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"ANALYSIS OF THERMAL BRIDGES"

MASTER THESIS

Master thesis submitted to the achievement of Master's degree in Building Constructions. Speciality in Technology.

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ABSTRACT

The European Union has committed itself to increase energy efficiency with 20% up to the year 2020. A main instrument for reaching this target in the residential sector is the Energy Performance of Buildings Directive (EPBD) as nearly 40% of final energy consumption is in buildings. This European directive proposes, among others, the introduction of energy performance labels for dwellings in all European Member States.

However, even in cases where impressive measures can be implemented in the densely built urban environment, the less glamorous measure of building's envelope thermal insulation remains a prerequisite towards the improvement of the building's energy efficiency. Despite the insulation requirements specified by national regulations, thermal bridges in the building's envelope remain a weak spot in the constructions. Moreover, in many countries construction practices tend to implement only partially the insulation measures foreseen by regulations. As a result, thermal losses are in practice greater than those predicted.

This research presents a study where the thermal bridges situated on the building envelope are analyzed in order to optimize the energy losses through the thermal bridges with respect both to its economic feasibility and to its environmental impact.

For the analysis is used the flixo program, that facilitates assess and improve thermal bridges and it also calculates frame U-values, P_{si}-values, Ψ-values, etc.

The calculations are based on EN ISO 10211, EN ISO 6946, EN ISO 10077, EN ISO 10456 and Flemish EPB-regulations.

Also the Passive House standards are used to compare and discuss the obtained results.

Moreover, the analysis of the thermal bridges' impact will in that sense also highlight the potential for energy renovation measures in older buildings.

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

1. INTRODUCTION

The European Directive 2002/91/EC on the Energy Performance of Buildings (EPBD) is the main EU policy instrument to improve the energy performance of buildings since the 1970s when, in the aftermath of the energy crisis, most national buildings regulations introduces mandatory thermal insulation requirements in the attempt to meet the kyoto commitment due to the building sector is responsible for nearly 38% of EU final energy consumption.

This gradually leads to the need to adopt advanced standards, technique and technologies while designing and constructing new buildings, but also in applying energy renovation measures in existing ones, in order to comply with the updated energy efficiency requirements. As a result, since its implementation the number of very low energy buildings and passive non-residential buildings has increases significantly.

In this way, in Belgium there are three regions so there are three regulations. In this master thesis the one used is the Flemish region EPB-regulation.

An important feature of the Flemish approach is the strict control scheme, where noncompliance may result in fines. In order to implement such an approach, a declaration (the so-called "EPB declaration") of the executed works has to be made after the finalization of the building. But the most important point is the performance of the details. With 3 basic rules, easy to apply, the detail can be performed in a high percentage.

In view of thermal losses are in practice greater than those predicted during the design stage and the importance of the effect of thermal bridges in the energy efficiency, the present research focuses in the analysis of them.

To reach this, a building has been studied. It is situated in Ledegem (West-Flanders) and it is a renovation to passive house by studying the thermal bridges and using renewable materials.

Thereby, the main aims of the present master thesis are:

- Analyze thermal bridges in the house studied.
- Compare results with Flemish EPB-regulation and Passive House standards.
- Optimize the construction details to decrease the thermal losses.

To reach them the methodology to use involves the analysis of each thermal bridge with flixo program. The calculations are done according EN ISO 10211, EN ISO

6946, EN ISO 10077, EN ISO 10456 and Flemish EPB-regulations. The next step is to compare the results with Flemish EPB-regulation and Passive House standards and discuss the results to optimize them with respect both to its economic feasibility and to its environmental impact.

In this way, the structure followed by the present research is:

- Methodology, where are described the standards used and its application.
- Case study, where the building studied is described as well as the construction details that are going to be analyzed.
- Results & discussions, where the analysis obtained results are shown and compared with Ψ-limits or other details such as Passive House details.
- Final conclusions about the analysis of thermal bridges performed.

2. METHODOLOGY

A thermal bridge usually gives rise to three-dimensional or two-dimensional heat flows, which can be determined precisely using detailed numerical calculation methods as describe in ISO 10211 standard.

Thereby, the software used for this research is Flixo. It produces thermal-hygro analysis of the component and façade cross sections, and it also calculates frame U-values, λ-values, etc. Flixo program analyzes two-dimensional component nodes based with boundary conditions using the finite element method. The calculation is made according some of the following standards, each of them explained below:

- EN ISO 10211:2007 to simplify in general [5].
- EN ISO 6946:2007 to simplify the sloping roof [3].
- EN ISO 10077-1 to simplify windows frame [6].
- EN ISO 10077-2 to simplify windows frame [7].
- EN ISO 10456 to design λ-values [8].
- Flemish region EPB-regulation [1].
- Passive House standard [16].

2.1. EN ISO 10211:2007 to simplify in general.

This standard sets out the specifications for a three-dimensional and a two-dimensional geometrical model of a thermal bridge for the numerical calculation of heat flows and minimum surface temperatures.

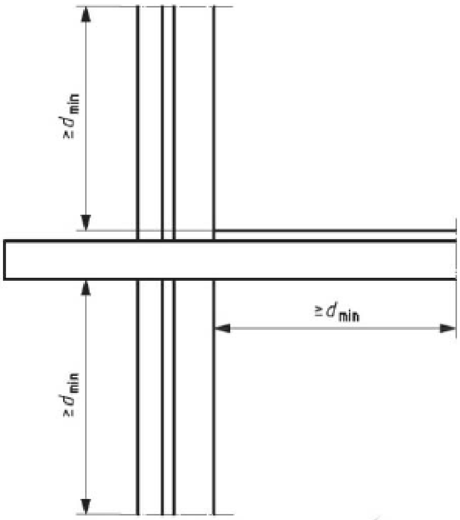
These specifications include the geometrical boundaries and subdivisions of the model, the thermal boundary conditions, and the thermal values and relationships to be used.

This standard has been applied in the follow steps:

- To simplifying the building in general, according point 5.3.2 *Conditions for adjusting dimensions to simplify the geometrical model*. This point allows deleting thin membranes which resist the passage of moisture, water vapor or wind-driven air and metallic layers that have a negligible effect on the heat transfer like metal flashing. The main condition is that just can be modified materials with thermal conductivity less than 3 W/(m·K).

- To determine the detail length of walls and slabs, according point 5.2 Rules for modeling, specifically in point 5.2.2 *Cut-off planes for 3-D geometrical model* and point 5.2.3 *Cut-off planes for 2-D geometrical model* is written that cut-off planes shall be positioned as follows:

Figure 1. Location of cut-off planes at least d_{min} from the central element.

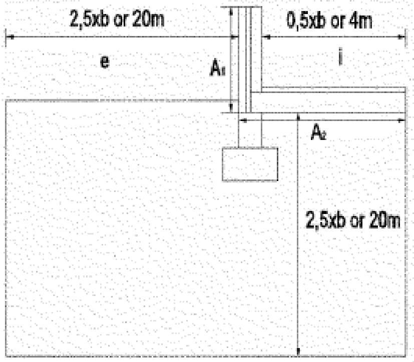


The distance of d_{min} ≥ minimum thickness, at least 1 m far from the thermal bridge.

- To determine the detail length of foundations and ground floors. Where the calculation involves heat transfer via the ground, the cut-off planes in the ground shall be positioned as indicated in point 5.2.4 *Cut-off planes in the ground. Table 1.*

  Say that in the study case has been considered the minimum length (4m to interior and 20 m to exterior and to ground in vertical position) to cut off planes in the ground as shows below:

Figure 2. Cutting edges of a geometric model in which the soil mass involved.



- To assign the materials with the corresponding λ-value according point 6.2 *Thermal conductivities of material* (λ-value of soil is 2,0 W/(m·k))
- To calculate the lineal thermal transmittance according point 10.3 *Determination of the linear thermal transmittance* amply explained on Flemish region EPB-regulations.

2.2. ISO 6946:2007 to simplify the sloping roof.

This standard provides the method of calculation of the thermal resistance and thermal transmittance of building components and building elements, excluding doors, windows and other glazed units, curtain walling, components which involve heat transfer to the ground, and components through which air is designed to permeate.

It has been applied to following steps:

- To simplifying the sloping roof. It will be considered like well-ventilated air layer according to this ISO 6946 point 5.3.4 *Well-ventilated air layer*. The total thermal resistance of the sloping roof shall be obtained by disregarding the thermal resistance of the air layer and all other layers between the air layer and external environment, and including an external surface resistance corresponding to still air (Annex A ISO 6946). Alternatively, the corresponding value of R_{si} from Table 1 (0,13 m^2·k/W) may be used and the software used in this master thesis, Flixo, uses it. Therefore tiles of the sloping roof will be deleted for the calculations and R= 0,13 m^2·k/W will be taken in its place.
- To give the Boundary conditions. Table 1 shows the boundary conditions adopted to calculate the thermal bridges in Flixo software.

Table 1. Boundary condition.

Type	Temperature ºC	Rsi, Rse m^2·K/W	Standard
Exterior, normal	0	0,04	ISO 6947
Exterior, ventilated	0	0,13	ISO 6946
Interior, normal, horizontal	20	0,13	ISO 6947
Interior, heat flux, upwards	20	0,10	ISO 6946
Interior, heat flux, downwards	20	0,17	ISO 6946
AOR, unheated room	0	0,13	Flemish EPB
Adiabatic	-	-	-

According to this ISO 6946 point 5.3.4 *Well-ventilated air layers*, the option exterior ventilated boundary replaces the tiles of the sloping roof and it is not allowed to calculate windows.

The exterior, normal boundary is used where there is no ventilated façade.

The interior, normal, horizontal is used when the heat flux is horizontal.

