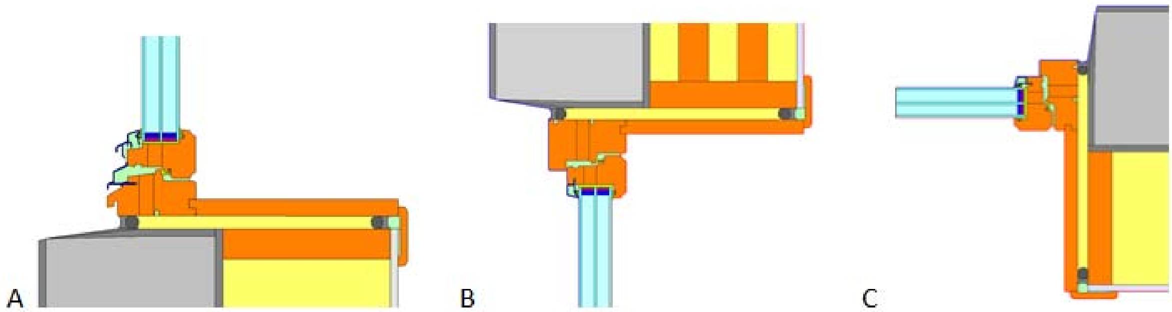

Figure 5 - Example geometries of window-to-wall for sill (A), head (B) and jambs (C) for concrete wall insulated from the inside, position 80 mm.

3. RESULTS AND DISCUSSION

Altogether simulations for 660 cases are conducted, and linear thermal transmittance values are reported. Due to the high volume of data, the results are presented as graphical plots, which show LTT values against window positions. The data is calculated for typical windows with the size of 1.23 m x 1.48 m as used in the testing procedure in ISO 12567-1 [24]. Similar graphs were also produced for windows with aspect ratios of 2:1 and 1:2. Relatively small differences of LTT values are found between jambs and heads, while sills presented a higher discrepancy due to the introduction of wooden shims under the frame. However, a maximum actual difference of 0.001 W/(mK) is found between positions for different aspect ratios, which is around 1% concerning the typical LTT values. As an approximation, it can be stated that the presented results are representative of most of the typical window units used in buildings.

Figure 6 presents results for wooden-framed walls. The LTT values are less sensitive to the window position changes and higher for thicker walls. Similar results have also been reported by Decheva [10]. Figure 6 presents results for frames incorporating 3P IGU (continuous lines) and 2P

IGU (dotted lines). For both windows, construction trends are similar and optimal window position is the same. In general, low-performing windows with 2P IGU glazing are characterized by lower values of LTT. For wall construction with insulation layers of 198 mm thickness, the optimal position is between 70 to 90 mm. For walls including 296 mm and 400 mm insulation, the most optimal positions are between 90 – 150 and 90 - 230 mm, respectively. For this wall type, it appears that the most optimal position regarding lowering thermal bridging effect is approximately in the middle of the wall and some distance towards the outside surface of the wall. The results revealed that the position of 4 mm (i.e., window outside surface is aligned with cladding) is not preferable from a thermal point of view. Presented results differ from our earlier studies since not only the sill is considered and the importance of wooden pieces used for window elevation is less significant. A temperature difference of 0.4 K is found comparing the lowest temperature on the internal surface, between the positions.

