# PARAMETRIC STUDY OF WINDOW FRAME GEOMETRY

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## ABSTRACT

This paper describes a parametric study on window frame geometry with the goal of designing frames with very good thermal properties. Three different parametric frame models are introduced, described by a number of variables. In the first part of the study, a process of sensitivity analysis is conducted to determine which of the parameters describing the frame have the highest impact on its thermal performance. Afterwards, an optimization process is conducted on each frame in order to optimize the design with regard to three objectives: minimizing the thermal transmittance, maximizing the net energy gain factor and minimizing the material use. Since the objectives contradict each other, it was found that it is not possible to identify a single solution that satisfies all these goals. Instead, a compromise between the objectives has to be found.

## INTRODUCTION

With current trends to reduce the energy use in buildings, there is a need to minimize the thermal transmittance of each part of the building envelope in order to reduce the transmission losses from the inside to the outside. Window frames cover a small part of the entire building surface, yet they can have a major impact on the heat losses, due to their poor insulation properties in comparison to other elements of the building envelope. Designing better frames with lower thermal transmittance can be very beneficial for energy savings in buildings (ASHRAE, 2009).

Various approaches can be taken to optimize a window frame. Many of the previous studies focused on developing slim frames that would cover a small fraction of the window area and promote solar heat gains, with little regard to the frame $U_f$ value (Appelfeld et al., 2010, Laustsen et al., 2005). Other investigations concentrated on the use of low conductivity materials to reduce the thermal transmittance of the frame (Gustavsen et al., 2011). However, not much effort has been taken to study and optimize the frame geometry. With the use of modern materials such as plastic (PVC), aluminium or fibre reinforced polymers (FRP) which can be crafted into various shapes, the engineers have a large freedom of design. Almost an infinite number of window frame geometries can be created, but not all of them will result in a satisfying $U_f$ value. It is important to determine how a proper design of the frame can contribute to the improvement of its thermal performance.

In the present study, an attempt is made to identify the key parameters describing the window frame design that can influence its thermal performance and to optimize the geometry of the frame. Such task can be solved by evaluating a large number of various frame geometries and comparing their thermal transmittance. Several programs exist that are capable of conducting finite element simulations and calculating the frame $U_f$ value, such as THERM (Mitchell et al., 2006) or HEAT2 (buildingphysics.com, 2013). The drawback of working with these tools is that it takes a large amount of time to draw the geometry and run the simulation, what makes them unusable for this study. To address this problem a special parametric design tool was created. The geometry is described by an array of parameters, representing dimensions of specific parts of the window frame and properties of the materials. As a result, many sets of parameters describing various frames can be inputted in the program and simulated automatically, allowing the user to evaluate a large number of designs.

This paper will present the background behind the tool and the results obtained in the parametric study. Three parametric frame geometries are introduced, that are based on existing highly insulated window frames. A sensitivity analysis is conducted to determine which parameters are the most important for improvement of the thermal performance of the frames. In the final part, an optimization process is conducted, with regard to three objectives: minimizing the thermal transmittance, maximizing the net energy gain factor and minimizing the area of the cross section of the frame. Weighted sum method was applied to address this multi objective optimization problem.

## METHODS

### Modelling assumptions

Window frames are modelled according to the international standard ISO 1077-2. Air cavities in the frames are treated as solid materials with equivalent thermal conductivity, representing the convective and radiative terms. Outside and inside boundary conditions used in the simulations are set according to the standard. Reduced radiation and convection occurs in edges or junctions between surfaces. The internal temperature is 20°C and the external 0°C. The heat transfer coefficients for internal, external and reduced boundary conditions are 25, 7.7 and 5 $W/m^2/K$ respectively. Material properties are listed in table 1. All the materials have emissivity of 0.9.

*Table 1*
*Thermal conductivity of the materials.*

| **Material** | **Thermal conductivity (W/m/K)** |
|---|---|
| FRP | 0.3 ÷ 0.4 |
| Insulation | 0.03 ÷ 0.05 |
| EPDM | 0.25 |
| Insulation panel | 0.035 |

**Parametric design tool**

The design tool is based on a finite element solver COMSOL Multiphysics (comsol.com, 2013), which is used to solve the equations for conductive heat transfer in the window frame and derive its $U_f$ value. Matlab (mathworks.se, 2013) is used to create the parametric design tool, and both programs are connected using the Livelink for Matlab module in COMSOL (comsol.com, 2013).