The interior, heat flux, upwards is used in the roof details.

The interior, heat flux, downwards is used in the first floor slab that separates interior of AOR.

The AOR boundary is used in the technical room because it is not heated and in the ground floor too.

The adiabatic boundary is used for all cut-off planes.

2.3. EN ISO 10077-1 to simplify windows frame

This standard is the first part of EN ISO 10077 "*Thermal performance of windows, doors and shutters-Calculation of thermal transmittance*". This Part 1: "*General method*" specifies methods for the calculation of the thermal transmittance of windows and pedestrian doors consisting of glazed and/or opaque panels fitted in a frame, with and without shutters.

The thermal transmittance of roof windows and other projecting windows can be calculated, provided that the thermal transmittance of their frame sections is determined by measurement or by numerical calculation.

Default values for glazing, frames and shutters are given.

Thermal bridges effects at the rebate or joint between the window or door frame and the rest of the building envelope are excluded from the calculation. The calculation also does not include effects of solar radiation, heat transfer caused by air leakage, calculation of condensation, ventilation of air spaces in double and couple windows and surrounding parts of an oriel window.

This ISO does not apply to curtain walls and other structural glazing and industrial, commercial and garage doors.

It has been used basically to simplifying windows frame according ISO 10077-1 point 4. *Geometrical characteristics*.

Should be considered that the aluminum is the only material used with more than 3 W/(m·k), used in a few pieces in the frame windows and in the shutters.

Thereby, the windows frame has been simplified in a new geometry with a new material that combines aluminum, still air and timber with a thermal conductivity provided by the trademark.

2.4. ISO 10077-2 to simplify windows frame

This standard is the second part of EN ISO 10077 "*Thermal performance of windows, doors and shutters-Calculation of thermal transmittance*". The method in this Part 2: "*Numerical method for frames*" is intended to provide calculated values of the thermal characteristics of frame profiles, suitable to be used as input data in the simplified calculation method of thermal transmittance of windows, doors and shutters given in Part 1: "*Simplified method*".

This standard has been applied as following:

- For calculating windows frame according ISO 10077-2 Annex C (also in Flixo tutorial adapting the construction).
- In shutters has been used the tool air cavity EN ISO 10077-2 to assign materials unventilated air cavity or slightly ventilated air cavity.
- To simplify windows frame according Annex D. There are several examples of simplified frame.

2.5. EN ISO 10456 to design λ-values

This standard has been used to assign materials with corresponding λ-value. Flixo database has tabulated values of thermal conductivities of building materials and products according this standard. Also it is possible create a new material with λ-value provided by trademarks. As it is mentioned before, in the present research majority has been calculated with the trademark data and just use Flixo database when it will be not possible.

2.6. Flemish region EPB–Regulation.

This regulation has been used to validate numerical calculations of thermal bridges. It has been applied as following:

- To calculate the lineal thermal transmittance.

  According point 7.2 *Meer dan 2 grenstemperaturen*, the Ψ-value is defined as below:

$$\Psi_e = \frac{\Phi_{2D}}{L \cdot (\theta_i - \theta_e)} - \frac{A_1 U_1}{L} - \frac{A_2 U_2}{L} \quad \left[\frac{W}{m \cdot K}\right] \qquad \textbf{(1)}$$

where:

Φ_{2D} (W): heat flux rate

L (m): length over which the linear construction node is modeled.

$\theta_i - \theta_e$ (K): if there are more than 2 boundary conditions temperatures.

U_1 (W/m²·K): U-value for the whole construction part 1

U_2 (W/m²·K): U-value for the whole construction part 2

A_1 (m): length of the projection of the line segment 1 *

A_2 (m): length of the projection of the line segment 2 *

* The most external dimension has been used for determining it, according point 7. *Berekening van U- en X-waarden*.

When it is including the subsoil, it is calculated as the total heat flow leaving the indoor environment according point 7.3 *funderingsaanzet van vloer op volle grond*, as it's follows:

$$\Psi_e = \frac{\Phi_{2D}}{L \cdot (\theta_i - \theta_e)} - \frac{A_1 U_1}{L} - \frac{\Phi_{2D,a}}{L \cdot (\theta_i - \theta_e)} \quad \left[\frac{W}{m \cdot K}\right] \qquad \textbf{(2)}$$

Where:

$\Phi_{2D,a}$ (W) = the total two-dimensional stationary heat flow leaving the indoor environment, calculated with validated numerical software, based on the model to be adapted as follows:

- neglect of all foundation massifs and/or edge insulation by replacing it by land with a thermal conductivity of 2 W/(m·K).
- impose adiabatic conditions where the wall is in contact with the floor or ground.

- To calculate the thermal conductivity of the window frame according point 7.4 *venster en deuraansluitingen*, as it shows below:

$$\lambda'_f = \frac{a}{\frac{1}{U_f} - R_{si} - R_{se}} \left[\frac{\mathrm{W}}{\mathrm{m.K}}\right] \quad \textbf{(3)}$$

Where:

a (m) = thickness of the frame (a_{door}=0,055 m; a_{window}=0,085 m)

U_f (W/(m²·K)) = Thermal transmittance of the frame (providing by trademark; U_{door} =0,88 W/(m²·K); U_{window} = 0,076 W/(m²·K))

R_{si} (m²·K/W) = internal surface resistance (0,13 m²·K/W has been used)

R_{se} (m²·K/W) = external surface resistance (0,04 m²·K/W has been used)

- To calculate frame windows according point 7.4 *venster en deuraansluitingen*. This method neglects the glass panel.

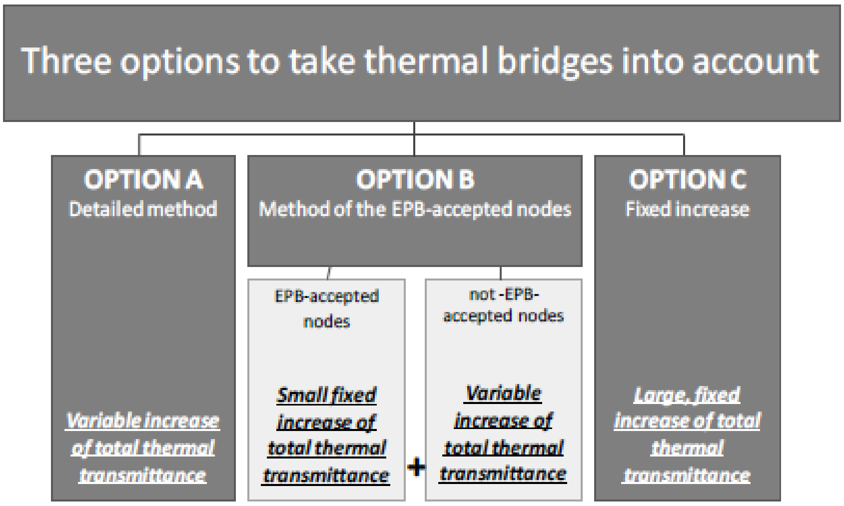
  This option is more interesting than one given on ISO 10077-2 Annex C because the most important in the detail is the joint between wall and window. The joint between glass and frame is resolved and tested by the trademark that sells the windows.

- To simplified calculation of connection window frame – wall explained in point 6.1.2 *Toegestane vereenvoudiginge aan het geometrische model.* Taking into account that these simplifications just are permissible if they meet the conditions of ISO 10211 standard.

- To determinate boundary conditions. According point 7.2 *Meer dan 2 grenstemperaturen (AOR, onverwarmde kelder of kruipruimte)* indicates that the temperature we must use to calculate in a non-heated room is the same than the external one as well as it indicates in which point the lineal thermal transmittance must be calculated.

- To interpret and compare the results. The three options to take the thermal bridges into account are illustrated in figure 3. The calculation is according to ISO 10211.

Figure 3. Overview of the three options to take thermal bridges into account.

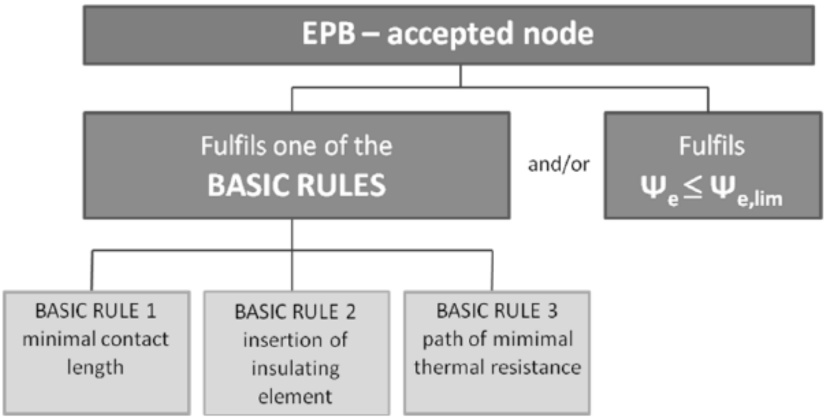


Each of which is explained below:

- Option A: Detailed method. It takes account all extra losses by multiplying for each thermal bridge the length/number with the linear/point thermal transmittance. Despite it is the most precise method, the time used to calculate is an important disadvantage.
- Option B: Method of the EPB-accepted nodes. All the thermal bridges are classified into two categories: EPB-accepted nodes and other thermal bridges. The EPB-accepted nodes, has a small fixed increase of total thermal transmittance (3 W/K) and requires three basic rules. The other bridges have a variable increase.
- Option C: No paying attention to thermal bridges and applying a large fixed penalty (10 W/K) on the overall thermal transmittance increasing strongly in insulation in the different building envelope.