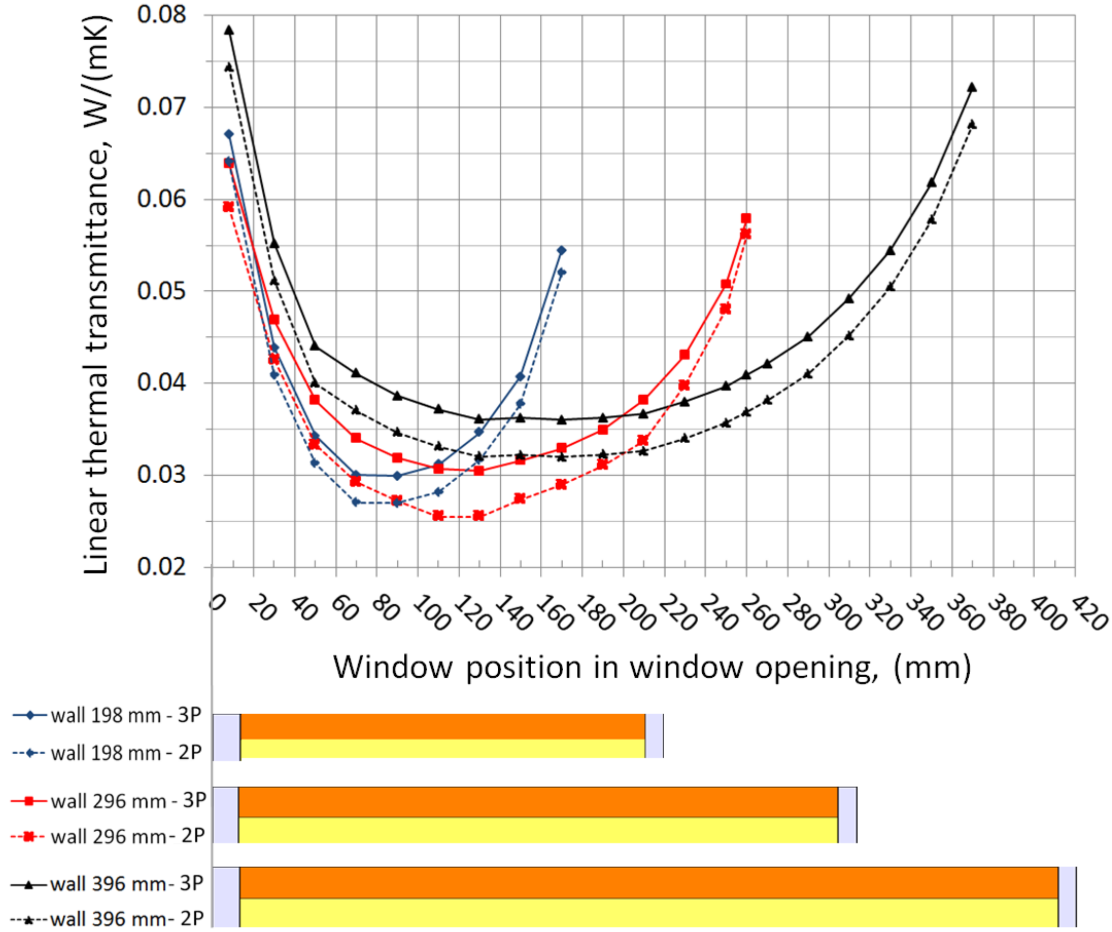

Figure 6 – LTT values versus window position in window opening for wooden-framed walls. Colors are indicating materials: light grey – gypsum board, orange – construction wood, yellow – insulation.

The LTT values for two concrete walls insulated from inside and outside are presented in Figure 7. Simulations are conducted using two window frames. Again, the window incorporating 2P IGU glazing unit has slightly lower LTT values, while trends are almost the same with windows including 3P IGU for each wall. For both walls, the position of the window has a significant influence on the LTT values. Regarding concrete wall insulated from the outside, a window placed in the insulation layer is the most efficient solution. It can be observed that except edges of the insulation layer, the thermal bridging effect is weakly sensitive to window position. Similarly to wooden-framed walls, the best values are achieved for positions approximately in the middle of the insulation layer and some distance towards the outside wall surface.