In traditional programs for evaluating thermal performance of window frames, the two dimensional geometry is either imported from CAD software or drawn in the program as a set of polygons representing the frame. In the design tool presented in this study, the geometry is built within the tool and is represented as a series of walls, each of them described by three parameters: length, width and rotation angle. The first wall starts in the base point of the coordinate system. Position of subsequent walls is based on the coordinates of the finishing point of the previous wall. Figure 1 presents the process of creating a simple geometry. An array of wall parameters can be inputted, describing the frame, as shown on figure 1a). Once the walls create a closed shape, a polygon is created, representing part of the frame, see figure 1b). The domain created in the middle is, by default, filled with air with equivalent thermal conductivity calculated according to the standard ISO 1077-2. This value can be later changed to represent other material, e. g. thermal insulation. As a next step, walls can be added inside the frame, described by similar parameters as the outside walls, with the addition of spatial coordinates of the starting point. After this step, the tool calculates the distance between every vertex on the inside of the frame to the nearby walls to check for any interconnections between cavities smaller than 2 mm. If such case occurs, the cavity is subdivided and the equivalent thermal conductivities are calculated for each of the newly created domains, see figure 1c).

Finally, the boundary conditions are assigned. All the surfaces on the left hand side are considered as exposed to external conditions, while the ones on the right hand side are assigned with internal boundaries. Reduced heat transfer coefficient is assigned to sloped surfaces, as described in the standard. Bottom part of the frame is recognized as junction between the frame and the wall and is therefore set as an adiabatic boundary condition. Similarly, the top part is identified as the glazing and is also set to adiabatic.

Once the geometry and boundary conditions are created, they are used as an input for the finite element solver, which simulates the heat transfer in the frame. Integral of the heat flux over the inside of the frame is used to calculate the $U_f$ value.

The main reason for designing the tool in such a way was to make it possible to generate and evaluate a large number of frame geometries in a relatively short time. In contrast to traditional programs, where each design needs to be drawn separately, here it can be represented by a set of numbers. An array of parameters describing various frames can be inputted in the program and simulated automatically, allowing the user to evaluate hundreds of various designs.

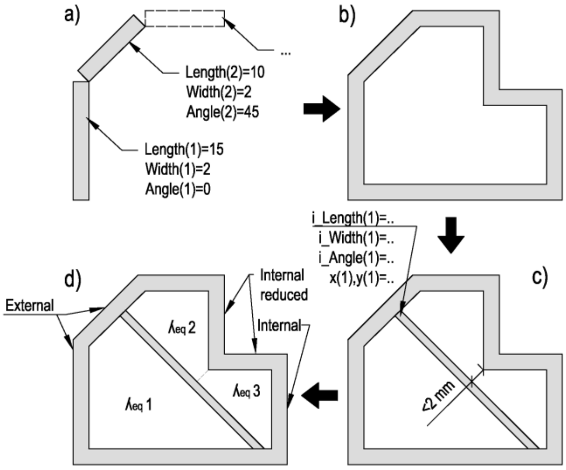



*Figure 1: The process of designing a frame in the design tool.*

**Validation of the design tool**

To ensure that the design tool produces accurate results, a validation process was conducted. The standard suggests executing this process by comparing the two-dimensional thermal conductance and thermal transmittance of a frame with values calculated for exemplary frames given in the standard. Differences of $L^{2D}$ not higher than ±3% should ensure a good accuracy. Two frame geometries were compared. It was found that the deviation in $L^{2D}$ was not higher than 2.8% and the difference in $U_f$ did not exceed 1.4%.

Small discrepancies could be explained by different rounding of decimal places when calculating the thermal conductivity of the cavities and differences in the simulation procedure of the programs (such as different mesh element size, etc.).

**Calculations and optimization criteria**

Several factors are calculated in order to evaluate the performance of the frame. Below a brief explanation of them and success criteria of the optimization process are presented.

**U value of the frame ($U_f$)**

This parameter is calculated according to methodology described in ISO 10077-2: simulations are conducted in the absence of glazing, which is substituted by an insulating panel. Thus, the effect of glazing and spacer on the $U_f$ value is removed.