The option of the EPB-accepted nodes is a pragmatic approach to increase the awareness of good thermal detailing as it shows below:

Figure 4. Options for recognition of a thermal bridge.

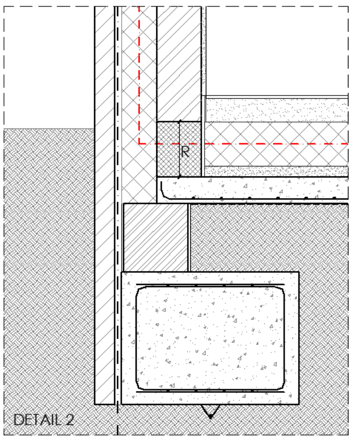


Essentially, the basic rules guarantee a continuous insulation layer within the building envelope getting better results with the basic rule 1 than with the basic rule 3.

The basic rule 2 has been applied in detail 2 and it consists in the insertion of insulating elements. This intermediate insulating element has to be foreseen than fulfils certain requirements:

- The thermal conductivity λ of it has to be less than 0,2 W/(m·k).
- The thermal resistance R of it has to be at least half the smallest thermal resistance of the adjacent insulation layers or 2 m²K/W.
- The contact length between insulating element and adjacent layers has to fulfill basic rule 1.

Figure 5. Basic rule 2 on Detail 2.



Apart from fulfilling one of the three basic rules a thermal bridge is also considered to be EPB-accepted if its thermal transmittance is smaller than a limit value. The limit value is depending on the type of thermal bridge (see Table 2)

Note that in Belgium the heat losses are calculated based on exterior dimensions, which results in possible negatives values for the linear transmittance coefficient.

Table 2. Limit values of the linear transmittance coefficient.

Type of thermal bridge	Ψ-limit (W/m·K)
1. External corners	
-Wall/wall connection	-0,10
-Other external corners	0,00
2. Internal corners	0,15
2. Wall/window and wall/door junction	0,10
3. Foundations	0,05
4. Balconies	0,10
5. Others	0,00
6. Combined construction (foundation starter + window/door sill)	0,15

2.7. Passive House Standard

This standard has been used mainly to interpret and compare the results as well as Flemish EPB-regulation.

Passive House is both a building energy performance standard and a set of design and construction principles used to achieve that standard. The Passive House standard is the most stringent building energy standard in the world: buildings that meet the standard use 80 % less energy than conventional equivalent buildings, and provide superior air quality and comfort.

Performance Criteria [16].

3. Heating or Cooling Energy ≤ 15 kWh/m2 per year

4. Total Source Energy ≤ 120 kWh/m2 per year ("Source Energy" by definition includes the energy required to produce and deliver the energy to the site, and can be offset with solar thermal and other measures. Photovoltaics cannot be used to offset this energy, but are recognized, at this time.)

5. Air Leakage ≤ equivalent to 0.6 air changes per hour at 50 Pascals (ACH50)

In addition, the following are recommendations which vary based on specific climate region:

6. Window u-value ≤ 0.8 $W/m^2/K$
7. Ventilation system with heat recovery with ≥ 75% efficiency with low electric consumption, 0.45 $W \cdot h/m^3$
8. **Thermal bridge free construction ≤ 0.01 W/(m·K)**

Stand out that the Passive house standard considers the limit of thermal lineal transmittance as 0,01 W/(mK) for all thermal bridges independently which kind it is, being too restrictive in some cases.

3. CASE STUDY

3.1. BUILDING DESCRIPTION

The house studied in the present research is situated in Dadizelestraat 10, Ledegem (West-Flanders). It is a renovation to passive house.

The house has two floors. It occupies a total volume of 748,7 m^3 and the conditioned floor area is 177,9 m^2.

Through shading and the largest windows surface orientation together the insulated elements used, the annual net energy need for heating is 13,8 KWh/m^2 fitting with passive house requirements ($\leq$ 15 KWh/m^2 per year).

The maximum air tightness level is 0,6 h^{-1} fulfilling the Passive House requirement ($\leq$0,6 h^{-1}).

Figure 6 and Figure 7 shows the two floors of house with all measured parts.

Figure 8 is a vertical section where it shows the stair to access from ground floor to first floor. There are all parts with the corresponding measures too. South, East and West sides are showed on Figure 9 to Figure 11. The main access is in the West side.

All house surfaces from wall, floor, windows to individual room surfaces as well as the total protected volume surface are given on Table 3.

Table 4 shows general vision of the construction of the envelopment where there are the materials used in each element with the thermal conductivity value and the total thermal transmittance value of the wall/floor/roof. The order of how the materials are shown is from inside to outside except the sloping roof and flat roof that it is to contrary. Following there is a description of window/door used.

Table 5 shows the general technical characteristics of the three insulation elements studied (lamdablock, Ytong-kimblock and cellular glass). A comparison between them is done.

Figure 6. Ground floor.

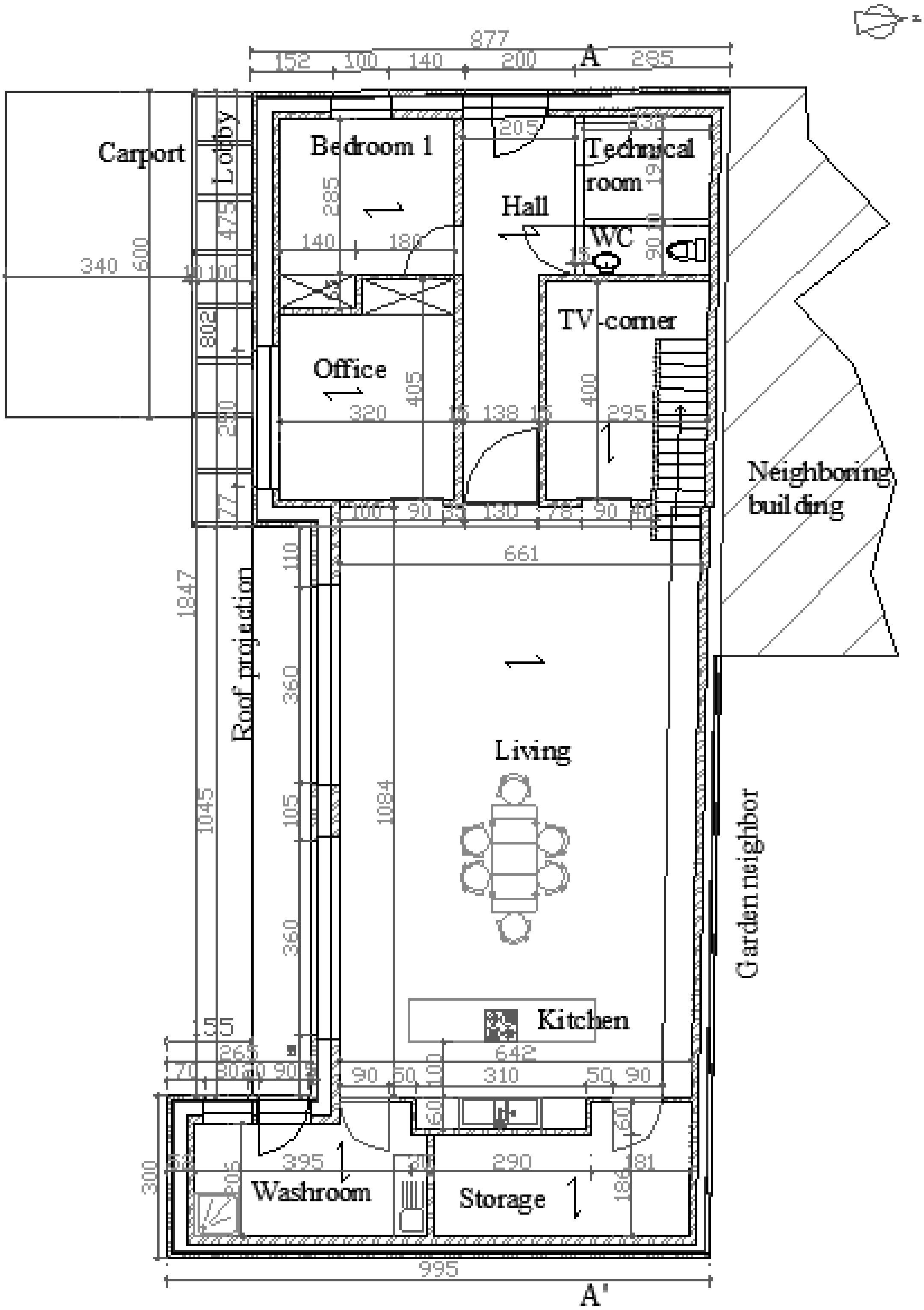


Figure 7. First floor.

