Thermal analysis of Curtain Wall Systems - a parametric study

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ABSTRACT HEADING

The thermal performance of curtain wall systems can easily be calculated using 2D numerical simulations. Several commercial software packages are available, and international standards provide a methodology to calculate the thermal transmittance. However, even though these methods are well known in academia and the research community in general, thermal optimization has not reached its full potential in the building industry yet and there is considerable margin for improvement. Based on a market survey in North America and Europe, generic curtain wall sections were developed, and typical approaches for improving the thermal performance of curtain wall systems have been identified and described. Subsequently, the impact of separate improvements, as well as combined effects have been studied using both standardized and advanced calculation methods. For this, the heat transfer phenomena and the way these are modelled according to standard calculation procedures are discussed. Moreover, for a number of important aspects the current calculation standards do not provide adequate guidelines which results in diverging interpretations with a large impact on the overall performance. Next to that, a number of secondary effect originating from standards are discussed, e.g. the thickness of the IGU, the depth of the window rebate, equivalent thermal conductivities and the impact of reduced heat transfer coefficients. Finally, the relative impact of the thermal performance of curtain walls system on typical commercial buildings is analysed and evaluated.

INTRODUCTION

Throughout the last few decades there has been a growing interest in reducing the energy use in buildings. There are many aspects that contribute to the overall energy efficiency of a building, e.g.: orientation, compactness, HVAC systems (Heating, Ventilation and Air Conditioning), airtightness and of course an appropriate insulation level. Particularly the performance of insulation has been investigated thoroughly in past studies as it may be perhaps the first aspect that needs to be tackled in reducing the energy use of buildings. Moreover, countries throughout the world are now implementing specific standards and guidelines to take the impact of thermal bridges and 2D-effects into consideration in the overall heat loss coefficient calculation. However, one building component remains a source of concern, more specifically window frames and curtain wall systems. These are rather complex components due to specific boundary conditions relating to mechanical performance, operability, acoustics etcetera. For walls, roofs and floors typical guidelines for maximum thermal transmittance in central to north-European countries are situated between 0.1 and 0.3 W.m²K, which can easily be realized with common construction types. For windows the guidelines are less strict, and typically vary between 0.8 W/m²K and 2.4

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W/m²K. In some countries there are specific requirements on the IGU's as well. Commercial double glazing with low-e coating and argon gas filling have a thermal transmittance of 1.1 W/m²K, whereas triple glazing and vacuum glazing can go as low as 0.5 W/m²K. To the knowledge of the authors, there are no specific restrictions in different countries on the thermal conductivity of the window frames or curtain wall systems. Note that imposing specific restrictions would render it impossible to construct some specific window configurations. Moreover, a performance based approach towards energy use should be preferred over a prescriptive regulation.

The information on thermal optimization of curtain walls systems in scientific literature, and literature in general, is rather scarce. The research community has moved away from the rather simple heat transfer calculations of components, towards more dynamic and complex effects (e.g. impact of shading devices, computational fluid dynamics of cavities in double skin façades etc.). Not a single scientific publication was found that provides clear guidelines on the thermal optimization of mullions and transoms. Alternatively, a few publications can be found on the thermal performance and optimization of window frames. Gustavsen et al. (2008, 2011) studied the impact of thermal conductivity of frame material and thermal breaks, to define material performance targets for currents window designs. Note that a U-value of 0.5 W/m²K was chosen as required performance level, simply based on the fact that the best commercial IGU's (Insulating Glass Units) on the market now have a U-value of 0.5 W/m²K. Based on that approach, it was concluded that thermal breaks should have a thermal conductivity below 0.02 W/mK (or 0.005 W/mK if 'new' materials are developed), structural insulating materials for wood composite profiles should have a thermal conductivity below 0.03 W/mK, and ideally aluminum and PVC frames should comprise cavities with an emissivity below 0.05 for the surrounding materials. No design guidelines for window geometry were presented, and no pathways were specified on how to acquire the specified conductivities. Similarly, Byars and Arasteh (2010) also focused on the impact of thermal conductivity on the U-value of the frame. Research by Gustavsen et al. (2008) indicated that although convection is modelled in EN ISO 10077-2 by adopting a simplified approach with equivalent thermal conductivities, results compare well with the fluid flow simulations. ISO 10077-2 prescribes that cavities with an interconnection not exceeding 2 mm are to be considered as separate. Any reference to papers or research is lacking for that assumption, and by means of CFD simulations it was shown by Gustavson that 7mm would be a more realistic criterion.

SIMULATION METHOD

In this paper an analysis is presented on the thermal performance of typical North-American and European curtain wall systems. In order to assess and evaluate that performance, a uniform calculation methodology was adopted. Note that the North-American and European approach are not completely identical. This has two consequences: first of all, small discrepancies may arise between the results in the analysis presented in this report, and results published by manufacturers using a different calculation method. Different calculation rules lead to different heat transfer results. However, in this report only a relative comparison is made to evaluate the impact of specific parameters. Consequently, small differences in absolute value are not as important, and the specific choice of calculation method should not be overrated. Secondly, the sheer existence of very specific calculation rules inevitably leads to adapted industrial designs. E.g. in North-America two cavities are considered as independent and connected with a "throat" region when the shortest distance between two sides is smaller than 5 mm (cfr. ISO 15099), whereas in Europe a value of 2 mm is used as criterion (ISO 10077-2). So when two parts of one cavity are separated by a throat region that is only 2 mm wide, the two zones of the cavity can be considered as two separate zones. By consequence, window frame and curtain wall designs might slightly differ in different regions, as profiles are most likely optimized according to local calculation methods. For the example described above relating to cavity subdivision, one will find a lot of 4.9 mm throats in North-America, and 1.9 mm throats in Europe. By consequence, simulating frame sections according to a calculation sequence for which it was not optimized might lead to a "sub-optimal" design.

Only the U-value of the curtain wall is considered in this analysis, which excludes the impact of the IGU (center of glazing), the spacer (edge of glazing), and the window-wall interface. The specific geometry of the IGU, i.e. thickness and width, does have an impact on the U-value of the frame, and will thus be considered. The spacer and window-wall interface do not have an impact on the U-value of the frame, and by consequence is not comprised in the analysis. This approach isolates the impact of the curtain wall itself on the overall performance, and the results of this analysis can be combined with separate simulations on IGU and IGU spacers. Furthermore, there is a big discrepancy between the European and North-American approach. In Europe only the center-of-panel U-value of the IGU is considered (and multiplied with the total IGU surface), whereas the impact of the IGU edge spacer is accounted for by means of a linear thermal transmittance. In contrast, in North-America the IGU area is separated in two distinct areas: the center-of-panel, and a band of 63.5 mm wide with a U-value that incorporated the edge effect of the spacer (i.e. the alternative approach described in section 4.1.4 of ISO 15099).