**U value of the entire window ($U_w$)**

$U_w$ includes heat transfer through the window frame, heat transfer through the glazing and additional linear heat loss caused by assembly of frame and glass:

$$U_w = ( U_g \cdot A_g + U_f \cdot A_f + \psi \cdot l_\psi ) / ( A_g + A_f ) \qquad (1)$$

In this study, $U_w$ is calculated for a standard window size of 1.23 x 1.48 m. Fictional triple glazing with $U_g$ = 0.7 W/m$^2$/K and g = 0.5 was chosen. A spacer with “warm edge” technology is used, giving a ψ value of 0.04 W/m/K.

**Net Energy Gain Factor (E)**

This factor evaluates the energy performance of the entire window during a standard heating season. It is described as the solar heat gains subtracted from the transmission heat losses. If the E factor has a positive value, it indicates that the window is contributing to the heating of the building. It is described by the formula below (Nielsen et al., 2001):

$$E = g_w \cdot I - U_w \cdot D \qquad (2)$$

I and D are coefficients for heat gain and heat loss respectively. They are dependent on the location and for Denmark they have been calculated to be equal to I=196.4 kWh/m$^2$ and D=90.36 K kh (Nielsen et al., 2001). The $g_w$ is the solar heat transfer coefficient multiplied by the fraction of glazing in the entire window. The solar heat gain through the window frame was neglected in this study.

The E factor provides a simplified, but fairly accurate approximation of the energy saving potential of a window in heating dominated buildings. Previous studies show that the energy savings found using the E factor are comparable to the savings found with a detailed, dynamic simulation program (Nielsen et al., 2001).

**Area of the cross-section of the frame (A)**

This factor is used as an indicator of the cost of the frame, which is mainly related to the volume of the structural material used. Area of the cross section of the walls of each frame is calculated.

**Design criteria**

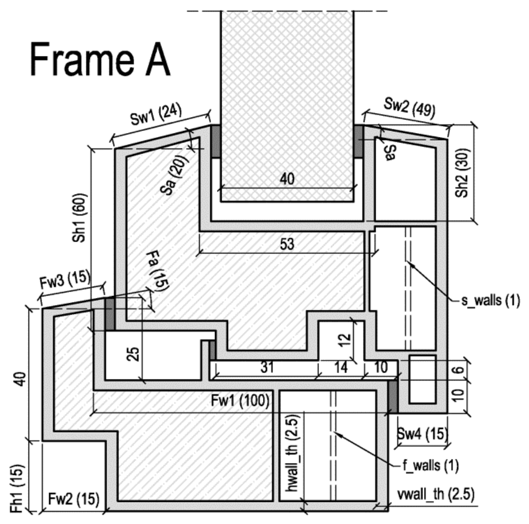
The maximum $U_f$ value is usually not described in the building codes, but a suggested $U_w$ value is given instead. For example, the Danish building regulations require the windows to have $U_w$ < 1.4 W/m$^2$/K (Danish Building Code, 2010). More strict PassivHaus standards suggest using windows with $U_w$ not higher than 0.8 W/m$^2$/K (www.passiv.de). To comply with these requirements it was decided to use maximum $U_f$ value of 0.8 W/m$^2$/K as design criteria.

The current regulations for new windows in Denmark require that the E factor is higher than -33 kWh/m$^2$/year (Danish Building Regulations, 2010). It is expected that this criteria will change to -17 kWh/m$^2$/year in 2015. To be on the safe side, window frames that result in energy gain higher than -10 kWh/m$^2$/year will be designed in this study.

**Window frames**

Figure 2 presents three frames investigated in this study. All frames are the inward-opening casement type. The geometries are inspired by existing PVC frames with PUR insulation and steel reinforcements that comply with PassivHaus requirements. In this study PVC is replaced by Fiberglass Reinforced Plastic (FRP), a material that gained a lot of attention in recent years in the window frames market, due to its fine thermal and mechanical properties (Appelfeld et al., 2010). Since the mechanical properties of FRP are superior compared to PVC, it was decided to remove the steel reinforcement. The window frame is composed of two parts: the lower, fixed part that will be further referred to as the frame and the upper openable part called the sash. An air gap is present between the two parts.

Frame models presented in this study are a simplification of real geometries. In reality, the window frame is more complex and has to include several functionalities, such as water drainage, places for hinges and fixing the frame to the wall, etc. The simple geometry used in the design tool is used as a way to identify the key parameters connected to the thermal performance of the window frame and ease the optimization process. The results obtained here should not be used as the actual performance of a frame, but rather as an approximation.