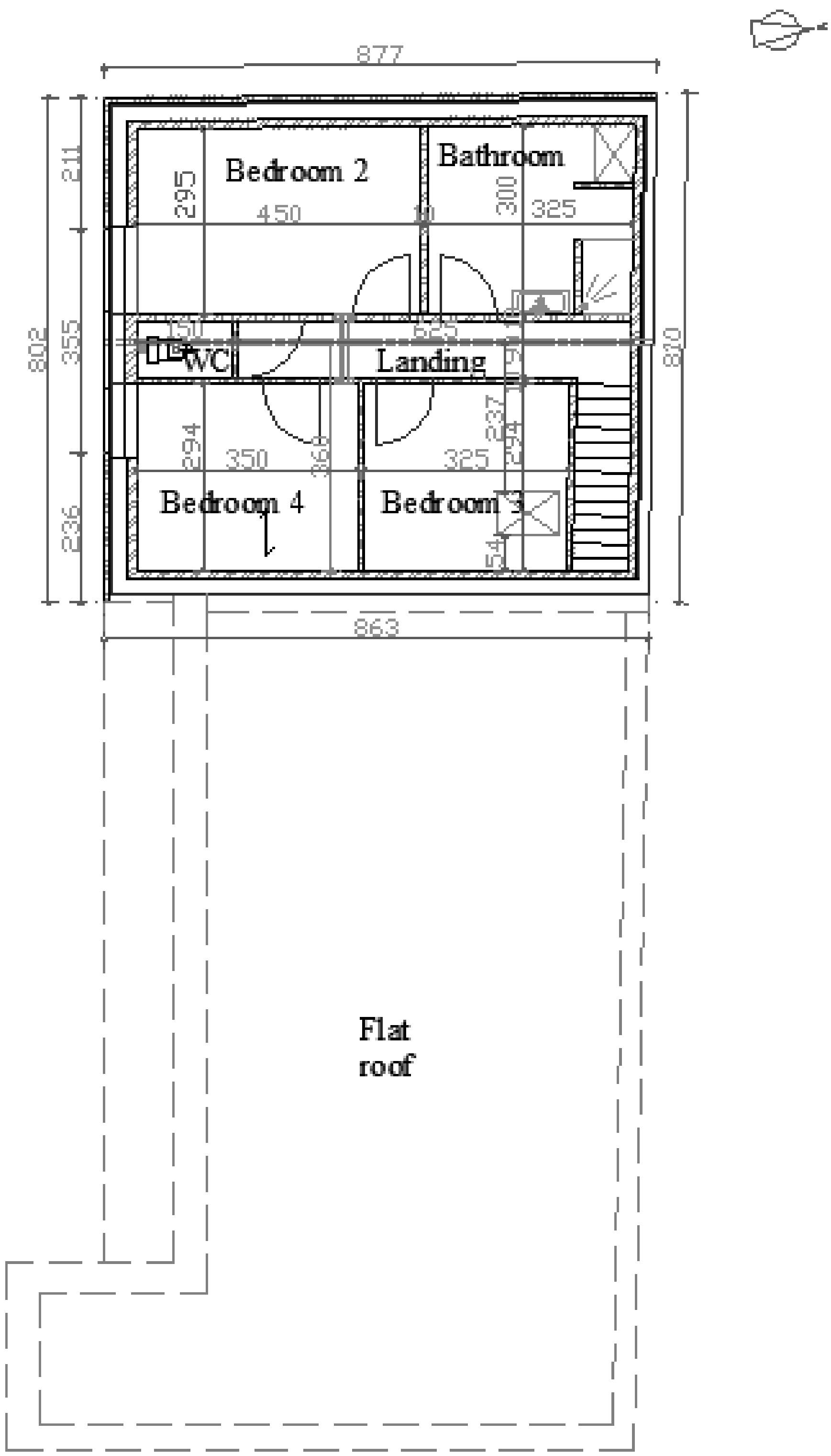


Figure 8. Section A-A'.

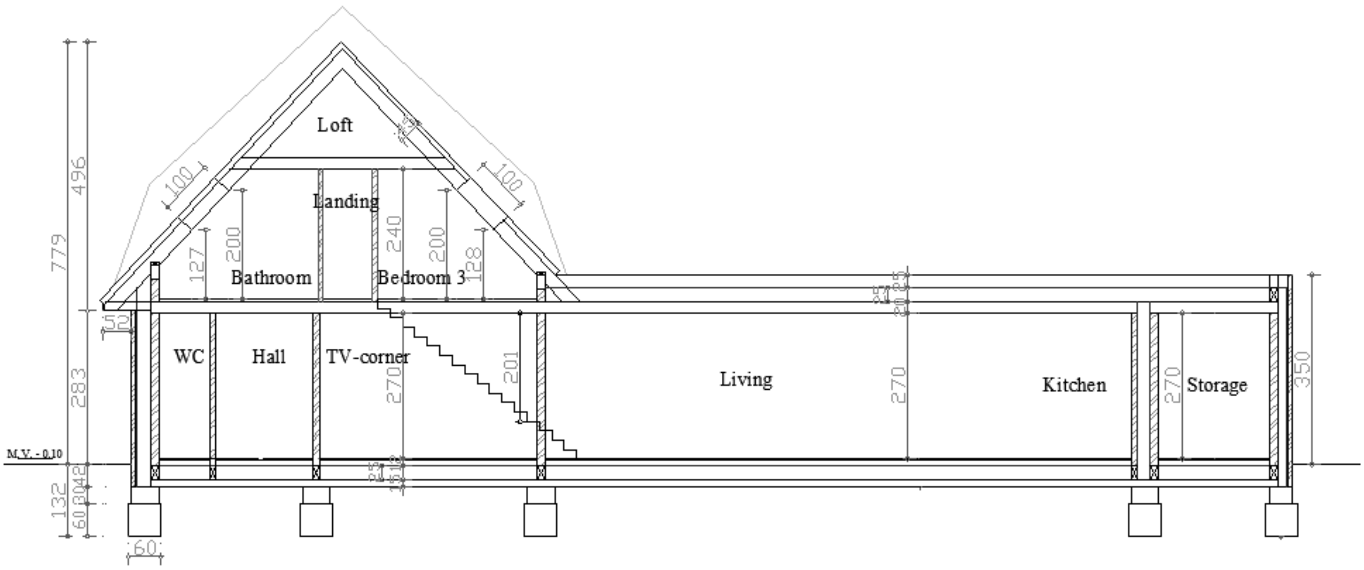


Figure 9. South side.

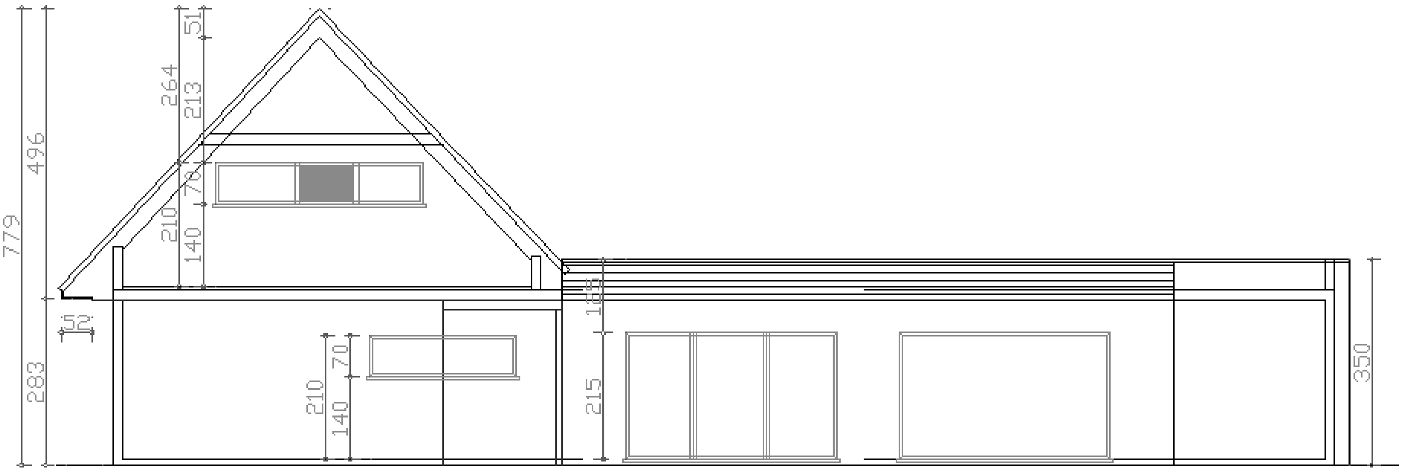


Figure 10. East side.

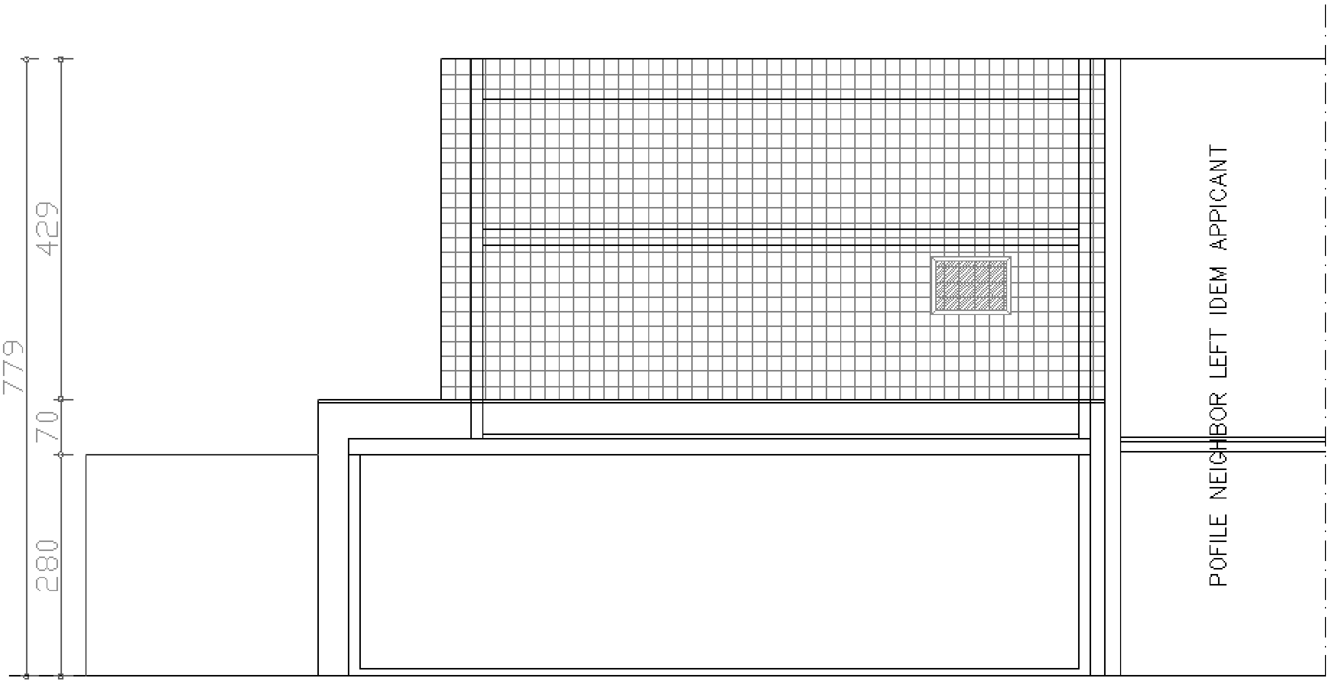


Figure 11. West side.