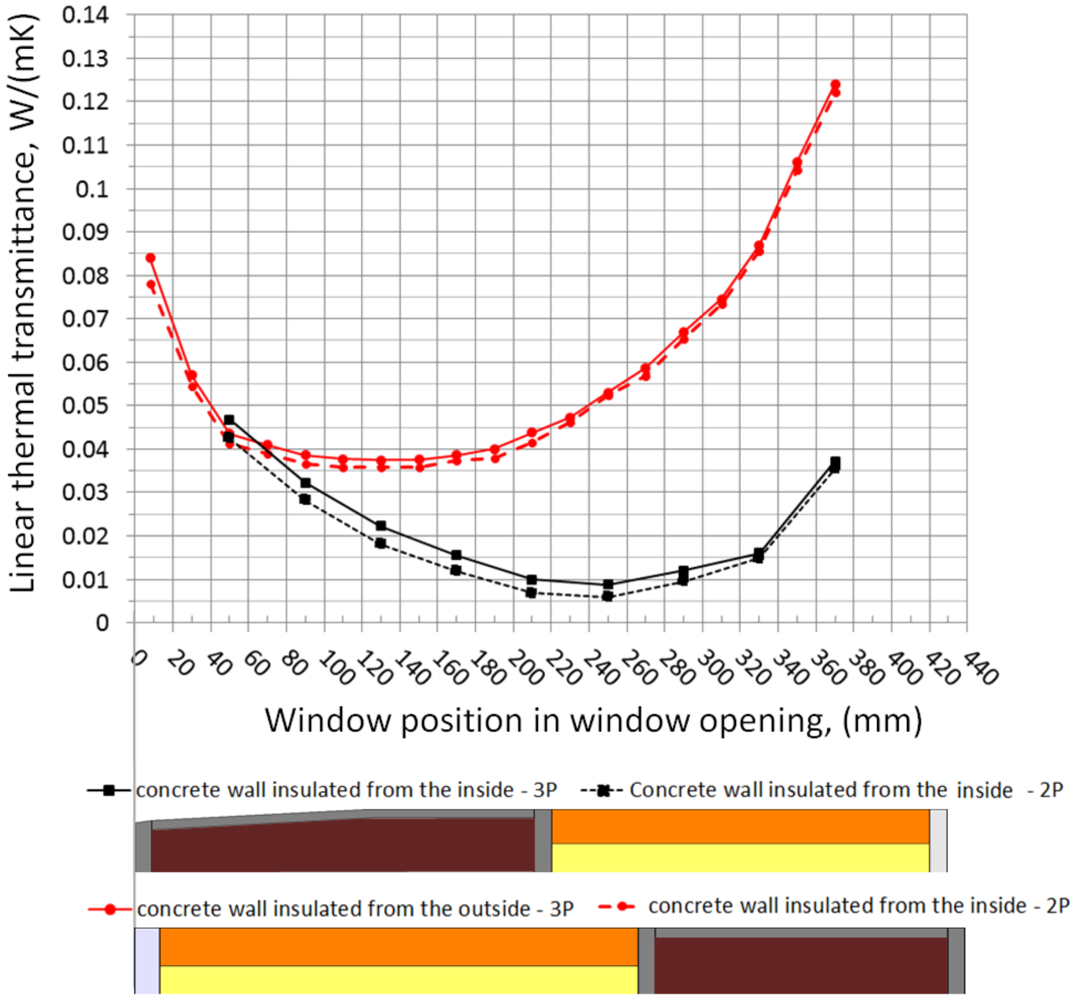

Figure 7 - LTT values versus window position in window opening for cases of concrete wall insulated from inside and outside. The colors indicate the following materials: light grey – gypsum board, dark grey – plaster, red – concrete, orange- construction wood, yellow – insulation.

For concrete walls insulated from the inside, a preferable position appears to be at the distance of 250 mm. In that position, the window is approximately in-line with the outer surface of the insulation. Moving window inside the interval of 200-290 mm provides similar LTT values.

Similarly to wooden-framed walls, window position has a minor influence on the internal window surface temperature, where maximum variation is 0.3 K.

