Practical Methods for Ensuring Energy-Efficient Window-to-Wall Connections

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ABSTRACT

Nowadays, saving energy and reducing carbon emissions is one of the top priorities in each sector of human activity. The building sector accounts for a significant part of the world's total energy use and greenhouse gas emissions. Windows are inseparable components of the building envelope. In modern designs the trend of increasing the area of fenestration products for residential and commercial constructions is seen worldwide. Windows contribute to a better standard of living with daylight and useful heat gains, but, on the other hand, cause higher heat losses or non-desirable heat gains. Currently, the thermal transmittance of fenestration components is still much higher than for walls. Recent improvements of the walls' and windows' thermal properties contribute to a better building performance and hence cause the thermal bridging effects occurring in the building envelope to be more important. Among the other thermal bridges the one of the window-to-wall connection appears to be especially important in energy context and should not be underestimated.

Window placement in the window opening can be accomplished in several ways. Well insulated walls are relatively thick, so the window can be placed at several locations in the window opening. Moreover, different strategies for sealing and insulating the connection between window and wall can be used. This study focuses on investigating different solutions for window-to-wall connections and their potential of ensuring a better thermal performance (reducing the thermal bridge effect). Several heat transfer simulations have been done for various solutions of the window-to-wall connection, using the THERM 6.3 computing software. Based on those calculations, a parametric study is carried out to show the importance of various factors on the linear thermal transmittance.

Results show that different window placements influence the linear thermal transmittance values significantly. The optimal window position, considering the reduction of heat loss, was found to be about 35 mm from the surface of the external wind barrier to the edge of the window frame (for timber wall case, regardless of the wall thickness). Furthermore, the lowest surface temperatures of inside window sill were compared for different window locations. The lowest temperature for optimal solution was found to be only 1°C lower than that for other placements. In addition, alternative designs of inside window framing, which can substantially lower the linear thermal transmittance, are presented.

INTRODUCTION

Nowadays, saving energy and reducing carbon emissions is one of the top priorities in each sector of human activity. Buildings are an important part of human life, since people use them for the majority of the day. Energy use in buildings worldwide accounts for over 40% of primary energy use and for around 24% of greenhouse gas emissions. Energy and emissions include both direct usage of fossil fuels (on-site) and indirect use of energy in the form of electricity, district heating, district cooling, and embodied energy in construction materials (Voss and Musall 2011).

Windows are inseparable components of the building envelope. In modern designs a trend of increasing the area of fenestration products for residential and commercial construc-

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tions is seen worldwide. Windows contribute to a better standard of living and useful heat gains but on the other hand can cause higher heat losses or non-desirable heat gains. Currently, the thermal transmittance of fenestration components is still much higher than those for walls. Studies show that up to 60% of the total energy loss through the building envelope can be due to windows (Gustavsen et al. 2008a), but this is of course very dependent on the building geometry/configuration, assemblies' and windows' thermal performance, and amount of windows.

Recent improvements of walls' and windows' insulating properties contribute to better building performance, and addressing thermal bridging effects occurring in the building envelope can thus be more important. Among other thermal bridges, the one in the window-to-wall connection appears to be especially important. The study by Gustavsen et al. (2008b) shows that for a typical 160 m^2 Norwegian dwelling, the window-to-wall interface can be responsible for about 40% of the total heat loss caused by thermal bridging effects. For the same building but with the focus on reducing thermal bridges, the window-to-wall interfaces were responsible for 17% of the total heat loss through thermal bridges. Similar results were reported in the ISO 14683:2007 standard (ISO 2007d) regarding thermal bridges calculation methods, where it was concluded that for relatively low performing generic buildings, thermal bridges caused 36% of the total energy loss through the building envelope, while the window-to-wall connection was responsible for 38% of this value. This demonstrated that the heat loss through the window-to-wall connection is very important in energy context and should hence not be underestimated.

Window openings are created in order to give support for window placement in a wall and should have the ability to protect from water intrusion and air leakage into the building envelope. The study of Maref et al. (2011) concluded that this interface has the lowest temperature indices throughout building envelope, which makes it the most likely location for condensation to occur. Window placement in the window opening can be accomplished in several ways. Well insulated walls are relatively thick, therefore a window can be placed at several locations in the window opening. Moreover, different strategies for sealing and insulating the connections can be used. However, there are usually conflicting recommendations and requirements for the diverse solutions driven by thermal performance, moisture resistance, structure durability, solar heating, daylight distribution, and architectural conditions.