NFRC 100-2014

In North-America the NFRC 100-2014 “Procedure for determining Fenestration Product U-factors” by the National Fenestration Rating Council is typically used to evaluate the thermal performance of window and curtain wall systems. The document provides guidelines on how to determine the U-value of product lines (how to cope with different sizes, how to select a test matrix, rules for extrapolation etcetera) and custom products. For the simulation and calculation individual frames the document refers to ISO 15099. Next to that, it is specified that only area-weighed methods are allowed. Furthermore, a number of technical aspects are listed, only the most important ones are summarized below:

- Boundary conditions: T_{in} 21°C, T_{out} -18°C, wind speed 5.5 m/s
- Indoor convective heat transfer coefficient is based on center-of-panel IGU surface temperature
- On the interior side a detailed grey body radiation model shall be used
- The exterior convective heat transfer coefficient is based on the exterior wind speed (26W/m²K)
- On the exterior side a detailed black body radiation model shall be used
- A cross-section should include at least 150 mm of glazing section

Note that NFRC 100-2014 does not specify what correlation should be used to calculate the convective heat transfer coefficient on the inside and outside. For both several correlations can be found in literature. Next to that, it does not include specific calculation procedures for curtain wall systems. ISO 15099 provides guidelines on the calculation of the thermal performance of windows and doors. Two different thermal indices are presented to normalize absolute heat loss through a component: the linear thermal transmittance ψ [W/mK] and the frame thermal transmittance U [W/m²K]. ISO 15099 refers to ISO 10077-2 and ISO 10211 for the details regarding the required two-dimensional numerical analysis, and specifies following boundary conditions:

- T_{in} 20°C
- T_{out} 0°C
- Interior convective heat transfer coefficient $h_{cv,in}$ is 3.6 W/m²K
- Exterior convective heat transfer coefficient $h_{cv,ex}$ is 20 W/m²K

ISO 15099 also provides correlations for the exterior convective heat transfer coefficient: $h_{cv,ex} = 4.7 + 7.6*v$

Next to that, the treatment of cavities according to ISO 15099 depends on the orientation. In this report only horizontal heat flows are considered (the curtain wall is assumed to be in a vertical position). Please refer to the standard for the detailed calculation of the Nusselt number. Finally, the Therm 6.3 / Window 6.3 NFRC simulation manual comprises an approach to take the effect of screws into account. Basically the impact of thermal bridges is accounted for by simulating the cross-section at the thermal bridge itself, adopting a surface area based “effective” thermal conductivity for the component that introduces the thermal bridge.

ISO 12631

The only ISO standard that specifically deals with calculating the thermal performance of curtain wall systems is

ISO 12631 “Thermal performance of curtain walling – calculation of thermal transmittance”. Two different calculation approaches are presented: the single assessment method and the component assessment method. The component assessment method is more suited for evaluating product lines and considers the frame, IGU and spacer of the IGU as separate components, which allows an easy approach towards calculating the performance of different combinations of frames, IGU’s and spacers. The energy transmission is normalized by dividing the heat loss by the surface area of the frame. This approach is often used in both Europe as North-America (where it is the only accepted method). The single assessment method was developed to calculate the thermal performance of systems that were developed for a specific project, and allows to combine the effect of the frame and spacer in one calculation. But every time a single parameter is changed, the whole simulation needs to be repeated. The heat loss is expressed as a linear additional heat loss, similar to linear thermal transmittance that is used in thermal bridge calculation. NFRC 100-2014 does not support the use of this approach. For determining the thermal transmittance of frames, mullions and transoms, ISO 12631 refers to the numerical approach in ISO 10077-2, or the experimental assessment with a hot box. ISO 10077-2 is the reference standard on the numerical aspects for determining the thermal performance of window frames. According to this approach, following boundary conditions should be adopted:

- T_{in} = 20°C
- T_{out} = 0°C
- Interior surface resistance is
  0.13 m²K/W (~ heat transfer coefficient of 7.7 W/m²K) in plane surfaces
  0.20 m²K/W (~ heat transfer coefficient of 5 W/m²K) at edges or corners with reduced heat transfer.
- Interior surface resistance is 0.04 m²K/W (~ heat transfer coefficient of 25 W/m²K)
- A cross-section should include at least 190 mm of glazing section

The radiation heat transfer is calculated in a similar way in NFRC 100-2014. Please refer to the ISO 10077-2 standard for the detailed calculation of the Nusselt number. Note that this calculation procedure does differ significantly from the one described in ISO 15099. Mind that the ISO 10077-2 was developed specifically for the calculation of heat transport in window frames, which arguably would result in a narrower range of Nusselt correlations, in accordance with the typical geometry of the cavities found in window frames. The only specific aspect of curtain wall systems that is not addressed in the ISO 10077-2, is the impact of screws connecting the internal to the external sections of mullions and transoms. ISO 12631 provides two approaches to take this into account: either a default ΔU is added to the U-value of the frame without screws, or it can be calculated according to the approach described in annex C of ISO 12631. The only default value for ΔU that is listed is 0.3W/m²K. This can be used for screws in stainless steel, with a diameter ≤ 6mm, and a distance between the connectors between 200 and 300 mm. Annex C provides an approach using an equivalent thermal conductivity for the screw. The simulation is done assuming the screw is a continuous metal plate in the profile, but by changing the thermal conductivity the actual performance can be determined.

Simulation approach

The NFRC 100-2014 refers to the ISO 15099 for the calculation procedures, but specifies a number of small changes in respect to boundary conditions and modeling the surface heat transfer coefficients. In turn, the ISO 15099 standard refers to ISO 10077-2. The ISO 12631 standard also refers to ISO 10077-2 to determine the heat transmittance, but adds specific guidelines to account for screws (similar to the approach in the Therm 6.3 / Window 6.3 NFRC Simulation Manual). Consequently, the ISO 10077-2 is the basis for numerical simulations in both North-America as Europe. The most important differences refer to the boundary conditions and convection in cavities. Next to that, the calculation of thermal bridges is also of importance. As stated in the introduction, in this report the focus lies on a comparative analysis, and as such the relative difference between different systems is more important than the absolute value of an individual calculation.

A comparison of convection correlations can be found in (Gustavsen, 2001). Considering a range of aspect ratio's, he concluded that the ISO 10077-2 over-predicts the convection for aspect ratios below 0.4 compared to measurements reported in literature, whereas it under-predicts the convection for aspect ratio's between 0.4 and 10 and shows a good correlation for higher aspect ratios. The ISO 15099 seems to work well for Rayleigh numbers up to 105. However, the impact of the chosen correlation should not be overestimated. Simulations by Blanusa et al. (2007) indicate that the difference in the overall thermal performance is never larger than 3%. Mind that this only refers to the difference in convection correlations in the cavities. By consequence, the ISO 12631 (and ISO 10077-2 which both ISO 12631 as NFRC 100-2014 refer to) is adopted here. Furthermore, this is the only ISO standard that was specifically designed for curtain walls, and is used in several continents. Next to that, as European optimization parameters and approaches will be considered for thermal optimization, the European approach is best fit to evaluate the effectiveness of the thermal improvements. Similarly, fixed heat transfer coefficients are adopted that take into account reduced heat transfer at corners according to ISO 10077-2. Again, the impact of different heat transfer coefficients is of limited importance for a comparative analysis, and the impact reduces for thermally improved systems.

Simulation of mechanical fixings

Although heat conduction through mechanical fixings is a 3D phenomenon, a 2D simulation method can provide a relatively precise estimation. According to Annex C of NBN EN ISO 12631:2012, the screw has to be modeled as a 'smoothed' screw with its thickness equal to the real diameter with an equivalent thermal conductivity. The airspace surrounding the screw needs to be treated as a single air space, to avoid inaccurate results.