Figure 8Figure 8 presents results for a concrete wall insulated from both sides, and two typical wooden-framed walls with an insulation layer of 148 and 198 mm retrofitted with encapsulated VIPs in expanded polystyrene (EPS). Again, two windows are tested for each wall. Similar as for earlier cases, for the wall with 148 mm thick insulation, LTT values for windows incorporating 2P and 3P IGU have very similar trends (with slightly lower values for 2P IGU window), thus for clearer view only results for the 3P IGU window have been shown. For the concrete wall, the lowest LTT values are achieved for positions in the vicinity of connection between the concrete wall and the internal insulation layer. Those results are analogic to the concrete wall insulated from outside. However, the presence of insulation from outside caused a small shift of the window position towards the outside surface.

For typical wooden-framed walls retrofitted with VIPs, the window position is the most sensitive of all considered walls regarding thermal performance. Results showed that regardless the thickness of the conventional insulation layer, the preferable window position is just above VIPs. Maximum differences of lowest temperature on the internal window surface between positions are found to be 0.5 K.

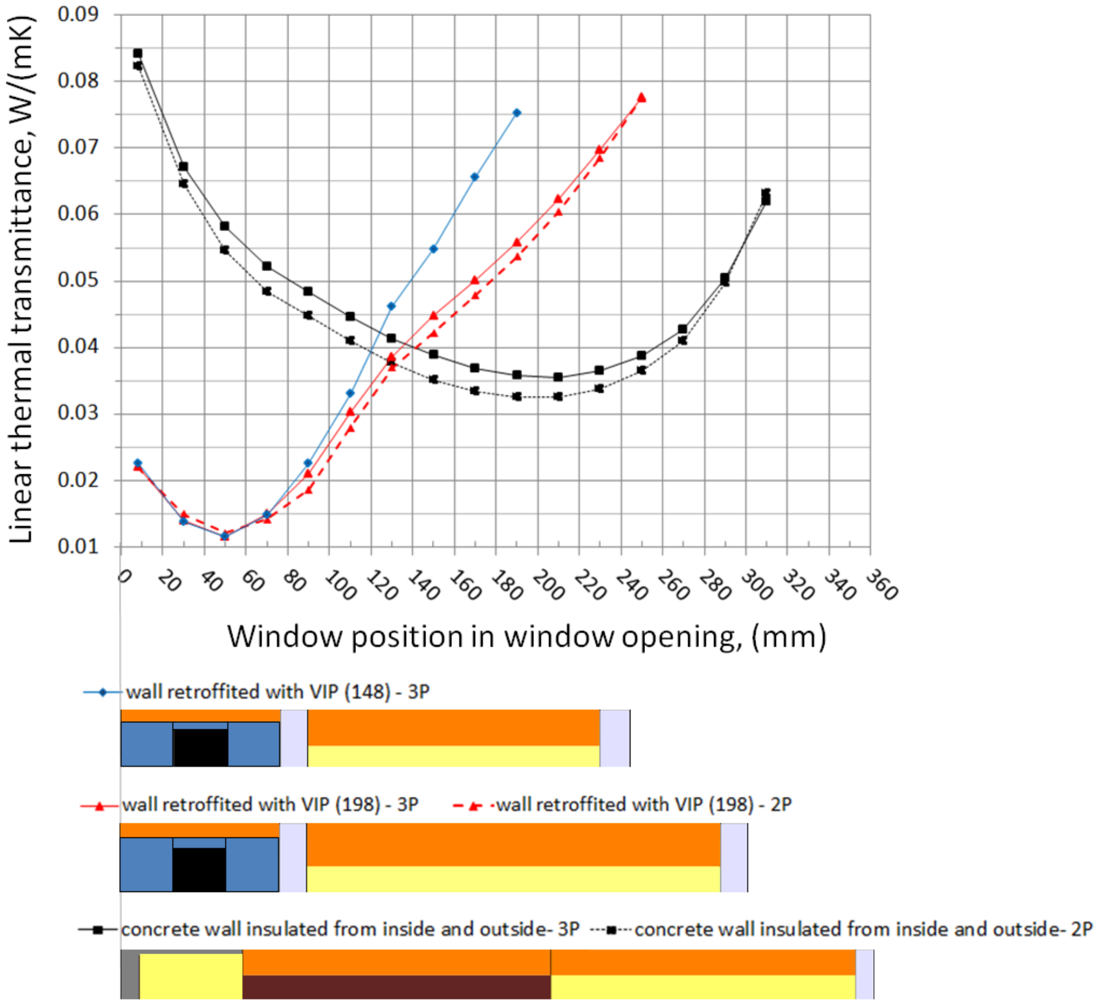

Figure 8 - LTT values versus window position in window opening for cases of concrete wall insulated from inside and outside and walls retrofitted with VIPs. The colors indicate the following materials: light grey – gypsum board, dark grey – plaster, red – concrete, orange- construction wood, yellow – insulation, blue – EPS, black - VIP.

The presented results indicate the most efficient positions regarding minimizing thermal bridging effects on different window-to-wall connections. There may be a few possible reasons why the indicated positions show the best insulating properties, which transforms to the lowest LTT values. Due to the problem and geometry complexity, it would be difficult to justify the optimal position based only on energy governing laws and equations. For better understanding temperature contours are analyzed for different positions. An example temperature contours for window positions with high LLT value (8 and 150mm) and optimal position (40mm) in wooden framed wall including 198mm of insulation (wall A) are presented in Figure 9.