This study focuses on investigating different solutions for window-to-wall connections and their potential of ensuring better thermal performance (reducing thermal bridge effect). Thermal bridge effect for different connections depends on the wall type, window position in the opening, thermal resistance between frame and window opening, and internal window framing construction. The work focuses on these factors and aims to find the optimal solution for a window-to-wall connection. In order to accomplish this goal, several heat flux calculations have been carried out for various solutions of window-to-wall connections, using the THERM 6.3 software. Based on calculations, a parametric study is carried out to show the importance of various factors on the linear thermal transmittance. The linear thermal transmittance defines the additional heat loss of thermal bridge in comparison to the reference one-dimensional heat loss of the undisturbed element.

LITERATURE REVIEW

The topic of window-to-wall connections has been studied before in literature, however the issue of thermal bridging effect on window-to-wall connections has not been widely explored yet. Experimental studies by Maref et al. (2012, 2011) investigated the influence of air leakage through window-to-wall connections with respect to condensation risk. These studies concluded that filling the gap between the window frame and window opening with spray-in-foam insulation lowered the possibility of condensation—since less cold air is transported to the warm side of the window. Another study by Lacasse et al. (2009) concluded that the window-to-wall connection is important from a water intrusion point of view. Water intrusion can lead to premature failure of the building envelope. Many solutions have been designed over the years in order to guard the envelope from water intrusion. The study assessed effectiveness of water intrusion in the window-to-wall connection by laboratory testing. The investigation was performed for typical Canadian window-to-wall connection solutions.

SINTEF, which is the largest non-commercial and independent research organization in Scandinavia, has been a major contributor to the research on thermal bridging effects. In various reports and guidelines, the window position in the window opening is referred to as an important parameter for minimizing thermal bridges. SINTEF building research design guideline 471.015 (Gustavsen and Roald 2008) gave an example of the relationship between the window position and the linear thermal transmittance for a timber wall with 250 mm insulation. The simulated wall was constructed with exterior vented cladding, wind barrier, gypsum board, and interior lining. The geometry is illustrated in Figure 1 and values of linear thermal transmittance for the various window positions are shown in Table 1.

The study shows certain window location (35 mm from the outside wall edge) is the most favorable in terms of reducing the thermal bridge effect (among the positions studied). For cases in which a window was placed at an outside position (hanging out –42 mm from the wind barrier to line up with the exterior cladding), the linear thermal transmittance is five times higher. Choosing the solution for window placement is important not only from the thermal point of view. Other factors must be taken into account, such as moisture conditions, solar heating, daylight distribution, window durability, maintenance needs, and architectural aspects. The optimum window location according to some other SINTEF recommen-

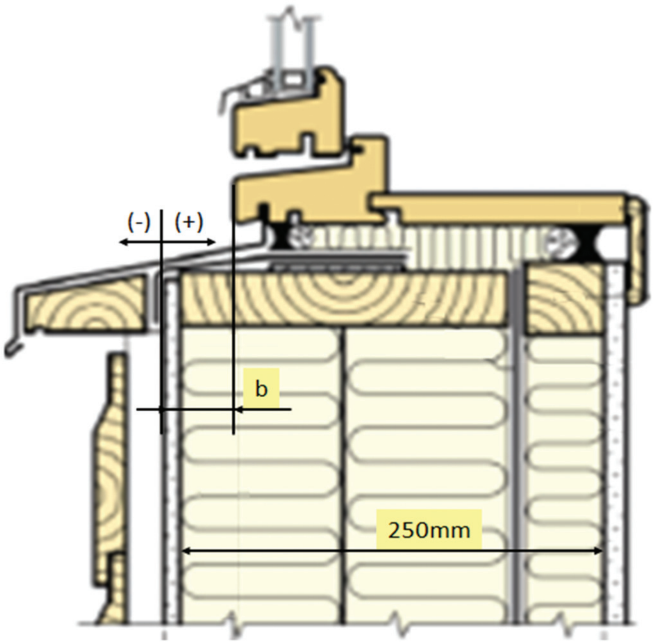

Figure 1 *Examples of window position regarding linear thermal transmittance (Gustavsen and Roald 2008).*

Table 1. Linear Thermal Transmittance for Different Window Positions (Gustavsen and Roald 2008)

Distance from Wind Barrier to Frame b, mm	Ψ, W/(m·K)
–42	0.05
0	0.02
35	0.01
85	0.02
140	0.03

dations differs from presented solution. SINTEF building research design guideline 523.701 (SINTEF 2003b) (concerning window installation details in the timber walls) and 523.702 (SINTEF 2003c) (concerning window installation details in masonry and concrete walls) recommend two ways of installing windows depending on the climate. Outer window position (equivalent to –42 mm in Table 1) is recommended for coastal Norwegian regions—according to the guidelines such a position makes the sealing process against rain water easier. Inner position (equivalent to 85–140 mm in Table 1) is suggested for midland climates—with limited amounts of wind driven-rain. The justification for this position is the fact that placing a window inside the opening gives higher inner surface temperatures on the window—which lowers the risk of condensation. This paper aims to determine if the inside surface temperatures for highly insulating windows depend strongly on window position in the opening.