Table 1 provides an overview of some results on simulating the screws in curtain wall systems. For these simulations, software programms Bisco, Trisco and Solido were used (please refer to the manual for a more detailed description of the calculation procedure; Bisco 2012). There programs have been developed by Physibel, and are generally considered as state-of-the-art models in the research community. The three programs are rather similar, but Bisco uses a triangular grid, Trisco has an orthogonal grid and Solido also uses a rectangular grid with node fitting so it can almost perfectly replicate the original geometry (Bisco, 2012). The results show that the difference between those three programs is limited (0.1%). When the actual geometry of the screw is modeled accurately, the U-value is 2.526 W/m²K. When the smoothed lambda-value is applied, as adopted in Annex C of NBN EN ISO 12631:2012 and Therm 6.3 / Window 6.3 NFRC Simulation Manual, the heat loss through the screws is underestimated by 6% (or 0.16 W/m²K) compared to the correct simulations. The simulations point out it is better to adopt the smoothed thickness approach: the screw is replaced by a continuous plate which has the same overall cross section as the screws. For example, if each 250 mm a screw (simplified, 5x5 mm) connects both aluminum parts, the smoothed thickness of the thin plate is 0.1 mm (5 mm x 5 mm = 25 mm² = 250 mm x 0.1 mm). In that case the heat loss through the screws is overestimated by 2%. However, based on the Solido simulations the impact of the screw itself is 0.267 W/m²k, 0.107 W/m²k based on the smoothed lambda approach in Bisco, and 0.329 W/m²k according to the smoothed thickness method. Based on these results, it was decided to use the smoothed thickness method. All simulations presented in this paper were done with the software program Bisco, and the ISO 10077-2 standard calculation method is adopted.

Table 1: Simulation results on simulation of screws in Bisco, Trisco and Solido

	Q [W/m]	Q [W]	U_f [W/m²K]	
		Frame without screw		
BISCO	8.3127		2.256	
TRISCO	8.3205		2.259	
SOLIDO	8.3205		2.259	
		Frame with screw		
SOLIDO		1.1049	2.526	Reference
TRISCO		1.1141	2.564	**+2%**

BISCO[1]	8.4918	2.363	**-6%**
BISCO[2]	8.9182	2.585	**+2%**
TRISCO[2]	8.9260	2.571	**+2%**

[1] Smoothed lambda method (EN 13947)
[2] Smoothed thickness method (EN 13947)

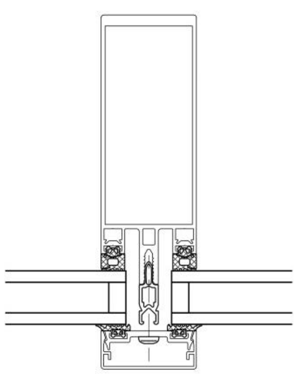
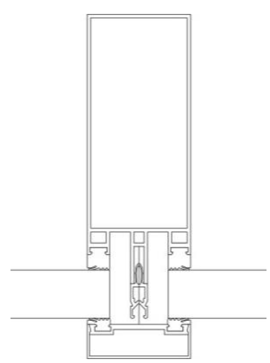
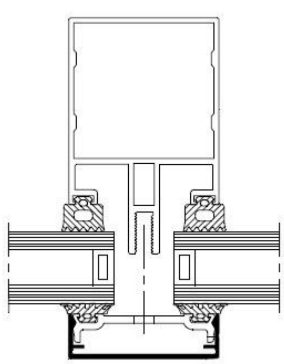
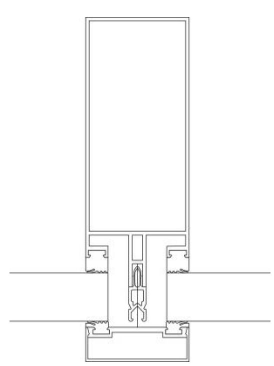
MODELS

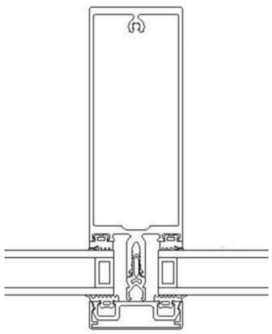
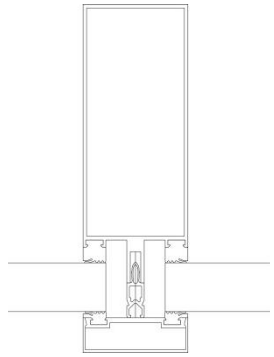
In order to design generic curtain walls systems, an overview of typical sections of North American and European commercial curtain wall systems is listed. Technical information on typical aluminum curtain wall systems is gathered from company websites, industry guidelines, public test reports, CE-marking databases and local technical approval documents.

Commercial European curtain wall systems

In Europe, a variety of curtain wall systems can be found. In general, the width of the frame varies between 50 and 60 mm, depending on the specific application. The length of the total frame varies as well; but only the interior frame will have a major influence on the thermal performance. In table 2, 3 exemplary frames of 60mm width, 200 mm length and a glass thickness of 28 mm are simulated and compared. As required by NBN ISO EN 10077-2, the IGU length in simulations is 190 mm; measured from the outer surface of the aluminum frame.

Table 2: Selection of typical European curtain wall system sections

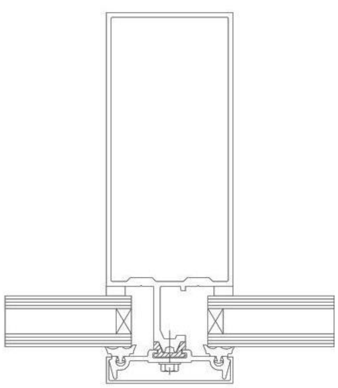
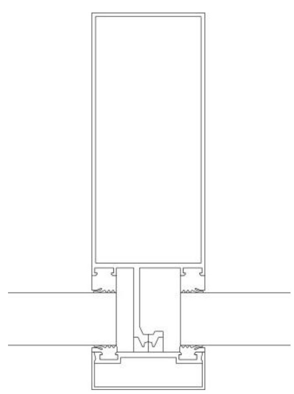
Company A	Simulation model	Results
		U_f = 4.203 W/m²K Ψ = 0.581 W/mK
Company B	Simulation model	Results
		U_f = 3.961 W/m²K Ψ = 0.567 W/mK

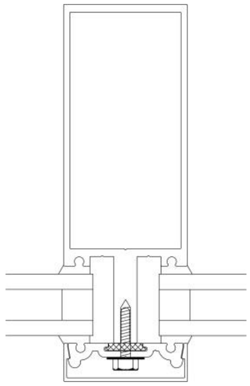
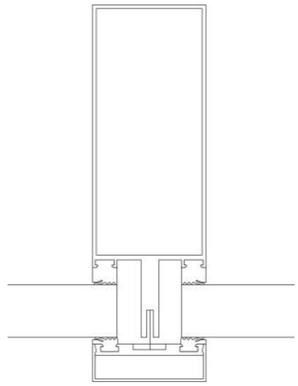
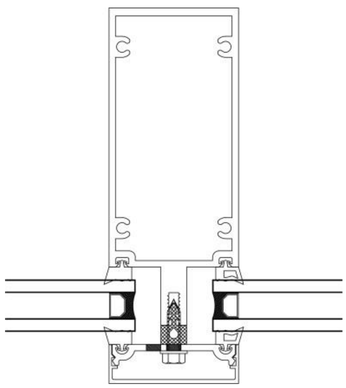
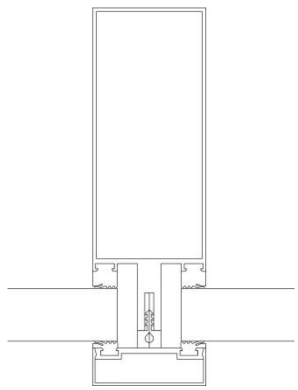
Company C	Simulation model	Results
		U_f = 4.352 W/m²K Ψ = 0.590 W/mK