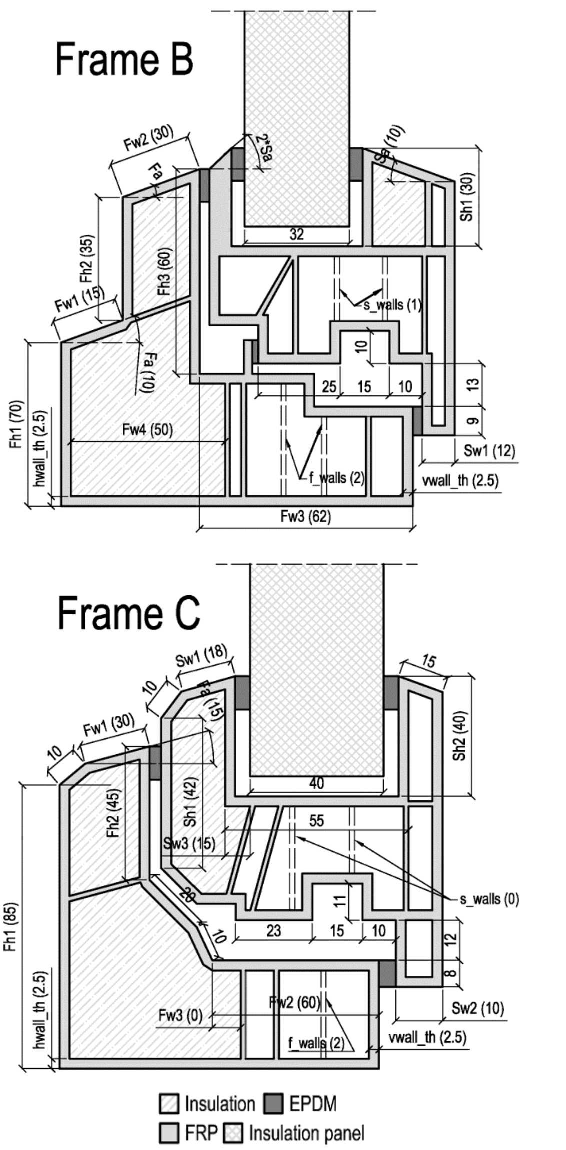



*Figure 2: Parametric frames A-C. The dimensions that are parametric are described as symbols (e.g. Fh1, Fw2). The numbers in brackets are the values of these parameters for optimized frames (see the chapter Results and discussion)*

**Sensitivity analysis**

A model of a window frame can be described by a large number of parameters, such as dimensions (width, height, thickness of the walls, etc.) and the material properties (thermal conductivity). To identify the most important factors, a sensitivity analysis is conducted. A one-at-a-time Morris method is used for this purpose (Morris, 2001).

Figure 2 presents the frames under investigation and the parameters that are considered in this study. A more detailed description of each parameter and their distribution can be found in table 3. Most of the parameters describe the dimensions of the frame, such as width and height of its particular parts and angle of sloped walls. Thickness of the walls is also investigated, with a distinction between horizontal and vertical walls. Another important parameter is the thermal conductivity of the constituent materials. Each of the frames has some amount of insulation material inside. Its thermal conductivity is varied between 0.03 and 0.05 W/m/K, which could represent, for example, polyurethane foam with various densities. In this study, FRP is used as material for the frame walls. Its thermal conductivity is dependent on several factors, such as the glass content and type of resin. In this analysis it is varied between 0.3 and 0.4 W/m/K. An additional parameter is the amount of vertical walls placed in the hollow cavities, which can lead to reduction of convective and radiative heat loss.

SimLab software (Giglioli et al., 2000) is used to generate the samples distribution, which are used as input for the design tool. Frame geometry is built in the tool based on each set of inputs and its thermal transmittance and E factor are calculated. These values are then returned back to SimLab, which provides the sensitivity analysis.

**Optimization scheme**

The optimization process of the frame geometry is determined by the number of objectives considered. If the only objective is to minimize the $U_f$ value, the solution will be to create a large frame with cavities filled with insulation. On the contrary, if the goal is to maximize the E factor, the resulting frame will have a small size, with little regard to the $U_f$ value. When considering both of these objectives at the same time, the task becomes more complicated.

The optimization problem stated in this study can be described as a three objective optimization process. The three objectives are to minimize the $U_f$ value and maximize the E factor, while minimizing the cross-section area of the frame.