Another study by Cappelletti et al. (2011) investigated the influence of window installation details on the thermal bridging effect on window-to-wall connections for clay-block walls. Wooden windows have been numerically tested with two different wall constructions (brick wall insulated from outside and brick wall with insulated cavity) at three different positions (outside, intermediate, inside) for each wall design. For each case the linear thermal transmittance based on external dimensions was calculated (in accordance with EN ISO 10211:2007 [ISO 2007b]). It was found that window positioning and connection construction details of the window opening have an impact on linear thermal transmittance, which differs by 70%—75% between cases. In addition, the actual method used to include the thermal bridging effect of window-to-wall connections with the window U-factors has been proposed.

SCOPE AND LIMITATION OF WORK

The scope of this study is to do the following:

- determine the most efficient position of a window in window openings in terms of minimizing the linear thermal transmittance value for typical wooden wall constructions with insulation of three different thicknesses (198, 246, 298 mm),
- determine how an internal window framing thickness and design influence the linear thermal transmittance on window-to-wall interfaces for a typical wooden wall,
- show the influence of the thermal bridging effect on the U-factor for different window sizes, and
- determine temperature changes of internal window surfaces with regard to window position in the opening.

It should be noted that this study does not investigate the air leakage or water drainage capabilities of the modeled solutions. Moreover, flashing is not included in the simulating models. Flashing made of high conductivity materials may have influence on the linear thermal transmittance value. However, the study compares the linear thermal transmittance between different cases rather than determining its actual value. Air flow along the surfaces was not simulated in detail; simplified convection coefficients were used. Presented optimal solutions for each case must be further investigated in terms of the other aspects of window-to-wall connections. The connection of window sills and window openings was the only connection modeled.

NUMERICAL SIMULATIONS

The objective of the heat flow calculations was to evaluate thermal bridges at the window-to-wall connection. Heat flow calculations during the study were carried out using the computer program THERM, version 6.3. The software is developed by Lawrence Berkeley National Laboratory

(LBNL) in California. THERM is a two-dimensional finite element program that calculates conduction, radiation heat exchange, and also estimates the influence of convection phenomena in the air cavities (LBNL 2011). The software was used to prepare geometry and conduct two-dimensional heat transfer simulations. Window frame geometry was prepared in accordance with ISO 10077-2 (ISO 2012) standard and overall geometry of window-to-wall connection in accordance with ISO 10211 (ISO 2007b).

This study investigates a typical wooden wall structure with ventilated cladding (a sketch of the wall intersection is presented in Figure 1). Wall geometry was simplified and external cladding was not modeled. This influenced outside boundary conditions described below. Wall geometry is presented and described in Table 2. Influence of non-continuous (in horizontal direction) wall construction was neglected in the study. The simulations for all cases were performed using a well thermally insulated window produced by a Norwegian manufacturer (an aluminum-clad wood window with polyurethane thermal braked, total window U-factor of about 0.7 W/[m^2·K]). For simulation purposes, the glazing unit was replaced with an insulating panel (thermal conductivity of 0.035 W/[m·K])—value typical for 3P insulated glazing unit employing two low-e coatings and argon gas fill) and glazing spacers were neglected in the model. Moreover, no window fixings elements were modeled in the study. The edge U-factor of windows equals 0.82 W/m^2·K (with insulating panel as glazing). The window sketches and THERM geometry are presented in Figure 2 and Figure 3. Wall and window material properties are shown in Table 3. Only the connections of window openings and window sills were considered in this study.

Boundary conditions (BC) used for simulations depended on the simulation scope. For simulations used to determine linear thermal transmittance values, simplified ISO 10077-2:2012 (ISO 2012) boundary conditions were applied to the window unit. Since external cladding and ventilated air cavities were not included in the wall model, the outside surface of the gypsum board was treated as a surface facing a ventilated air cavity. BCs on the surface were set according to the procedure described in the standard ISO 6946:2007 (ISO 2007a). In order to determine the lowest temperatures on the window inside surfaces, the boundary conditions for surfaces facing the outside environment were set to values recommended by National Fenestration Rating Council (NFRC 2012a) for both wall and window geometry. The reason for using different BCs was to determine the actual temperatures on the inside surfaces at severe winter conditions in order to assess risk of condensation (although condensation usually should not occur for such a good window). Boundary conditions are described in Table 4.