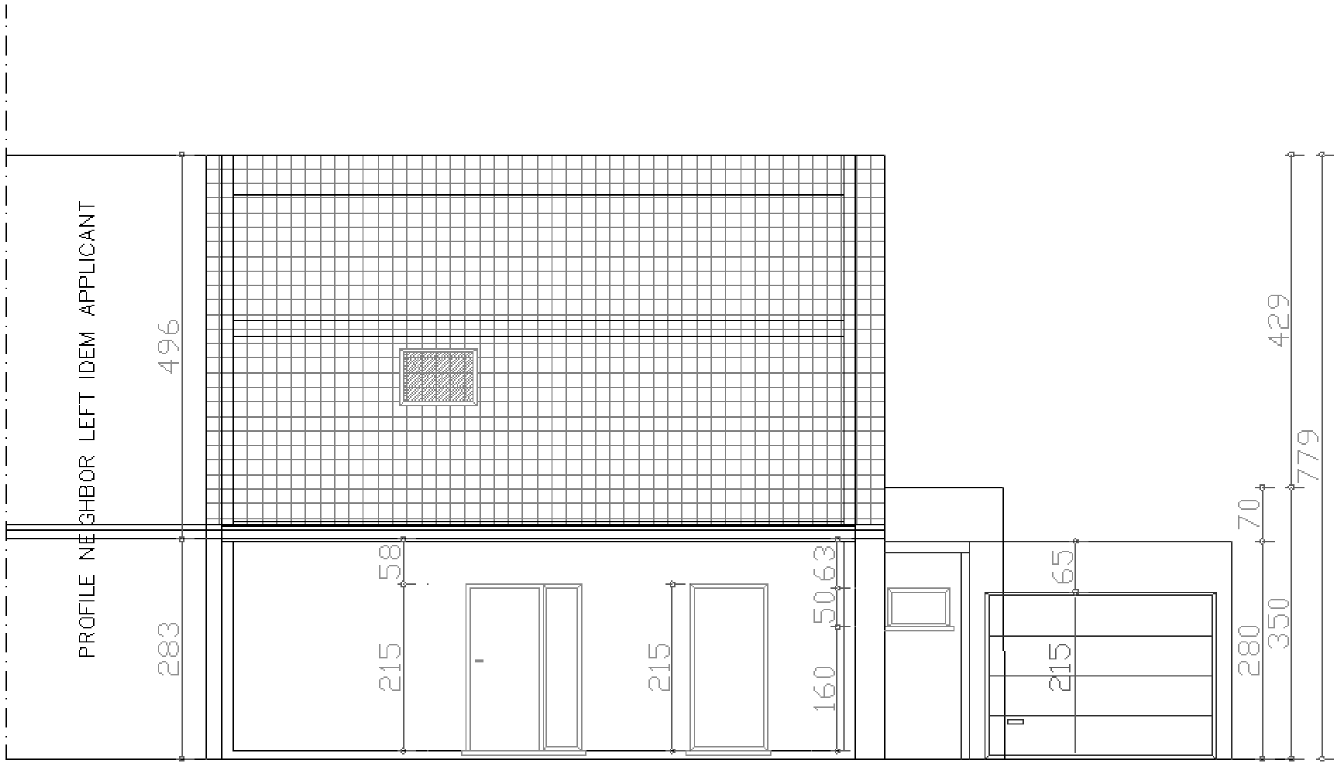


Table 3. House surfaces.

General parts	Elements	Surface (m²)	Total Surface (m²)
Conditioned floor area	Bedroom 1	10	177,85
	Hall	17,6	
	WC 1	1,8	
	Office	12	
	TV-corner	11,7	
	Living space	76,2	
	storage	9,3	
	Bedroom 2	7,5	
	Bedroom 3	7,1	
	Bedroom 4	8,7	
	Landing	8,4	
	Bathroom	6,2	
	WC2	1,4	
North windows			0
East windows			3,53
South windows			23,09
West windows			9,19
Horizontal windows			0
Door			0
Outer contact outside	south facade	22,4	168,6
	east façade laundry	2,5	
	south facade laundry	2,2	
	facade east corner wash	2,6	
	south facade corner wash	6,5	
	east façade	19	
	north facade garden	40,3	
	west facade	27	
	south facade gable	41,9	
	south east façade return	4,2	
Outer contact ground			0
Roof / ceiling air contact	sloping roof	46,6	189,36
	pitched roof behind	49	
	flat roof	93,8	
Base	On ground floor	160,93	160,93
Neighbor's wall	north facade building	46,74	46,74
Total protected volume			**554,69**

Table 4. Materials of construction elements.

Material	λ-value W/(m·K)	U-value W/(m²·K)
WALL STRUCTURE		
Gypsum plastering	0,52	0,115
Brick construction	0,26	
Glass wool	0,032	
Air layer unventilated	0,167	
Calcium silicate brick	0,90	
NEIGHBOR WALL STRUCTURE		
Gypsum plastering	0,52	0,134
Baksteen (brick)	0,90	
resol	0,023	
Air layer unventilated	0,167	
Calcium silicate brick	0,90	
GROUND FLOOR		
tiles	2,90	0,116
Concrete screed	1,30	
PUR-insulation	0,024	
Concrete screed	1,30	
Concrete reinforced with 1% steel	2,30	
FIRST FLOOR		
tiles	2,90	0,962
Concrete screed	1,30	
Glass wool	0,032	
Concrete reinforced with 1% steel	2,30	
Gypsum plastering	0,52	
SLOOPING ROOF		
celit	0,05	0,099
cellulose	0,039	
Unventilated air cavity	-	
timber	0,18	
Gypsum plastering	0,52	
FLAT ROOF		
resol	0,023	0,095
EPB-concrete screed	0,10	
Concrete reinforced with 1% steel	2,30	
Gypsum plastering	0,52	

For the window frames, the new European Standard EN 10077 requires that the thermal loss coefficient U of such Passive windows are lower than 0,8 W/(m²·K).

To meet these requirements, the window frames used, combine triple panel insulated glazing and specially developed thermally broken window frames, which provides excellent thermal comfort even near the window. It has U-value = 0,76 W/(m²·K) and it is providing by Bierber trademark.

This kind of window is used in details 3 and 9-12. They correspond to seating (D.3, 9) and bedroom 4 (D.10, 11, 12) and they are situated in the thermal envelope.

The door frame is made of aluminum and the kind chosen is the CS 104 door system, providing by Reynaers trademark. It is used in detail 4 corresponding to the door of the main entrance and it is the introducing a solution for passive buildings. The high insulation levels, down to an U-value of 0,88 W/m²·K, are achieved by the use of a patented insulation technology which contains special foam, firmly fixed in the chamber of the insulation strip so that no extra manipulation is required when handling, processing and composing the door. A new set of specifically developed gaskets also assures the high level of the wind and water tightness of the system.

With these characteristics this kind of door meets with the requirements of Passive House, aim of the present house studied in this master thesis.

A considerable part of the savings of construction costs is in the area of the exterior walls. Considering this, here have been studied three insulation elements: lamdablock (Ploegsteert), cellular concrete (Ytong kimblock) and cellular glass.

Table 5 shows the general technical characteristics of them.

The differences on U-values obtained can be seen in section 4.1. Results analysis.

Table 5. Technical characteristics of insulation elements.

	Lamdablock	Ytong c4/500 (Cellular concrete)	Celllular glass
Density (kg/m³)	1500	450-500	115
Thickness (cm)	19, 25	15,20,25,30	5,8,10,11’5
Thermal conductivity (W/(mK))	0,16	0,125	≤0,041
Reaction to fire	Class A1	Euroclass A1	Euroclass A1
Compressive strength (N/mm²)	≥12 N/mm²	1,2	≥1,6

Comparing them, cellular glass has the lower λ-value and the difference of thickness is greatly lower than lamdablock or Ytong, but it is the most expensive.

Lambdablock has a compressive strength of 12 N/mm² and Ytong C4/500 only 1,2 N/mm². The lambdablocK can therefore carry 10 times more weight than Ytong C4/500 and this does make it a possible solution for incited foundation, e.g. apartment buildings where Ytong C4/500 cannot be used. Moreover, it is the most economic.

Possessing all the thermal properties such as excellent heat insulation, fire resistance together with an exceptionally high unit compressive strength, cold bridging is significantly reduced and structural integrity maintained.

3.2. DETAILS

The construction details are described in this paragraph. Each figure shows a short description of the thermal bridge, where it is situated and the detail with the elements that build it.

A general vision of the location of details, all of them in the exterior envelopment, is given in figure 12 to 14.

Figure 12. Ground floor. Details location.