Various methods exist to address multi objective optimization problems such as this one. One of the most simple and common approaches is the weighted sum method, where all of the objectives are combined into a single function by summing up the objective functions multiplied by individual weight factors (Marler et al., 2004).

$$V = \Sigma\, w_i \cdot F_i\,(x) \tag{3}$$

Where V is the utility function, $w_i$ is the weight of each objective function and $F_i$ (x) are the respective objective functions, which in the present study are: the $U_f$ value, the E factor and the area of the frame cross section. Therefore in the present study:

$$V = w_1 \cdot U_f + w_2 \cdot E + w_i \cdot A \tag{4}$$

The weights are assigned by the decision maker before the optimization process is started and represent the relative importance of the corresponding objectives. This method is simple in use, but many studies report difficulties with correct determination of the weights. The first choice might not result in a satisfactory solution and the problem would need to be solved again with new selection of weights. In the present study the weights will be modified throughout the process so that the solution will converge into the criteria stated before.

The optimization of the utility function is a multivariable optimization problem, the variables being the parameters describing the window frame. Such problem can be solved by use of the search methods (Stoecker, 1989). In this study, the univariate search is used, where the function is optimized with respect to one variable at a time, while others are substituted by trial values. When optimal state of the investigated parameter is found, it is substituted into the function and the optimization of succeeding variable continues until the optimal solution is found. Individual parameters are optimized by use of the exhaustive search method, where the parameter is spaced uniformly through the interval of interest and the objective function is calculated at each of these values to find the optimum.

Another optimization scheme that would be applicable for this study could be a genetic algorithm (Kalyanmoy, 2001). It is a global optimization technique, which means that it can identify a set of semi optimal solutions, from which the designer can choose afterwards. Although it has many advantages, the genetic algorithm is also much more demanding regarding the computational time, therefore it was discarded at this point. It will be however, a part of the future studies on this topic.

## RESULTS AND DISCUSSION

### Results of the sensitivity analysis

Figures 3 to 5 present the results for sensitivity analysis of all the frames, for both the $U_f$ value and the E factor. Each parameter is described by two values: the mean value, $\mu$, which describes how large is the influence of the parameter on the output and the standard deviation, $\sigma$, which indicates how correlated the factor is to the other parameters or if its effect is non-linear.

Analysis of the $U_f$ value shows that the frame width (Fw1) is by far the most crucial parameter for frame A. It influences the overall size of the frame and the sash and, indirectly, the amount of insulation material inside the cavities. This parameter also has the highest standard deviation. Second most important factor is the height of the sash, followed by thermal conductivity of the insulation and the walls, as well as thickness of horizontal walls. Thickness of vertical walls proves to be less significant. Vertical subdivisions in the frame cavity can also have a major impact on the outcome, but are highly correlated to other factors, most probably the size of the cavity.

In the analysis of E factor, parameters which affect the height of the frame gain larger significance. This can be explained by the fact that the E factor is largely influenced by the size of the frame. The larger it is the smaller fraction of the window is covered by glazing, what leads to lower amount of solar heat gain received through the window.

Similar trends can be observed in the results for frame B. Parameters that regulate the size of the frame and the sash and have an impact on the size of cavities filled with insulation rank high in the importance (Fh1, Sh1, Fh2, Fw2). Thermal conductivity of the walls and insulation material still hold a large significance. Thickness of horizontal walls has a larger influence on the result compared to the vertical walls. In the analysis of the E factor, the shift of parameters connected to the height of the frame is even clearer than in the previous case.

Similar conclusions can be drawn from the analysis of frame C. The frame height, Fh1, has a major impact on the size of the frame and the amount of insulation; therefore it influences the $U_f$ value the most. The Sw3 factor, which is responsible for additional insulation in the sash ranks in the middle in terms of importance, but has a very high standard deviation. This could be explained by correlation of this factor to thermal conductivity of the insulation, as well as the size of the sash. The angle of sloped outside walls seems fairly insignificant, what is in agreement with results for the previous frames. The sensitivity analysis of E factor is again dominated by factors related to the height.

The purpose of conducting the sensitivity analysis was to highlight the most important parameters, but also to limit the amount of factors to be used in the optimization process and, consequently, reduce the computational time needed to optimize the designs. The parameters chosen for the next step are marked in grey on figures 3-5. Parameters like the thickness of the walls or thermal conductivity of the materials have high importance but are not considered for optimization, because their impact on the thermal properties of the frame is rather obvious. Minimum wall thickness was chosen from the considered range. The thermal conductivity of insulation material was set to minimum value and for the FRP a value of 0.35 W/m/K was chosen.