Wall structures were drawn with a length of 1.2 meters and a window was inserted in the desired position. The sketch showing the geometry of the model is presented in Figure 4

The linear thermal transmittance was calculated according to the formula (1).

$$\Psi = L^{2D} - \sum_i U_i \cdot l_i \text{ W/(m·K)} \tag{1}$$

where

L^{2D} = the thermal coupling coefficient obtained from a two-dimensional calculation of the component separating the two considered environments.

U_i = the thermal transmittance of the one-dimensional component separating the two considered environments (see Figure 4).

l_i = the length within the two-dimensional geometrical model over which the value of U_i applies (see Figure 4).

RESULTS AND DISCUSSION

For all simulations, typical wooden wall structures were used, which consisted of thermal insulation enclosed between two gypsum boards and a wooden opening window frame. Any divisions in the materials are not taken into account. Vapor barrier has not been considered in this study due to its low impact on thermal resistance..

First, simulations were conducted for five window locations in the wall with 246 mm insulation (see Case 1 in

Table 2. Wall Construction Used in the Study

<table>
<tr><td>Geometry</td><td colspan="2">
</td></tr>
<tr><td rowspan="2">Construction</td><td>Material (from inside to outside)</td><td>Thickness [mm]</td></tr>
<tr><td>Gypsum board
Insulation
Gypsum board</td><td>13
198/246/296: differs for cases
9</td></tr>
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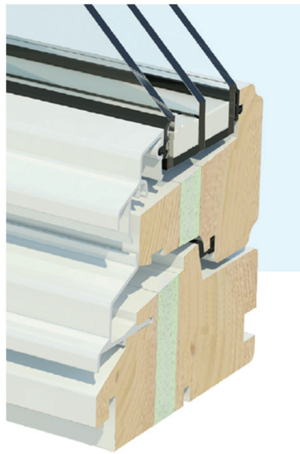


Figure 2 Sketch of window intersection used in the study. (NorDan 2010).

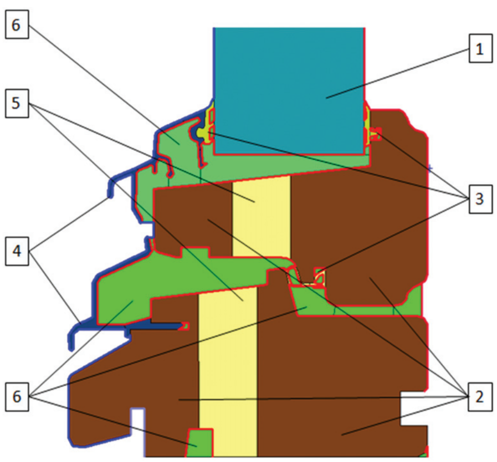


Figure 3 THERM model of the simulated window. Number 6 indicates frame air cavities, other labels are described in Table 3.

Table 5). For this case the calculated wall U-factor equals 0.19 W/(m^2·K). Placement of the window was based on the distance from the outside surface of the external gypsum board to the outside edge of the window sill (this distance is represented by value b [mm]). Additional 14 mm thick wooden elements/shims were added to the window elevation for the following still positions: b = +85 mm and b = +140 mm. This was necessary to fulfill the requirements of minimum slope of the outside flashing, according to the SINTEF building research design guideline 523.701 (SINTEF 2003b).

The next two variations of the same wall construction with different insulation thickness were considered. In the first case, the insulated wall with 198 mm thick insulation (U-factor 0.22 W/[m^2·K]) was analyzed. Calculations were also performed for a wall with a 296 mm thick insulation layer (U-factor 0.15 W/[m^2·K]). Linear thermal transmittance values were calculated for all cases (refer to Table 5). In order to investigate the influence of insulation thermal conductivity (between window frame and window opening) on linear thermal transmittance, the insulation thermal conductivity was set to 0.02 W/(m·K) (Case 4). Case 5 included standard wall construction (246 mm insulation thickness) but with thicker inside window framing (the thickness was changed from 19 mm to 32 mm). In Case 6 the alternative internal window framing design was presented. Details of the connection are shown in the graph for Cases 6–8 (Table 5). The proposed design allows more insulation than the standard design. The two last cases (Cases 7 and 8) involve the same geometry as used in Case 6, but insulation thermal conductivity between the window frame and the window opening is set to 0.02 and 0.01 W/(m·K), respectively (the 0.01 W/[m·K] material is included to investigate possible improvements if new insulation materials are found). Moreover, different exterior boundary conditions for Cases 1, 3, 6, and 8 were applied to determine the lowest temperature of the inside frame surfaces.