Commercial North-American curtain wall systems

In general, North-American curtain wall systems do not differ much from European frames, except for the shape of the aluminum frame itself. In most cases, the frame width is equal to 60 mm. In both Europe and North-America the mullions and transoms of curtain wall frames consist of an aluminum structural member on the inside, an aluminum pressure plate on the outside, and for reasons of esthetics an aluminum cap to finish the exterior. The IGU's are installed with dry seals (typically EPDM). The most important difference between systems is the way the pressure plate is mechanically fixed to the structural member. To optimize the thermal performance of the system, the continuity of the insulation should be maintained in the space between the IGU's, by avoiding materials with high conductivity, and reducing the section of these components. In Table 3, 3 exemplary frames of 60 mm width, 200 mm length and a glass thickness of 28 mm are simulated and compared.

Table 3: Selection of typical North-American curtain wall system sections

Company D	Simulation model	Results
		U_f = 7.344 W/m²K Ψ = 0.770 W/mK
Company E	Simulation model	Results

		$U_f = 6.648$ W/m²K $\Psi = 0.728$ W/mK
Company F	Simulation model	Results
		$U_f = 7.453$ W/m²K $\Psi = 0.777$ W/mK

Development of generic curtain wall system

The development of a generic curtain wall system allows for an analysis that is independent of specific products and manufacturers. A generic model is representative for current building practice and allows for the implementation of all relevant thermal enhancements. In a first analysis, common techniques in curtain wall design are investigated and evaluated. The reference profile should act as a basis for further development and should leave sufficient room for improvement. Design parameters were chosen to be rather poor, creating possibilities for optimization.

- Profile lengths usually vary from 100 mm up to 300 mm. A representative length of 200 mm was chosen as a starting point, leaving room for increasing and decreasing the profile length.
- The width of the curtain wall frame is commonly 50 or 60 mm. A representative width of 60 mm was chosen as a starting point, leaving room for increasing or decreasing the profile width.
- The glazing panel was chosen to be double glazed, resulting in an IGU width of 28 mm.
- The outer point of the IGU was positioned just below the inner side of the gaskets. In this way, the effect of positioning the IGU towards the inside and the outside of the frame can be investigated.
- After a first analysis, it was clear that the length of the screw fins could have a major impact on the overall performance of the frame. The length of the screw fins was chosen to be on the poor side (30 mm), as a result of which the influence of a decrease in length could be investigated.

After analyzing both European and North-American curtain wall systems, two generic curtain wall frames are proposed in Figure 1.

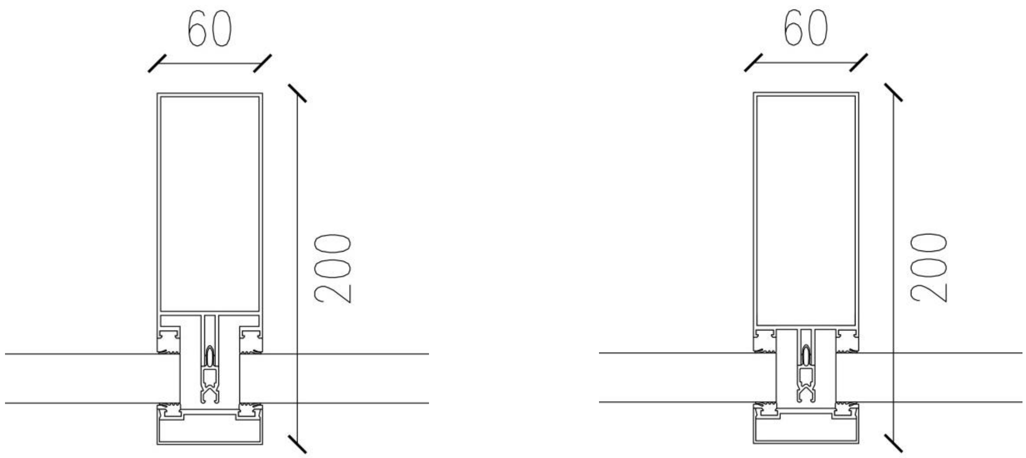


Figure 1: European (left) and North-American (right) generic curtain wall frame

European versus North-American generic curtain wall frames

Two systematic differences that are evident from analyzing a series of European and North-American curtain wall systems are the location of the interior gasket and the more/less solid screw connection. In European systems there is an additional member in the interior aluminum profile that holds the gasket, whereas in North-America the gasket is often installed directly into the aluminum structural member. Note that this difference in design does not originate from a thermal point of view, but from watertightness. As the curtain walls are designed as drained and pressure equalized systems, the drainage plane is located at the back of the cavity between the IGU's. During rain events water will reach that plane and drain at the bottom to the exterior by means of weep holes. Due to the use of pressure equalization, the larger part of the wind gusts will be transferred to the interior gaskets. Consequently, if some water would in fact infiltrate into the system and reach the back of the cavity, it will be subjected to significant driving forces to infiltrate into the interior. In European systems the additional member that holds the gasket ensures that the gaskets are not located at the drainage plane. Moreover, in North-American systems the water will run down along the gasket of the mullion, and due to surface tension the water will be partly redirected horizontally where the vertical gasket connects with the horizontal gasket of the transom. It is well known in the industry that specific location is the primary source of water leaks in lab conditions as well as in practice.

To compare the generic curtain wall frames, simulations were performed to assess the (linear) thermal transmittance. Table 4 shows that little difference between both frames can be discerned; the North-American frame performs slightly better. Similar results are evident when simulating a generic European frame with solid screw fin connection; where the U-value only increased with 0.021 Wm^2K. The lower Uf-value of the North-American frame can be linked to the shorter length of the screw fins. The absence of the profile member holding the gaskets in the North-American reference frame, leads to different heat flux pathways in both frames. A shorter screw fin length results in less heat loss through these fins, although more heat will pass through the pressure plate below the outer gaskets. Similarly, the solid screw connection does not have a significant impact on the heat fluxes through the curtain wall frame.

Table 4: Performance of generic curtain wall frames

	U_f [W/m²K]	Ψ [W/mK]
Europe	3.947	0.566
North-America	3.792	0.557

When executing 1D calculations, the combined interior and exterior surface resistance would be equal to 0.04 + 0.13 = 0.17 m²K/W, resulting in a U-value of 5.88 W/m²K of a thin aluminum plate (disregarding the thermal resistance in conduction of the plate). One might be temped to consider that value as a theoretical and practical upper limit for U-values. Nevertheless, the 2D simulations show results of approximately 7 W/m²K. This difference is generated by discarding the material influence in 1D simulations. In 2D simulations, the cooling fin effect results in an increase of thermal transmittance as the most influential parameter for heat loss in highly conducting components is $\sum A_i * R_{si}$. A larger interior surface results in a higher U-value, because the interior heat transfer coefficient is in fact the bottleneck for the overall heat flux, whereas in typical building constructions this is the thermal resistance of the component itself. When discarding the interior aluminum frame, the U-value decreases from 7.344 W/m²K to 5.274 W/m²K.