### Optimization of the geometry

The optimization was conducted with the use of weighted sum method. It was found that the frames can be optimized and fulfill the design criteria, however the final result is highly dependent on the ratio between the chosen weights of each objective. If the weight put on the $U_f$ value is too high, the final frame will have very large dimensions and achieve low thermal transmittance with no regard to the E factor. On the other hand, small, but poorly insulated frames will be produced when the weight assigned to the E factor is too large. Between these two situations, there are a number of weights that will result in a balance between the two factors. Figure 6 shows the change of variable Fh1 in frame C and corresponding values of the utility function for

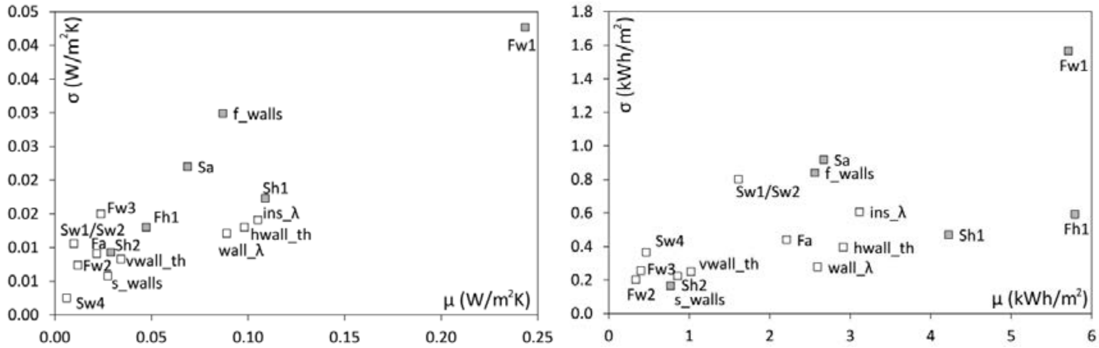



*Figure 3 Sensitivity analysis for $U_f$ value (left) and E factor (right) for frame A*

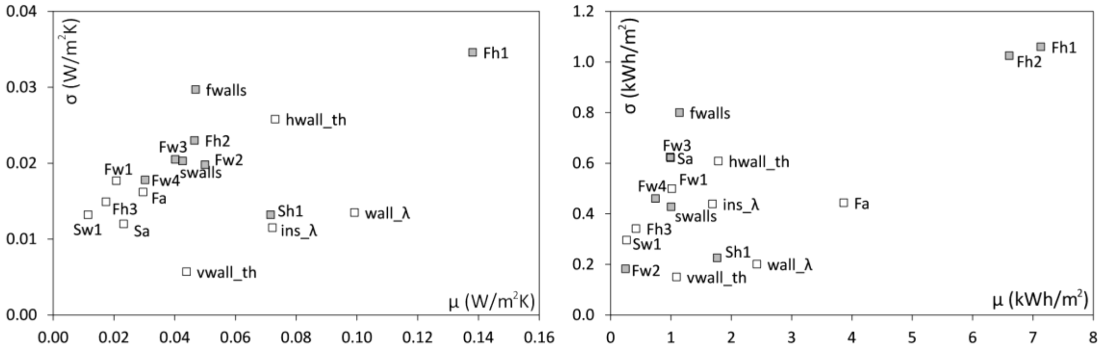



*Figure 4 Sensitivity analysis for $U_f$ value (left) and E factor (right) for frame B*