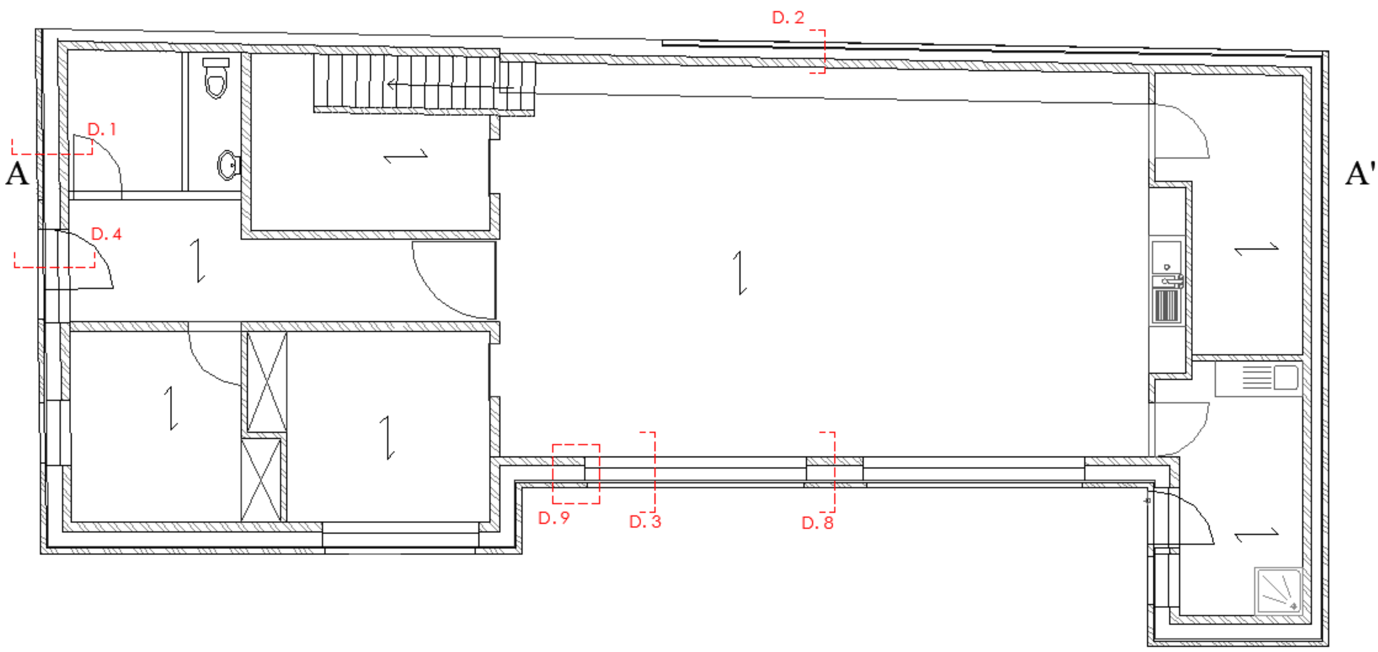


Figure 13. First floor. Details location.

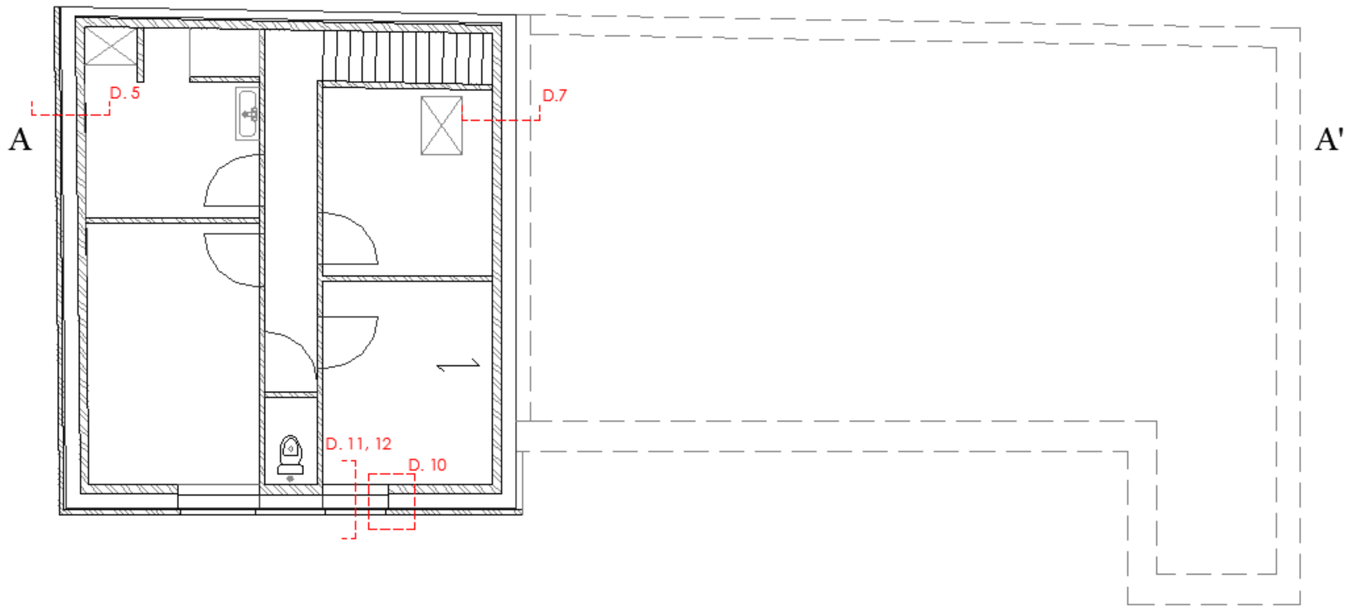
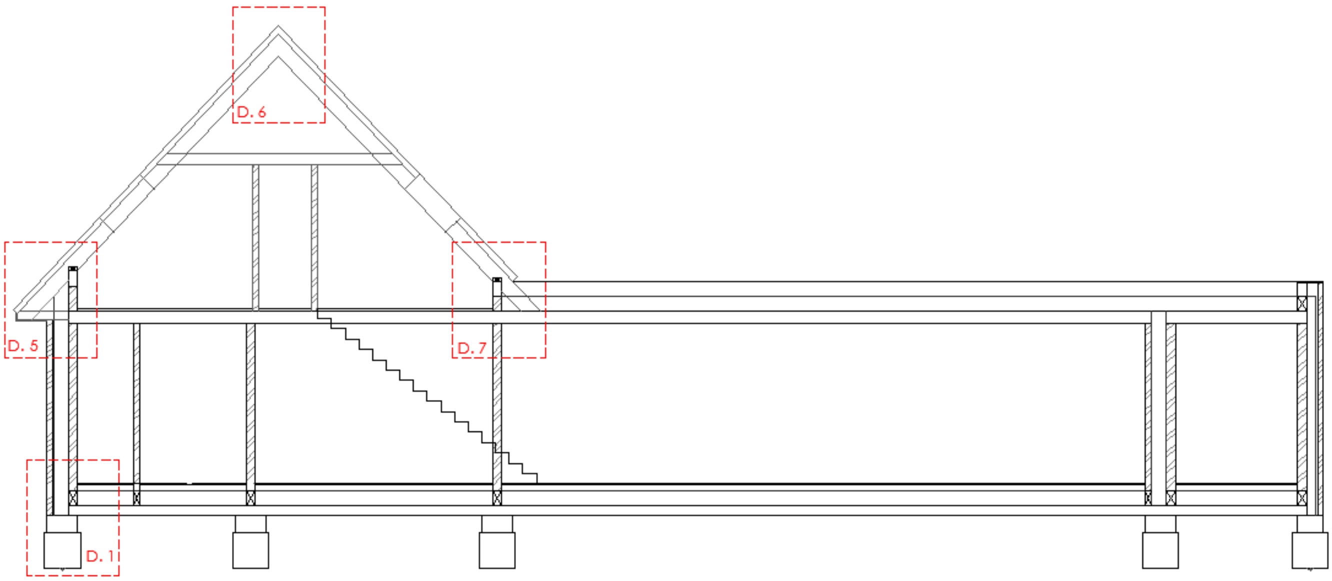


Figure 14. Section A-A'. Details location.



DETAIL 1

Connection external wall to ground floor at the front side of the building.

Figure 15. Location of detail 1.