PARAMETER ANALYSIS

A series of simulations were executed to analyze the influence on thermal performance of the design parameters shown in Figure 2, which is the same as the European reference in figure 1. The parameters that will be simulated are: (1) profile width and (2) depth, (3) length of the screw fins, (4) position of the insulating glass units, (5) influence of intermediate distance between mechanical fixings, (6) glass unit thickness and (7) length of the snap cover. Furthermore, the influence of the λ-value of screws and compartmentalization profiles is investigated. To achieve a thermally optimized curtain wall frame, several techniques to insulate the inner gasket are compared and simulated as well.

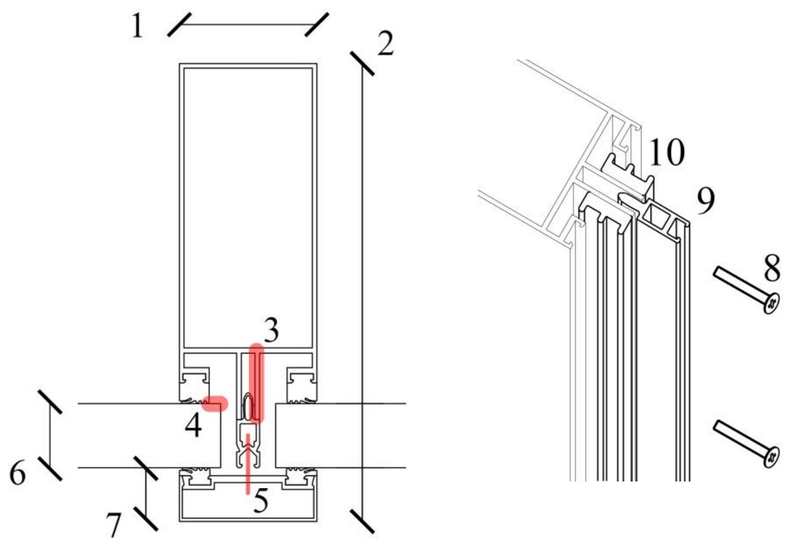


Figure 2: Visualization of sensitive parameters (1: Profile width, 2: profile length, 3: length of the screw fins, 4: position of the IGU, 5: intermediate distance between mechanical fixings, 6: IGU thickness, 7: snap cover length, 8: λ-value of the screws, 9: λ-value of compartmentalization profile, 10: insulating interior gasket.)

Table 5 lists the materials used in the simulations and their respective λ-value (thermal conductivity). If this value is varied for a specific part of the parameter study in the simulations, the specific λ-values are given further in the report. The values reported in Table 5 originate from annex 1 of EN ISO 10077-2. Output results from the simulations are the thermal transmittance of the frame (U_f), and the linear thermal transmittance (ψ). Results of the simulations are discussed below.

Table 5: λ-value materials

Material	λ [W/mK]
Aluminum frame	160
Insulation panel (glass)	0.035
EPDM gaskets	0.25
Fiber Reinforced Polyamid	0.3
Stainless steel (screw)	17

Profile width and length

Firstly, the dimensions of the curtain wall frames affect its thermal performance. Figure 2 shows the varying parameters that were simulated; 1 indicates a change in profile width, 2 indicates a varying profile length. Profile widths of 50 and 60 mm and profile lengths of 100, 150, 200, 250 and 300 mm are compared and analyzed in Figure 3. From the results it is evident that the 50mm profiles are accompanied by a slightly lower heat flux as compared to the 60 mm profiles. Similarly, if the depth of a profile increases the thermal performance decreases. Adding more material to a specific configuration typically reduces the heat flux and as such increases the thermal performance by increasing the thermal resistance. However, in the case of aluminum profiles the thermal conductivity of the aluminum is excessively high, which leads to the situation that the material itself is not the most important bottleneck for heat transport, but the heat transfer coefficient at the interior surface. By increasing the size of the interior aluminum profile, a larger surface area is generated, and the heat transfer from the component to the air is facilitated. The effect is rather similar to the design of cooling fins to facilitate heat transfer. The values vary between 3.5 and 4.5 W/m²K, and the lowest Uf-value is found for a curtain wall frame of 50 mm by 100 mm (the smallest one that was evaluated). Next to that, it can be seen that the influence of the profile depth reduces for increased size. For larger profiles an equilibrium is becoming apparent for heat flux through the component and maximum heat loss at the interior side (defined by the convective and radiation heat transfer coefficient).

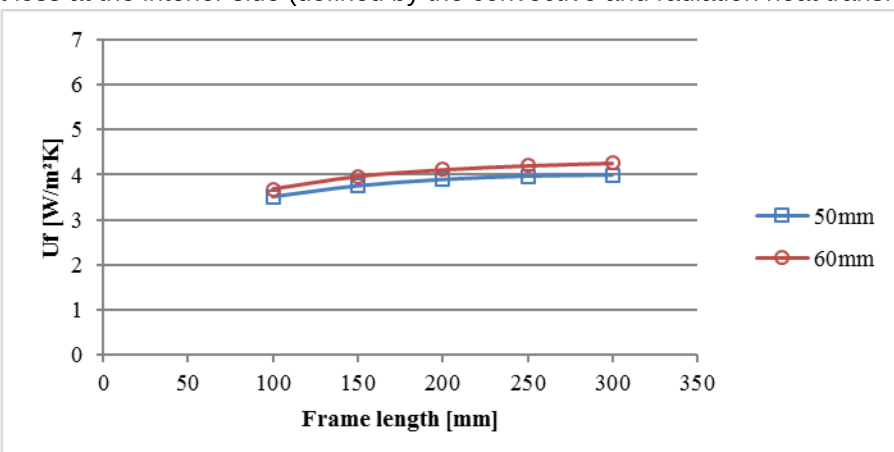


Figure 3: Impact of profile width and length on thermal performance

The IGU's are replaced by solid insulation panels in the simulations (please refer to EN ISO 10077-2 for the simulation procedure). Another important fact is the absence of a temperature gradient in the interior and exterior aluminum profiles. The thermal conductivity of the aluminum is easily 1000 times higher than the conductivity of the air inside the cavities. As a result, any thermal resistance that may be found in the air in the cavities is simply thermally bypassed by the adjoining aluminum frame members. To obtain a better understanding of the thermal behavior of the complex geometry of the curtain wall systems, the heat flux density throughout the section is visualized as well. Figure 4 shows the most important pathways that conduct heat from the interior to the exterior (normalized value for visual reference). Given the symmetrical layout of the section, this symmetry is reflected in the reduced heat flux at the central axis of the profile. The high thermal conductivity of the aluminum is likewise evident: the highest heat fluxes can be found at the aluminum parts connecting the interior to the exterior. The screw that is used to fix the pressure plate to the frame is modeled by means of very slender stainless steel continuous plate located in the center of the frame. Even though the screws do not necessarily make contact with the back of the tubular frame in practice, this is superseded by the conductivity through the aluminum. Even if the screws do make contact with the back of the frame, it hardly affects the overall thermal performance. Throughout the parameter study the heat flux density is used to evaluate the effectiveness of specific optimization strategies.