Table 5 describes and presents results for different cases of the timber wall. The results show that different window placements are crucial parameters for the linear thermal transmittance values. Theoretically for this wall type, window-to-

Table 3. Material Properties Used in the Study*

Material	Figure or Table Number/ Number of Element	Conductivity, W/(m·K)	Emissivity
Aluminum alloys	Fig 3 / 4	160	0.8
Ethylene propylene diene monomer (EPDM)	Fig 3 / 3	0.25	0.9
Foam panel	Fig 3 / 1	0.035	0.9
Mineral wool	Table 2 / 1	0.037	0.9
Gypsum board	Table 2 / 2	0.25	0.9
Polyurethane (PUR)	Fig 3 / 5	0.03	0.9
Wood (pine)	Fig 3 / 2, Table 2 / 3	0.13	0.9

* Material data used in the calculations are derived from ISO 10456 (ISO 2007c), SINTEF building research design guideline 471.010 (SINTEF 2003a) or NFRC 101 (NFRC 2012b).

Table 4. Boundary Conditions Applied in the Simulations

Description →	Simulations Determining Linear Thermal Transmittance —Window Geometry	Simulations Determining Linear Thermal Transmittance—Wall Geometry	Simulations Determining the Lowest Inside Surface Temperatures	Units
Boundary Condition ↓	**Values**			
Indoor temperature	20	20	20	°C
Outdoor temperature	0	0	–18	°C
Combined convection and radiation surface coefficient of heat transfer for the indoor frame and vision sections	7.692	7.692	7.692	W/(m^2·K)
Combined convection and radiation surface coefficient of heat transfer for the outdoor frame and vision section	25.0	7.692	26.0 (radiation model: BLACKBODY)	W/(m^2·K)
References	ISO 10077-2:2012	ISO 6946:2007	NFRC 100	—

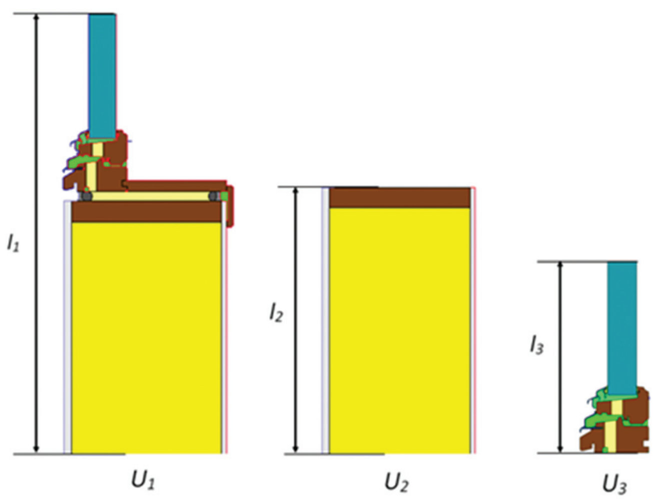


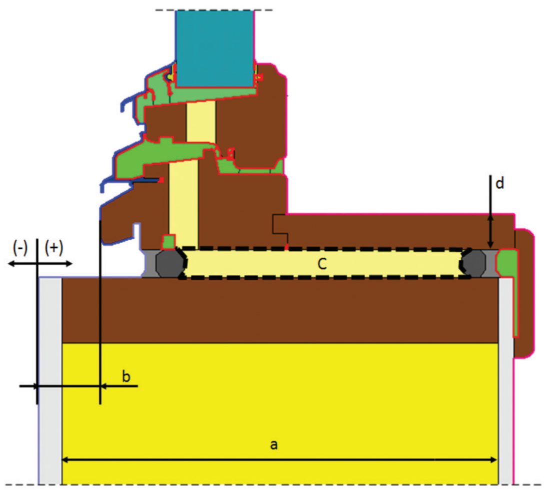
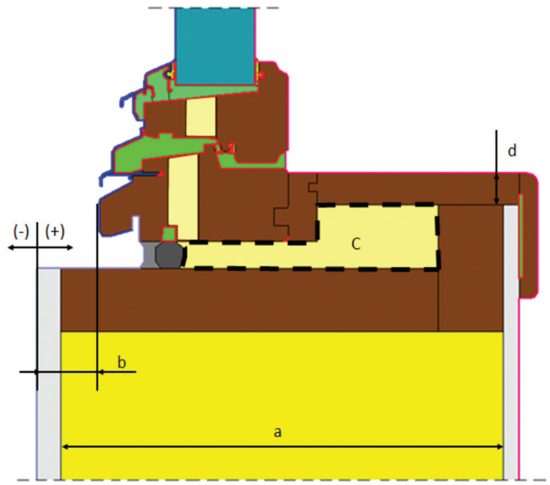
Figure 4 *Sketch of geometry modeled in the study (the model is not to scale).*