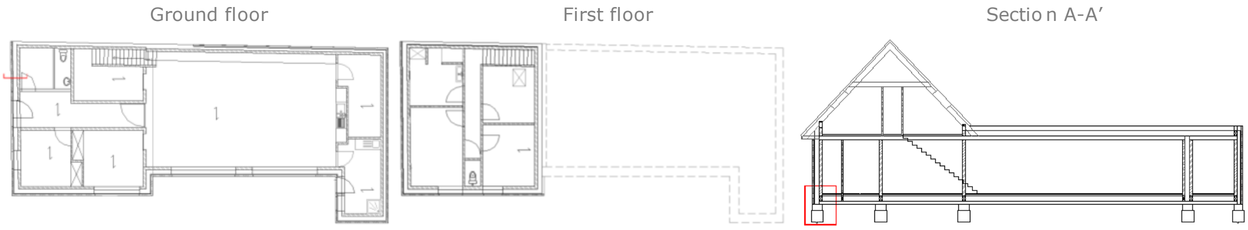
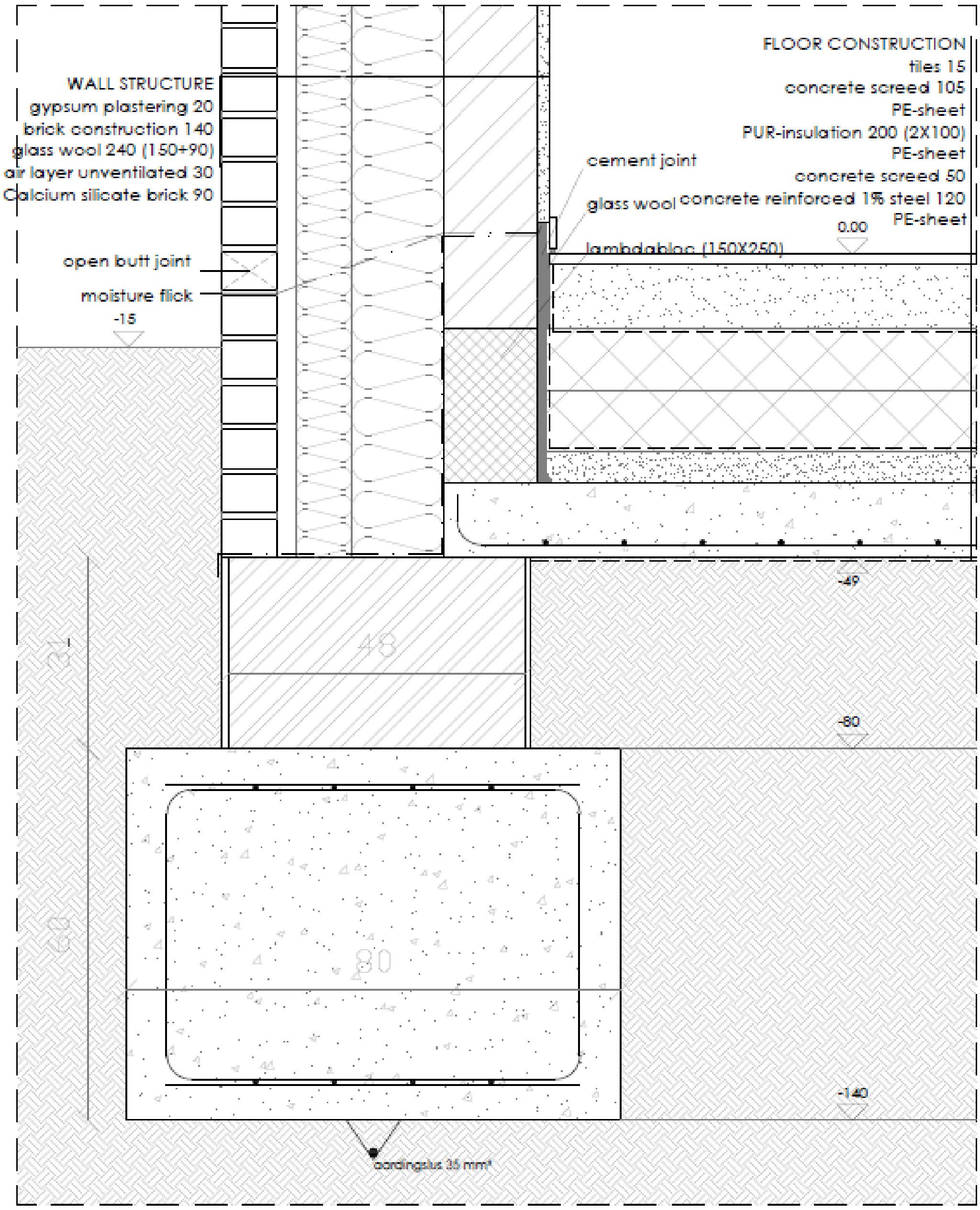


Figure 16. Materials used in detail 1.



DETAIL 2

Connection external wall to ground floor at the north side of the building.

Figure 17. Location of detail 2.

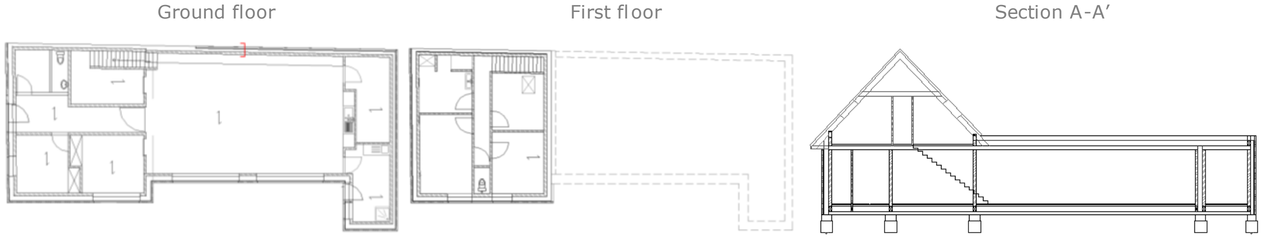
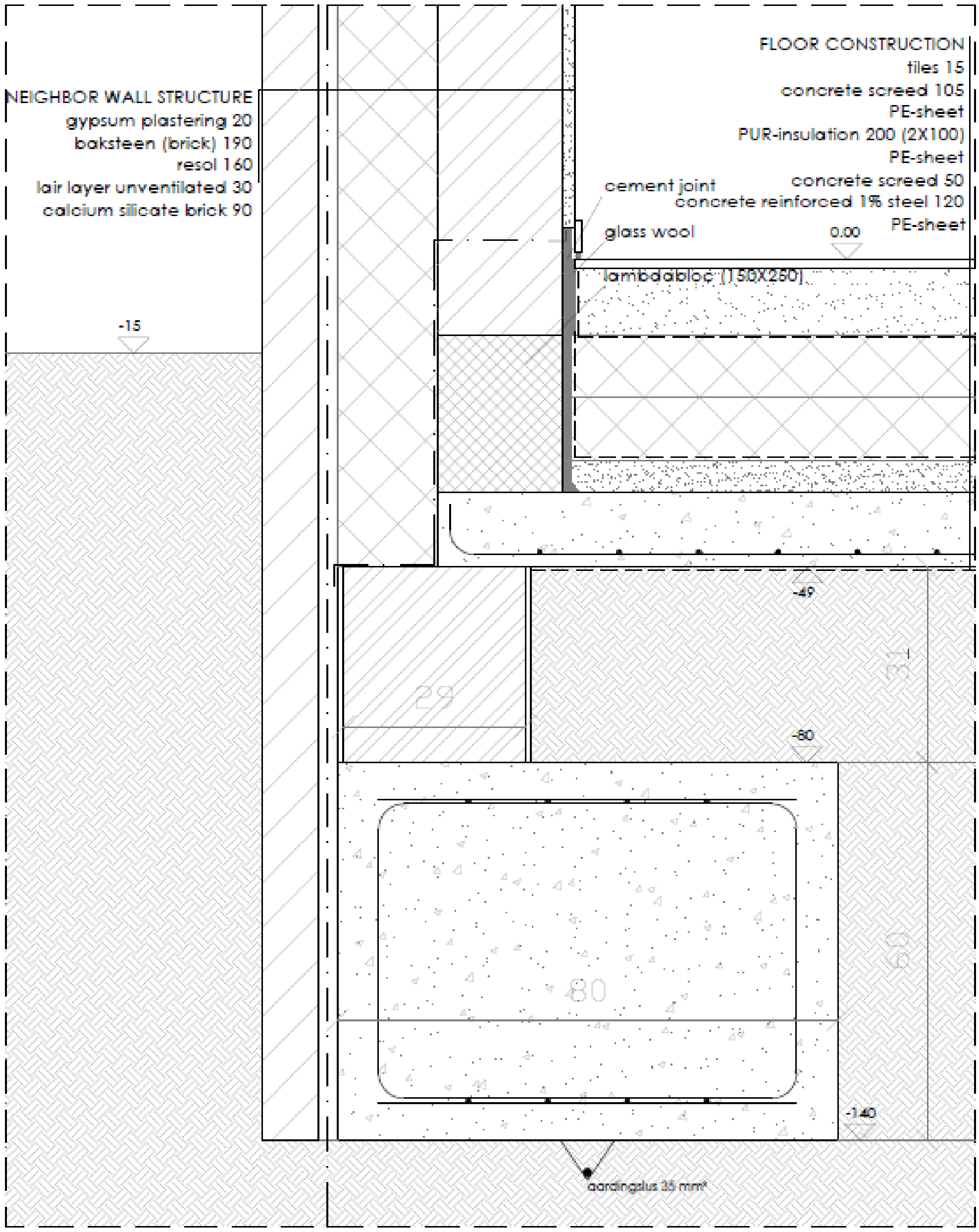


Figure 18. Materials used in detail 2.



DETAIL 3

Connection window frame to ground floor at the south side of the building

Figure 19. Location of detail 3.