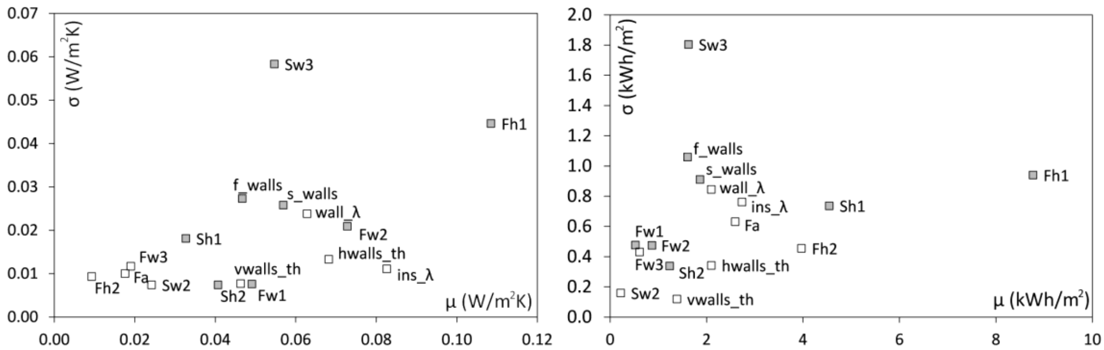



*Figure 5 Sensitivity analysis for $U_f$ value (left) and E factor (right) for frame C*

various weights assigned to the E factor, without changing the other two weights. A factor of 0.012 would lead to smaller frames, while weight of 0.08 promotes the largest possible frames. For the remaining factors, an optimum value is found somewhere in-between and it is suggested that the final factor should be chosen from this spectrum. It was also found that the factors need to be reconsidered for each individual frame design. The same factors that led to optimization dominated by $U_f$ value in frame A, might have a different effect in frame B or C.

No clear goal was selected in this study for the area of the frame, therefore the smallest importance was chosen for this objective. It was found however, that in most cases the improvement of this objective goes together with the improvement of E factor.

Table 2 presents the weighting factors and results of the optimization process. At first the factors $w_2$ and $w_3$ might seem irrelevant in comparison to factor $w_1$, but it has to be taken into account that E factor and the area are orders of magnitude higher than the values of $U_f$.

It was possible to fulfill the optimization criteria for all three frames. The best results are achieved for frame A. Very low $U_f$ value and the smallest area of the cross-section were obtained. Optimization for frames B and C was firstly conducted with the same weighting factors as for frame A. It was found that with these inputs, the objectives would converge to $U_f$ values exceeding the design criteria. The E factors on the other hand were very satisfactory. To optimize the $U_f$ value further, $w_2$ was then gradually decreased, until $U_f$ value lower than 0.8 was achieved. The E factor became worse, but still fulfilling the design criteria.

Dimensions of the optimized frames are shown in brackets on the figure 2. Frame A has the advantage of having the largest amount of insulation, hence the lowest $U_f$ value. This frame is also the largest, yet the area of FRP is smaller than for two other designs, where the thermal transmittance is decreased partly by placing walls to create smaller subdivided cavities.

*Table 2*
*Weighting factors and results of the optimization of the frames.*

| Frame | A | B | B | C | C |
|---|---|---|---|---|---|
| $w_1$ | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 |
| $w_2$ | 0.02 | 0.02 | 0.004 | 0.02 | 0.01 |
| $w_3$ | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| $U_f$ ($W/m^2/K$) | 0.71 | 0.89 | 0.8 | 0.86 | 0.79 |
| E ($kWh/m^2$) | -6.8 | -3.1 | -7.5 | -2.4 | -6.1 |
| A ($mm^2$) | 2319 | 2224 | 2512 | 2175 | 2395 |

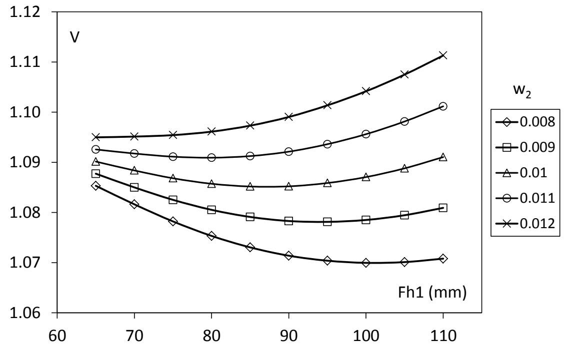



*Figure 6 Optimization of parameter Fh1, based on various weighting factors*

## CONCLUSIONS

A parametric design tool was successfully developed in this study. The largest advantage of the tool compared to other currently available programs is the possibility to test a very large amount of frame designs in a relatively short time what eases the optimization process. On the other hand, the parametric model puts a limitation on the design possibilities. The tool shows reasonable accuracy, but it is suggested that it is not used as a final calculation method.

Sensitivity analysis conducted in the program helped to distinguish the parameters that have the highest importance for the $U_f$ value and E factor of the frame and the parameters that are the most sensitive. Even though the frames have different designs, similar trends can be observed for all of them. In most cases height of the frame and sash, thermal conductivity of the materials, amount of insulation and thickness of horizontal walls proved to influence the $U_f$ value the most. E factor is mostly dependent on the parameters connected to the height of the frame.