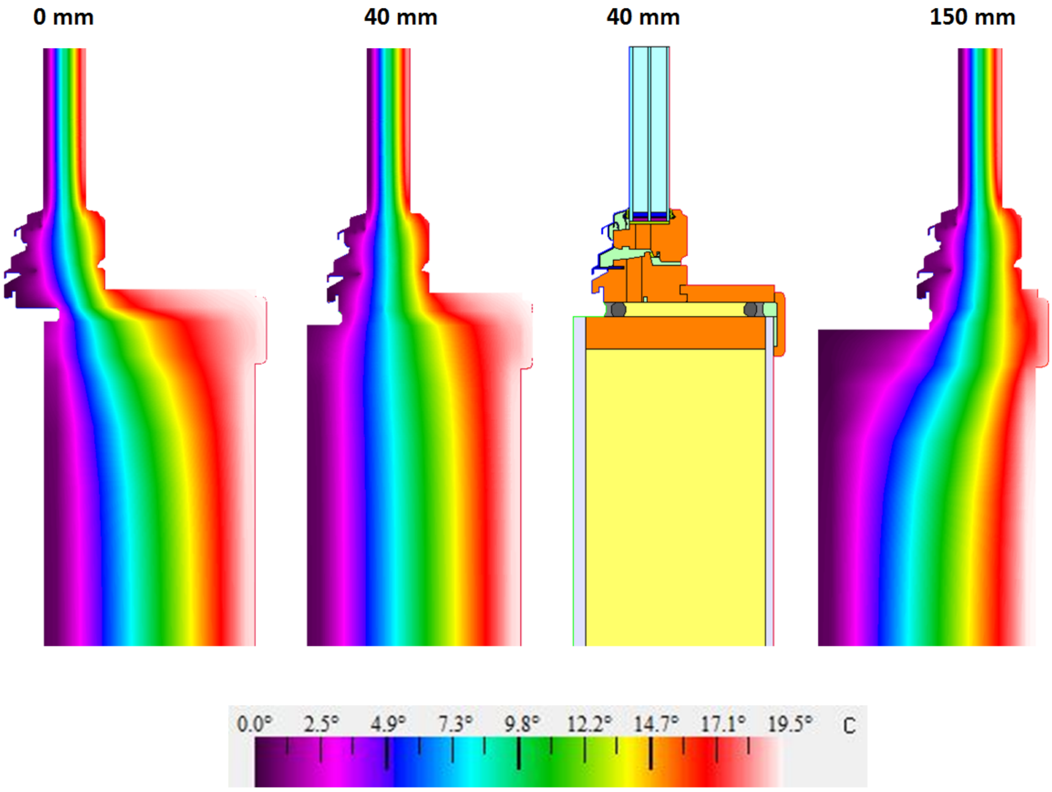

Figure 9 - Temperature contours for frame A (198mm) for different window positions. Additionally, the intersection of geometry in position (40mm) is added for a better understanding of connection details.

Observations are as following: positions 8 and 150 mm due to window placing have a greater heat exchange area on the cold/outdoor side than the window in optimal position. This causes higher heat losses of the assembly. Moreover, for both positions 8 and 150 mm isotherms in the upper part of the wall are close to each other what indicates higher local temperature gradients and effects in higher heat loss.

To show the importance of thermal losses from window-to-wall connections which can be related to window performance, we studied a window (dimensions of 1.23 m x 1.48 m, incorporating 3P IGU, U-value of 0.64 W/(m^{2}K)) inserted in a wooden-framed wall with an insulation thickness of 296 mm. The total heat loss of the window itself equals to 23.30 W (calculated according to the formula: window U-value x window area x dT; 0.64 W/(m^{2}K) x (1.23 m x 1.48 m) x 20K= 23.30 W) if we assume a temperature difference across the geometry equal to 20 K. For wooden-framed wall commonly seen in practice is flashing/aligning window surface with the external cladding (refer to position 4 mm). This position would result in an additional loss (caused by thermal bridge of window-to-wall connection) of 6.94 W (calculated according to the formula: LTT x perimeter of the window x dT; 0.064 W/(mK) x (2 x 1.48 m + 2 x 1.23 m) x 20 K = 6.94 W). For optimal windows position (110 mm) the additional loss equals to 3.36 W (calculated: 0.031 W/(mK) x (2 x 1.48 m + 2 x 1.23 m) x 20 K = 3.36 W). Calculations show that placing windows in the optimal position reduces losses by 3.58 W which is around 15% of the losses caused by the entire window itself.

4. CONCLUSIONS