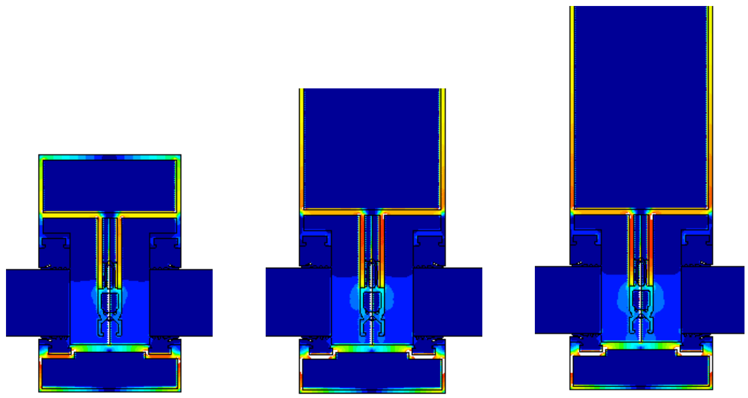


Figure 4: Heat flux profile for 100 m (left), 200 mm (middle) and 300 mm (right) profile length and 60 mm width

Length of the screw fins

From Figure 4 it is evident that the two aluminum fins in the central space between the IGU's are a very important heat flow pathway. It allows the fixation of screw that hold the pressure plate, and the width and depth are designed to accommodate the easy installation of screws. The thickness of the profile is determined by mechanical strength. Given that the interior and exterior aluminum profiles do not contribute to the overall thermal resistance, the thermal performance of the system basically depends on the configuration of the area between the IGU's, and between the pressure plate and the onset of the aluminum fins. Consequently, an important step to improve the thermal performance consists of decreasing the length of the aluminum fins; shown by parameter 3 in Figure 2. Results of the simulations on decreasing screw fin length are shown in Figure 5. It can be seen that a smaller screw fin results in a lower U_f-value. Screw fin were simulated with a length of 15, 20, 25, 30 and 35 mm. It can be seen that from a certain point, the impact of reducing the screw fins will stabilize and the influence on the thermal optimization will be negligible.

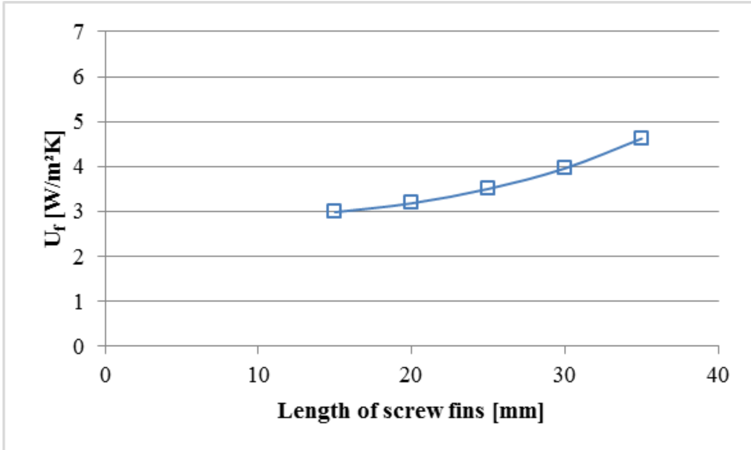


Figure 5: Impact of length screw fins

Position of the glass units

As discussed in the previous section, the thermal performance mainly depends on the configuration of the frame between the IGU's, and between the pressure plate and the aluminum fins. Given that the thermal resistance of that zone is typically significantly lower than that of the IGU's, one might consider increasing the height and width of the IGU panels. The distance between the glass unit and the screw fins should be at least 5mm in order to ensure a proper drainage of the system, and allow for a practical installation and adjustment on site. On the other hand, there is a minimum contact length between the IGU and gasket as well, for a reliable mechanical contact with the frame to transfer wind loads to the secondary and primary structure. Next to that, from an esthetical point of view the non-transparent edge seal is typically completely covered by the pressure plate. Note that when the IGU is inserted too much into the curtain wall system, the difference in solar exposure of the IGU at the edge increases the risk for thermal breaking of the glass panels. The effect of the IGU spacer is taken into account separately in the normative documents. In the standard configuration, the IGU is inserted 12 mm into the profile, which corresponds to the width of the gasket (i.e. the gasket is completely covered by the IGU, see position in figure 1). This corresponds to a U-value of 3.958W/m². When we increase the insertion by 5 mm, the U-value decreases to 3.434 W/m² (this is the situation shown in Figure 2). In contrast, when the IGU is only inserted 7 mm (recessed 5mm in comparison with the original position), the U-value increases up to 4.481 W/m²K. The increased IGU size narrows the area of the curtain wall where excess heat loss may be found and results in a lower U_f-value of the frame. Hence, this parameter should be considered when comparing different systems with their respective thermal performance. A slight change of IGU size by 5 mm can easily change the thermal performance by 15%.

Spacing between screws

In practice the pressure plate is fixed to the structural member by means of screws every 150 mm up to 300 mm. The distance between the screws is set by the maximum loads that the screws need to transfer. In turn, this is determined by the size of the IGU, the aspect ratio (height/width of the IGU), and maximum wind loads (suction). Peak negative pressures of building façades are typically higher the peak positive pressures. The mechanical fixation of the pressure plate also generates a number of secondary effects. First of all, by increasing the pressure a specific effect may arise similar to structural glazing: stress in the glass panes can get transferred to the aluminum profiles. Secondly, due to the elastic behavior of the gasket and low elastic modulus, it is very difficult to acquire a uniform stress on the gasket over the length of the mullion or transom. Most European system manufacturers mention that a specific torque should be applied for the installation of the screws. In contrast, on construction sites cordless electrical screwdrivers are used instead of a torque wrench. Even when a torque wrench is used, it typically takes 3 or 4 iterations of adjusting the individual screws to acquire a uniform torque and pressure within a 10% variance limit. As a result of these considerations, the number of screws incorporates major safety factors to account for the uncertainties in practice. To evaluate the influence of the mechanical fixings, the distance in between the screws is varied from 150 mm up to 300 mm. Assuming a spacing of 250 mm and a λ-value of 17 W/mK as a reference case, the equivalent λ-value of the screw in the simulations is changed in proportion to the specific intermediate distance (see results in Figure 6). For an increasing spacing between the screws, less material will be available for heat to pass through, resulting in a decreasing λ-value of the screw, and a decreasing U_f-value for an increasing intermediate distance.