wall connection causes the lowest thermal bridging if the window is installed at the middle of the insulation as is suggested in Table A.2/Case W5 in ISO 14683 Standard (ISO 2007d). This was also confirmed by a simple simulation prior to study. However, if wooden shims providing the required flashing slope are added at the middle position, it is not anymore optimal in terms of thermal performance. The optimal window placement was found to be around 35 mm from the outside surface of external gypsum board to the edge of the window frame (for all timber wall cases). Windows mounted more to the outside or inside of the wooden wall provided larger values of linear thermal transmittance. The lowest inside surface temperatures of the window frame were compared for different window positions in order to address recommendations from SINTEF building research design guideline 523.701 and 523.702. For Case 1 the difference between positions b = +140 mm and optimal position (b = +35 mm). equals 1°C, while actual temperatures are equal to 13.6 and 14.6°C, respectively. For an indoor temperature equal to 20°C, condensation might occur for window position b = +35 mm at the level of indoor air relative humidity (RH) 66%, while for position b = +140 mm, at the level of rh 70%. It was found that for the thicker wall (296 mm of insulation) the difference between the same cases is lower (0.4°C). The proposed new window framing design (Case 6) not significantly lowers the temperature to 13.1°C for optimal position (b = +35 mm)—what in this particular case may be caused by frame design. Filling the gap with improved insulation (Case 8) gives the same temperature values as for the traditional solution (Case 1) while lowering thermal bridging value around 87% (actual change of 0.013 W/[m·K]).

It was also found that the thermal bridging effect increases with increasing thickness of the wall construction—the exceptions are window positions in the window opening very close to the interior. In such a case the heat paths to the internal wall are shorter, thus causing a larger heat loss compared to the thicker walls with the same window distance from the external wall (dimension b). The thickness of the insulating layer in the wall is crucial for the wall U-factor and the wall thickness. Higher thermal resistance of the wall leads to a relatively larger heat transfer through the window-to-wall connection. Because the wall is thicker, heat flow paths are relatively shorter for the window-to-wall connection compared with the rest of the structure. It causes relatively higher thermal bridging effect, even if the total heat transfer through wall and window will be less. This effect is greatest for a window placed outermost in the window opening.

It was found that the linear thermal transmittance is reduced when the space between the window and the wall is insulated with a material of lower thermal conductivity. Changing conductivity from 0.032 to 0.020 W/(m·K) resulted in decreased linear thermal transmittance by around

Table 5. Simulation Results for Wooden Wall Cases*

Geometry									
Case Number		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Insulation Thickness a, mm		246	198	296	246	246	246	246	246
Internal Sill/Flashing Thickness d, mm		19	19	19	19	32	18	18	18
Insulation Conductivity C, W/(m·K) (dotted area)		0.032	0.032	0.032	0.02	0.032	0.032	0.02	0.01
Wall U-factor, W/(m^2·K)		0.19	0.22	0.15	0.19	0.19	0.19	0.19	0.19
		Linear Thermal Transmittance Ψ, W/(m·K)					**Linear Thermal Transmittance Ψ, W/(m·K)**		
Position in Window Opening b, mm	–42	0.047	0.040	0.052	0.041	0.032	0.025*	0.019*	0.014*
	00	0.019	0.014	0.024	0.015	0.014	0.009*	0.005*	0.002*
	+ 35	0.015	0.012	0.019	0.012	0.011	0.007*	0.005*	0.002*
	+ 85	0.025	0.031	0.026	0.023	0.022	—	—	—
	+ 140	0.041	—	0.032	0.040	0.039	—	—	—
		Lowest Inside Surface Temperature, °C					**Lowest Inside Surface Temperature, °C**		
Position in Window Opening b, mm	–42	12.5	—	11.3	—	—	11.8	—	12.3
	00	13.4	—	13.3	—	—	13.0	—	13.4
	+ 35	13.6	—	13.5	—	—	13.1	—	13.6
	+ 85	13.8	—	13.5	—	—	—	—	—
	+ 140	14.6	—	13.9	—	—	—	—	—

* These results are calculated with the assumption that the window frame U- factor is not changed due to changed projected area of window frame.