The study is investigating thermal properties of window-to-wall connections. The main scope is to determine the most optimal window position in a window opening regarding minimizing a thermal bridging effect. Five different wall constructions have been investigated along with two windows with various insulating properties. Results show that the position of the window has a crucial impact on the thermal bridging effect. Highest and lowest Linear Thermal Transmittance (LTT) values for the following wall types along with 3P window are: A (198mm): 0.067/0.030 A (296mm): 0.064/0.030, A (400mm): 0.078/0.036, B: 0.047/0.009, C: 0.084/0.036, D: 0.084/0.037, E(148mm): 0.075/0.011, E(198mm): 0.077/0.011 W/(mK) . For each wall type, the optimal position is found, considering the connection of the sills, head, and jambs separately. Estimated linear thermal transmittance (LTT) values for windows with different aspect ratios are very close. Thus results are applicable for most common window shapes used in the building industry. Moreover, no significant differences in trends and optimal positions are found between two tested windows, which may indicate that the window insulating properties have a limited effect on the optimal position. However, slightly lower LTT values are found for lower thermally performing windows, i.e., the thermal bridging effect is more important for highly performing products. Furthermore, the temperature differences on the internal surface of the assemblies are not significantly affected by the window position (a maximum difference of 0.5 K). It is shown by a simple calculation using specific geometries that additional heat loss caused by the thermal bridge on window-to-wall connection is relatively high. Placing a window in the position according to common practice results in additional loss up to 30% of the entire window heat loss. By placing a window in the optimal positions, the thermal bridge losses could be reduced by more than 50%. Thus it is important to design window-to-wall connections carefully.

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