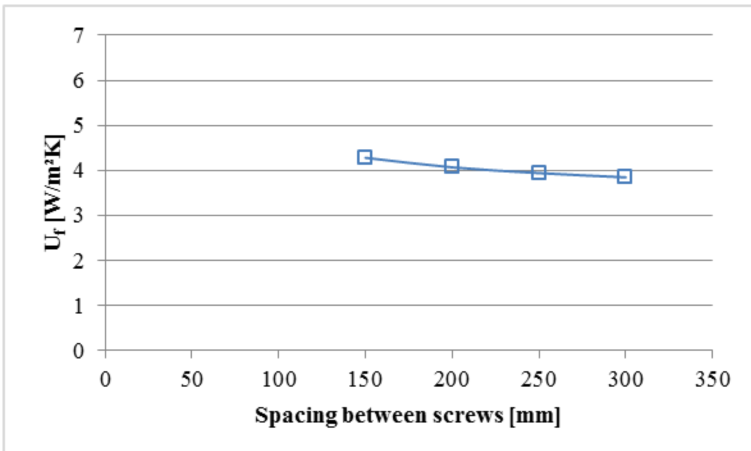


Figure 6: Spacing between screws

Glass unit thickness

As discussed in previous sections, only the space between the IGU's, pressure plate and aluminum fins contributes significantly to the thermal resistance of the frame. This might be optimized by increasing the thickness of the IGU panels, which will lengthen the pathway and reduce the thermal transmittance: see Figure 2, number 6. Figure 7 shows the influence of the glass unit thickness on the thermal transmittance of the frame. Increasing the thickness (20, 28, 36, 44, 52, and 60 mm) has a major influence on the thermal performance of the frame, showing that triple glazing can definitely contribute to the thermal optimization in curtain wall design. Due to the large difference in thermal transmittance of the IGU and the frame, the geometry of the IGU relative to the frame has a very large impact. Similar to the width and height of the IGU, the thickness of the IGU should always be considered when different systems are compared. In the simulations, no modifications were made to the frame when altering the thickness of the glazing units. In Figure 7, it can be seen that just by replacing a thin double glazing by thick triple glazing, the thermal transmittance of the frame can be reduced by half. This only accounts for the frame; the U-value of the IGU (center or edge) is not considered.

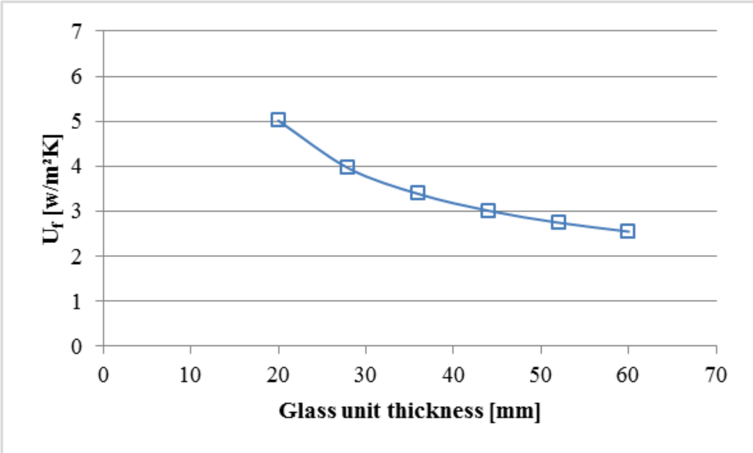
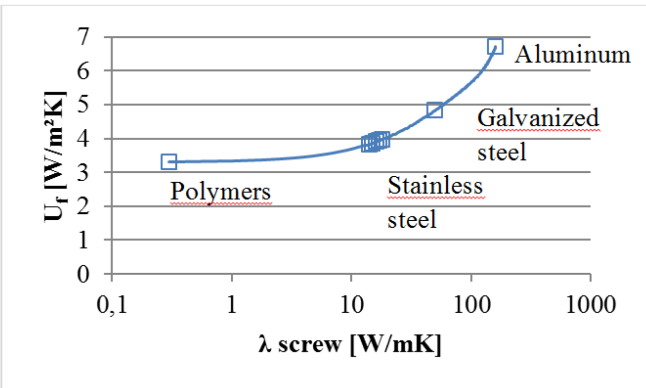


Figure 7: Glass unit thickness

λ-value of screws and compartmentalization profile

Figure 2, number 8 and 9, shows the influencing construction parts of which the λ-value will be varied during the simulations described below. Previous sections highlighted the impact of the screws and spacing of the screws on the overall thermal performance of the system. In practice the screws are stainless steel or galvanized steel. Figure 8 (left) shows that this choice in screw material already changes the thermal transmittance by 1 W/m²K. As a calculation example, following materials are considered: rigid polymers (λ-value typically 0.3 W/mK), different types of stainless steel (λ-value 14, 15, 16, 17, 18 W/mK), steel (λ-value 50 W/mK) and aluminum (λ-value 160 W/mK). Figure 8 (left) indicates that once the thermal conductivity approaches that of the adjoining materials and air cavities, the relative impact decreases. Although the stainless steel screws are now considered state-of-the-art, the adoption of e.g. fiber reinforced screws would further reduce the transmittance. Note that carbon fiber reinforced anchors are increasingly used in precast industrial concrete sandwich panels in Europe, which already indicates that the material is starting to become more popular in the building industry. Similarly, the thermal conductivity of the compartmentalization profile has an impact on the overall performance (Figure 8, right). λ-values of the compartmentalization profile that are considered are 0.1, 0.2, 0.28, 0.3 and 0.4 W/mK. In this case, a decrease of λ-value only induces a more moderate decrease in thermal transmittance (as the considered range is more limited as well).



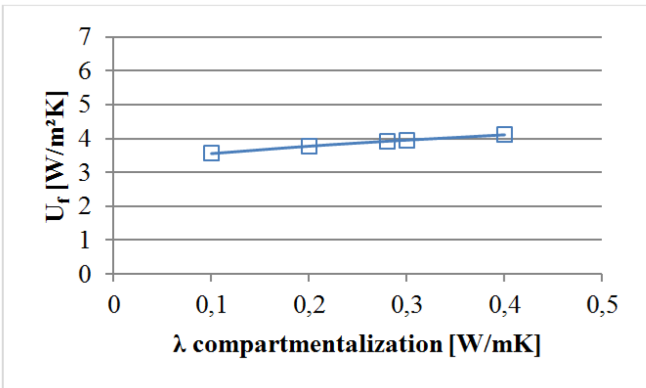


Figure 8: λ-values of different screw **(left)** and compartmentalization profile **(right)** materials

Snap cover length

Previous simulations reveal that the pressure plate and snap cover only have a minor influence on the overall thermal performance of the curtain wall frame. To investigate whether or not a variation in length of the snap cover has an effect on the thermal transmittance, simulations are executed for a snap cover length of 13.5, 18.5, 23.5, 28.5 and 33.5 mm (please refer to Figure 2, number 7). The results confirm the aforementioned statement and show that the snap cover length has a minor influence on the thermal performance of the frame. An increase of 20 mm increases the thermal transmittance by 0.1 w/m²K. The minor impact of the snap cover on the overall thermal performance is due to the higher exterior heat transfer coefficient (although the snap cover has a limited surface, this is compensated by the high convective heat transfer coefficient).

Materialization of the curtain wall frame

Since most of the heat loss can be assigned to the aluminum frame, a more insulating material could improve the thermal performance drastically. A first option is to tackle the insulating capacity of the overall frame. Glass Fiber Reinforced Plastic (GFRP, $\lambda = 0.40$ W/mK) is one option found in the industry to match the strength of aluminum and at the same time improve the thermal performance of the curtain wall system. Note that, although the thermal performance of the curtain wall frame increases drastically, the mechanical connection of the pressure plate to the inner frame can be questioned. Secondly, in traditional aluminum systems a significant amount of heat is directed outwards through the pressure plate. Another approach, is to replace the aluminum pressure plate by a polymer pressure plate ($\lambda = 0.30$ W/mK), creating an insulating barrier at the outside of the curtain wall frame.