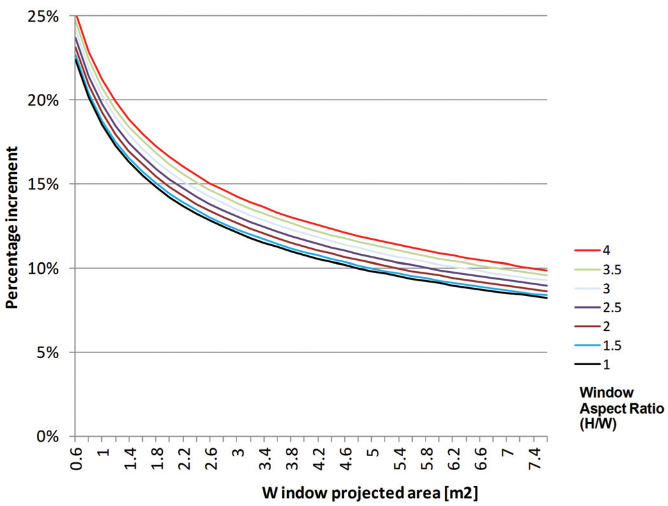


Figure 5 *Window U-factor increment for Case 1 (outer window position b = –42 mm).*

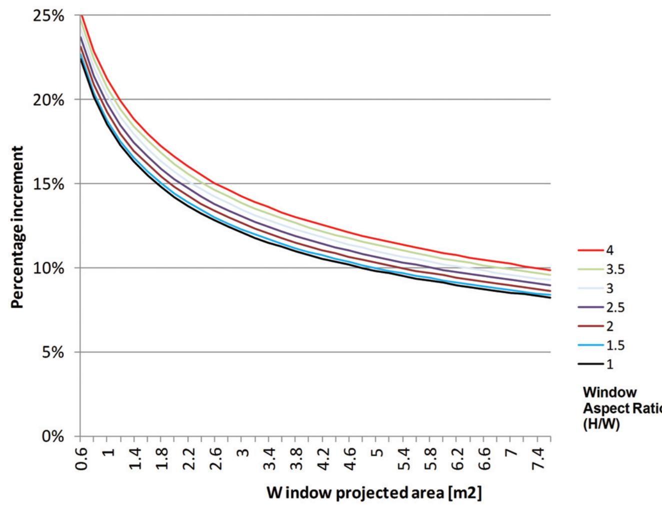


Figure 6 *Window U-factor increment for Case 1 (optimal window position b = +35 mm).*

20% (actual change of 0.003 W/[m·K]) (for an optimal window position, b = +35 mm). Placing a thicker inside window framing (32 mm instead of 19 mm) improved the thermal performance of the connection by around 26% (actual change of 0.004 W/[m·K]) for the optimal window position (b = +35 mm). A different design of inside window framing allows for accommodating additional insulation and has a great effect on thermal linear transmittance, due to increased volume of insulation and material in the region of window-to-wall connection and sill of the window frame. Linear thermal transmittance may be lower by 53% (actual change of 0.008 W/[m·K]) (using insulation with conductivity of 0.037 W/[m·K]) and 87% (actual change of 0.013 W/[m·K]) (using insulation with conductivity 0.010 W/[m·K]) for an optimal window positioning (b = +35 mm). The results were calculated with the assumption that the window edge U-factor is not changed due to changed window projected area for Cases 6–8. This way of calculation was applied as in Norway window manufacturers are not providing window inside framing as an integral part of the window. Usually, contractors take care of window wall connections and inside framing. The purpose of this assumption was to show how the wall connection can be improved by different ways of arranging inside framing using the same window in the same wall construction.

In order to show how the window position in the window opening influences the window U-factor by including the thermal bridging effect into window performance, percentage increment was calculated. The calculations intend to show how the window-to-wall issue is important, hence they should not be confused with U-values defined by ISO (ISO 2006) or NFRC (NFRC 2012b) standards. The methodology for this calculation was published in the study by Cappelletti et al. (2011). Window U-factor percentage increment was calculated according to the following formula:

$$\Delta U_w = \frac{U_{2D} - U_w}{U_w} \times 100\% \qquad (2)$$

where

$$U_{2D} = \frac{U_w A_w + \Psi_w (2H + 2W)}{A_w}$$

U_w = windows U-value, W/(m^2·K)

A_w = window projected area, m^2

Ψ_w = linear thermal transmitance on window – wall connection, W/(m^2·K)

H, W = respectively projected height and width of the window, m

In order to accomplish the calculation with available simulation results the following assumptions were made:

- Linear thermal transmittance for jambs and head has the same value as for sill for different window positions.
- Jambs and head of window frame have the same U-factors as a window sill. Foam insulation panel properties were used as a glazing (U-factor calculated for foam panel equals to 0.70 W/m^2·K).
- Window U-factors were calculated with accordance to ISO standard 10077-1:2006 (ISO 2006). Linear thermal transmittance describing thermal bridge caused by spacer was also derived from ISO 10077-1:2006 and set to the value of 0.06 W/(m·K).

Figure 5 and Figure 6 show increment of window U-factor with included thermal bridging effect, for different window positions in Case 1 (b = –42 mm and b = +35 mm). It can be seen that higher increments are observed for smaller windows, since edge region performance has a higher influence on the overall fenestration rating value. Moreover it appears that windows with aspect ratio equal to 1 (window height to window width) are the least influence by thermal bridging effect on the window-to-wall connection.