Optimization of the window frame is a complex multi objective process and cannot be concluded by finding one solution that would optimize all of the objectives. In the present study, the process was simplified to a single objective optimization, where the three objectives were substituted by a single utility function. In this case a decision needs to be taken regarding the relative importance of each goal and the highest focus was put on the $U_f$ value of the frame. Design criteria were formulated previously and it was possible to fulfill them for all three frames. The best frame achieved a $U_f$ value of 0.71 $W/m^2/K$ and E factor of -6.8 $kWh/m^2$.

Both the design tool and the optimization scheme presented in this study are far from ideal. Future studies will include using other optimization methods such as the genetic algorithm and analysis of new frame designs.

*Table 3*
*Parameters describing the frames. All the parameters concerning distance are in (mm), angles in (°), thermal conductivity in (W/m/K).*

| Param eters | Lower bound | Upper bound | Description |
|---|---|---|---|
| Frame A | | | |
| **Fw1** | 70 | 100 | Width of the frame |
| **Fw2** | 15 | 25 | Frame extension width 1 |
| **Fw3** | 15 | 25 | Frame extension width 2 |
| **Fh1** | 15 | 40 | Height of the frame |
| **Fa** | 0 | 30 | Frame outside walls angle |
| **Sh1** | 35 | 60 | Height of the sash |
| **Sh2** | 20 | 30 | Depth of the glazing |
| **Sw1 / Sw2** | 0.5 | 2 | Ratio of the width Sw1 to Sw2 |
| **Sw4** | 15 | 25 | Sash extension width |
| **Sa** | 0 | 30 | Sash outside walls angle |
| Frame B | | | |
| **Fh1** | 30 | 70 | Height of the frame |
| **Fh2** | 20 | 45 | Height of the frame 2 |
| **Fh3** | 50 | 65 | Depth of the sash |
| **Fw1** | 15 | 25 | Frame extension width 1 |
| **Fw2** | 20 | 30 | Frame extension width 2 |
| **Fw3** | 55 | 75 | Width of the frame |
| **Fw4** | 40 | 50 | Extra insulation in the frame |
| **Fa** | 10 | 30 | Frame outside walls angle |
| **Sa** | 10 | 30 | Sash outside walls angle |
| **Sw1** | 10 | 15 | Sash extension width |
| **Sh1** | 20 | 30 | Depth of the glazing |

| Frame C | | | |
|---|---|---|---|
| **Fh1** | 65 | 110 | Height of the frame |
| **Fw1** | 15 | 30 | Frame eextension width |
| **Fh2** | 30 | 45 | Depth of the sash |
| **Fw2** | 45 | 70 | Width of the frame |
| **Fa** | 0 | 30 | Frame outside walls angle |
| **Fw3** | 0 | 15 | Extra insulation in the frame |
| **Sh1** | 40 | 60 | Height of the sash |
| **Sh2** | 30 | 40 | Depth of the glazing |
| **Sw2** | 10 | 20 | Sash extension width |
| **Sw3** | 0 | 15 | Extra insulation in the sash |
| Common parameters for all frames | | | |
| **ins_λ** | 0.03 | 0.05 | Conductivity of insulation |
| **wall_λ** | 0.3 | 0.4 | Conductivity of the walls |
| **f_walls** | 0 | 2 | Frame cavity subdivision |
| **s_walls** | 0 | 2 | Sash cavity subdivision |
| **hwalls_th** | 2.5 | 4 | Horizontal wall thickness |
| **vwalls_th** | 2.5 | 4 | Vertical walls thickness |

## NOMENCLATURE

U – thermal transmittance (W/m$^2$K)

Ψ - linear thermal transmittance (W/mK)

$l_\Psi$ - perimeter of the glazing (m)

λ – thermal conductivity (W/mK)

g – solar heat transfer coefficient (-)

E – net energy gain factor (kWh/m$^2$/year)

I - coefficient for heat gain (kWh/m$^2$)

D - coefficient for heat loss (kKh)

$L^{2D}$ – 2D thermal conductance (W/m/K)

A – cross section area (mm$^2$)

V – utility function

$w_i$ – weighting factors

$F_i$ (x) – objective functions

Subscripts:

f – frame

g – glazing

w – window

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