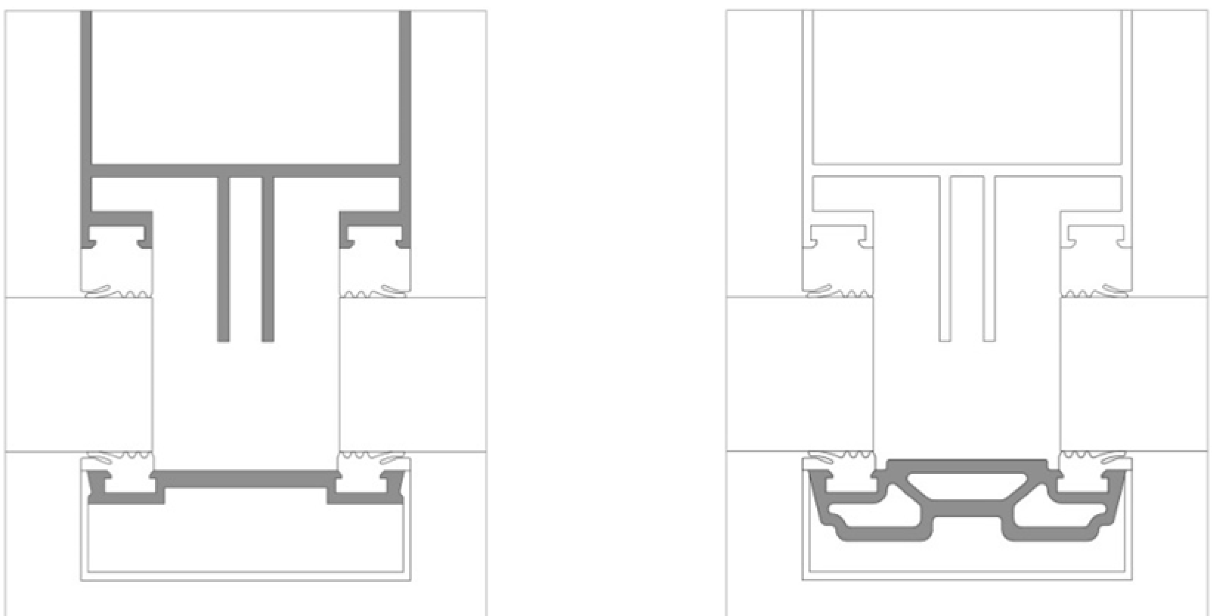


Figure 9: **Improved materialization** GFRP frame **(left),** Polymer pressure plate **(right)**

In Table, it can be seen that these changes in materialization have a major impact on the thermal performance of the overall frame. Both options result in a thermal optimization as compared to the reference frame. Note that, although the GFRP frame drastically decreases the heat loss through the frame, the mechanical connection can be questioned. Therefore, this option will not be taken into account in further optimization strategies.

Table 6: Thermal performance due to improved materialization of the frame

	U_f [W/m²K]	Ψ [W/mK]
Reference frame	3.947	0.566
GFRP frame	2.105	0.455
Polymer pressure plate	2.788	0.496

Additional insulation in the cavity

As a final step in thermal optimization of curtain wall frames, additional insulation can be installed in the inner cavity. Figure 10 shows three different options for insulation of the inner frame; the insulation material has a λ-value of 0.035 W/mK.

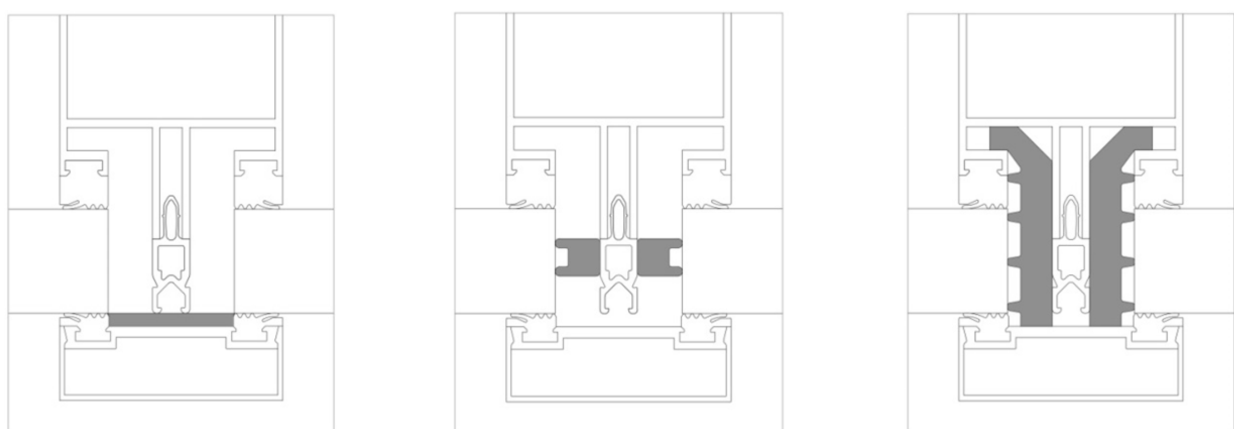


Figure 10: Additional insulation in the inner cavity: option a (left), option b (middle) and option c (right)

Table 7 shows the thermal transmittance for the insulated curtain wall frames as compared to the European reference frame. It is evident that the thermal transmittance decreases with an increasing amount of insulation in the inner cavity. Note that a complete filling of the inner cavity will prevent drainage of infiltrating water, increasing the risk for damage to the curtain wall. Since in this research only an analysis of existing techniques was performed, there is still room for optimization of the shape of the insulation.

Table 7: Effect of additional insulation

	U_f [W/m²K]	Ψ [W/mK]	I [-]
Reference frame	3.947	0.566	0.818
Option (a)	3.046	0.512	0.821
Option (b)	2.634	0.487	0.819
Option (c)	2.497	0.479	0.819

CONCLUSIONS

In this paper, a comparative analysis of current European and North-American curtain wall systems is performed to evaluate the thermal performance of existing curtain wall systems. When comparing existing standard systems (i.e. not thermally improved) for both continents, it can be seen that in general the European frames perform better and are more thermally efficient. A generic curtain wall frame was developed to investigate the influence of several design parameters on the thermal performance of the system.

Two systematic differences that are evident from analyzing a series of European and North-American curtain wall systems are the location of the interior gasket and the more/less solid screw fin connection. In European systems there is an additional member in the interior aluminum profile that holds the gasket, whereas in North-America the gasket is often installed directly into the aluminum structural member. Nonetheless, simulations show that the profile member that holds the gasket, which is only present in the European frame, does not have a major influence on the heat loss. The higher U_f-value of the North-American frame can be linked to the increased length of the screw fins.

A series of simulations was executed to evaluate the influence on thermal performance of several design parameters, such as: profile width and length, position of the insulating glass units, glass unit thickness, λ-values of screws and compartmentalization profile, … Results of the simulations show that the most influential parameters on the thermal performance of the curtain wall systems are:

- Length of the screw fin
- Glass unit thickness
- Additional insulation in the cavity

To design effectively thermal optimized curtain wall frames, the parameters mentioned should be combined into one optimal system.

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