Table 6 presents window U-factor increments calculated for three different window sizes for installing scenarios. Table 6 shows that U-factor increment calculated according to the assumptions for standard window size is relatively high – 15% for the window positioned –42 mm from the wind barrier which is recommended for coastal climates in SINTEF building research design guideline 523.701 and 523.702. Positioning windows in the thermally optimal location (b = +35 mm) reduces the increment to 5%. Arranging inside window sills in the proposed way (Cases 6–8 in Table 5) gives an increment value of 2% (standard size window). For the proposed solution if the insulation between window frame and window opening is replaced with insulation with conductivity equal to 0.1 W/(m·K) then the window U-factor increment is lower than 1% (Case 8).

UNCERTAINTIES

A number of geometrical simplifications in the developed model and material properties may influence the accuracy of the results. For the purpose of modeling, several intermittent layers were assumed continuous and simplified. Some other details were not included such as window flashing and vapor barrier. Moreover, simplified boundary conditions were used. Simulation accuracy was assessed using so-called energy error norm defined by THERM. The computational software estimates error in heat flux calculations using the fact that the superconvergent points coincide with Gauss integration points. Using this fact, the algorithm makes a "guess" at all the nodal points. Least squares method is used to fit a smooth function to the values of the gradient at these points. Values obtained from the smooth function are used to calculate difference between actual value of heat flux and the value calculated on the fitted smooth function. The ratio between this difference and predicted heat flux value (based on the smooth function) is used to estimate the accuracy of the numerical solution. The 10% criterion is usually used for mesh refinement. If the estimated error is higher than 10%, the numerical mesh is refined to obtain higher accuracy (i.e. decrease discretization error). According to numerical tests performed in THERM, a 10% limit for energy error norm ensures maximum 1% error in U-factor calculation—for more details refer to THERM technical documentation (LBNL 2011). For all simulations the energy error norm was kept around 6% which yields a U-factor uncertainty of less than 1%.

CONCLUSIONS

A well-insulated building envelope is essential for thermal comfort and energy savings. The individual building components and the connections should be carefully designed. Window-to-wall connections appear to be important in building envelope energy balance.

The study shows that the position of the window in the window opening is a complex subject. There are many factors and conditions related to the insertion of windows that need to be taken into account when selecting a connection solution. The current study is focused mainly on thermal aspects of the window-to-wall interface.

Results show that placement plays a crucial role in linear thermal transmittance. It was also found that thermal bridge increases with increasing thickness of wall construction for all window positions in the opening, except positions in which window is very close to the interior. The optimal window placement position, considering the reduction of heat loss, was found to be around 35 mm from the outside surface of external wind barrier to the edge of the window frame (for timber wall case, regardless of wall thickness). Moreover, the lowest interior surface temperatures were compared for different window positions. The lowest temperature for the optimal solution was found to be only 1°C lower than that for other placements.

It was also found that linear thermal transmittance is reduced when the space between the window and the wall is insulated with a material of lower thermal conductivity or when the window framing thickness is increased. Alternative designs of inside window framing were presented which can lower the linear thermal transmittance value by 53% (using

Table 6. Percentage U-factor Increments for Different Window Sizes

Window Size	Small Window	Standard Window	Large Window
Dimension (W × H), m	0.7 × 0.9	1.24 × 1.48	3 × 2.5
Base window U-factor, W/(m^2·K)	1.09	0.95	0.83
Case	**Increment (%) / Window U-factor (W/[m^2·K])**		
Case 1 (position –42 mm)	22% / 1.33	15% / 0.95	12% / 0.90
Case 1 (position +35 mm)	7% / 1.16	5% / 0.99	3% / 0.85
Case 6 (position +35 mm)	3% / 1.12	2% / 0.97	1% / 0.84
Case 8 (position +35 mm)	1% / 1.10	0.6% / 0.95	0.4% / 0.83

insulation with conductivity of 0.037 W/[m·K]) and 87% (using insulation with conductivity of 0.010 W/[m·K]).

It was shown that for a standard size window (1.23 m × 1.46 m) the outermost window position caused a window U-factor increment of 15%, while for the optimal location (b = +35 mm) the increment was reduced to 5%. Considering inside window sill in the proposed alternative way gives increment values of 3% and 1% for the case with improved insulation.

FUTURE WORK

The work presented in this paper is a good starting point for further investigation of window-to-wall connection properties. Further work might focus on the following:

- investigating window-to-wall connection including window jambs and head,
- investigating window-to-wall connection for walls with different materials/constructions, and
- investigating window-to-wall connection in three dimensions to capture influence of geometric thermal bridges (corners of the window).

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