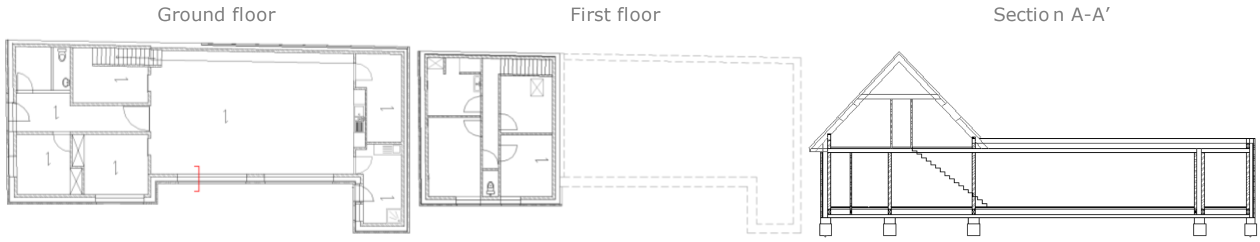
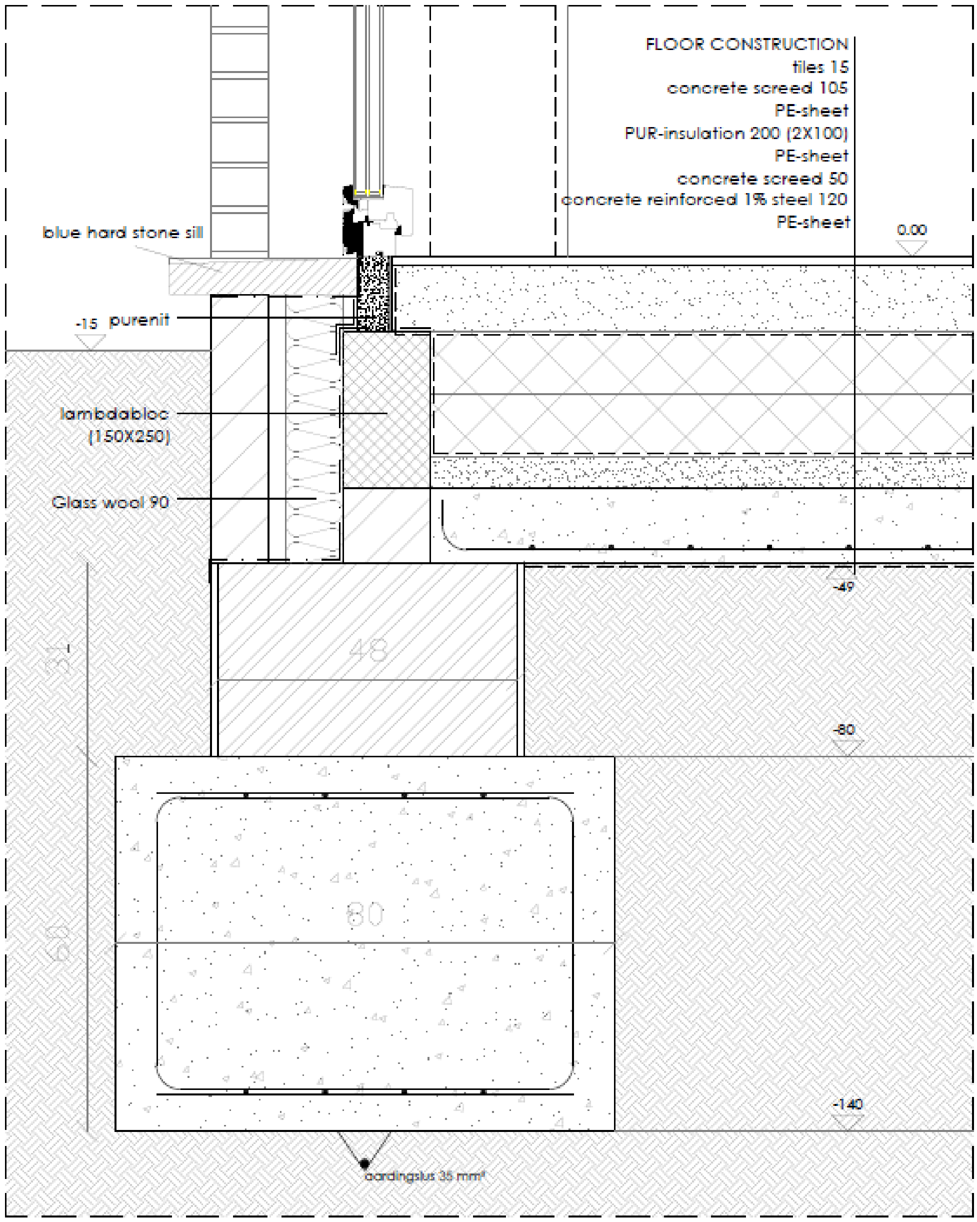


Figure 20. Materials used in detail 3.



DETAIL 4

Connection door frame to ground floor at the front side of the building.

Figure 21. Location of detail 4.

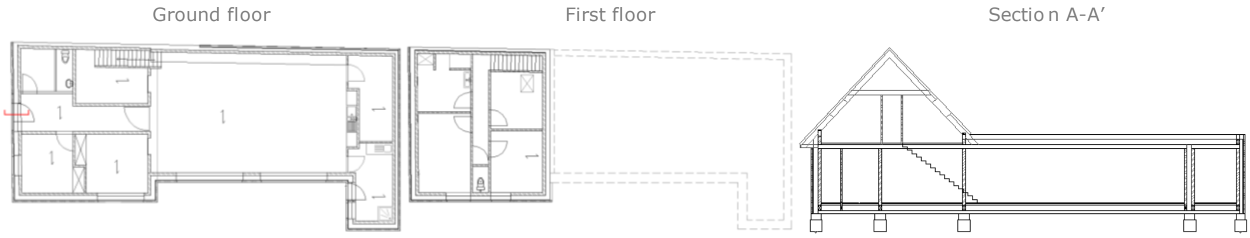
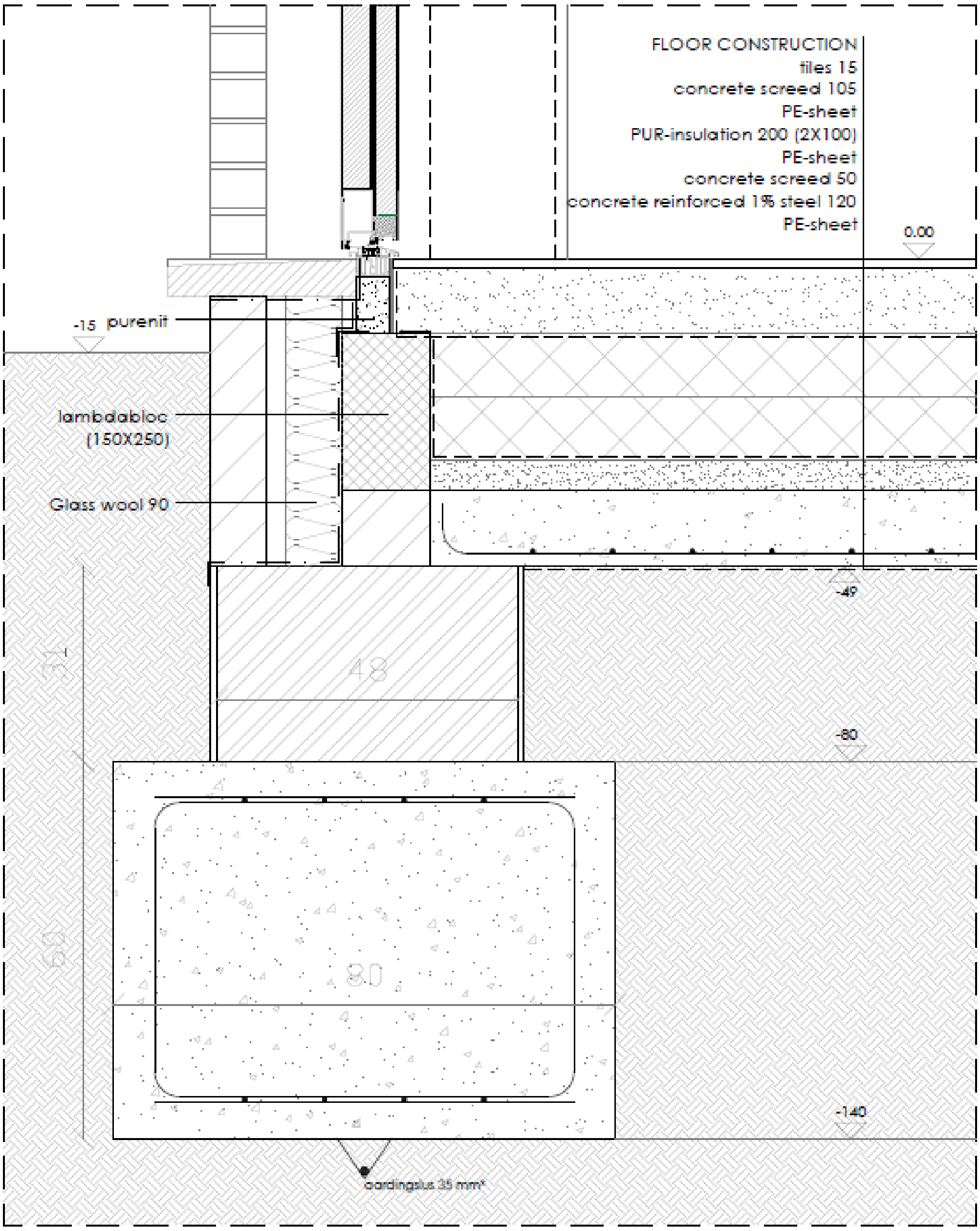


Figure 22. Materials used in detail 4.



DETAIL 5

Connection external wall to sloping roof at the front side of the building.

Figure 23. Location of detail 5.

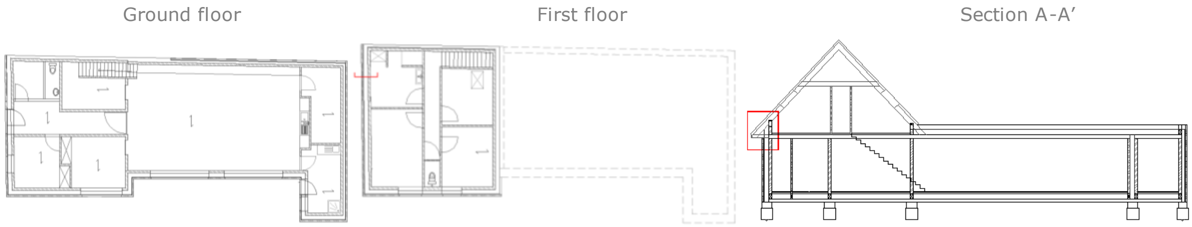
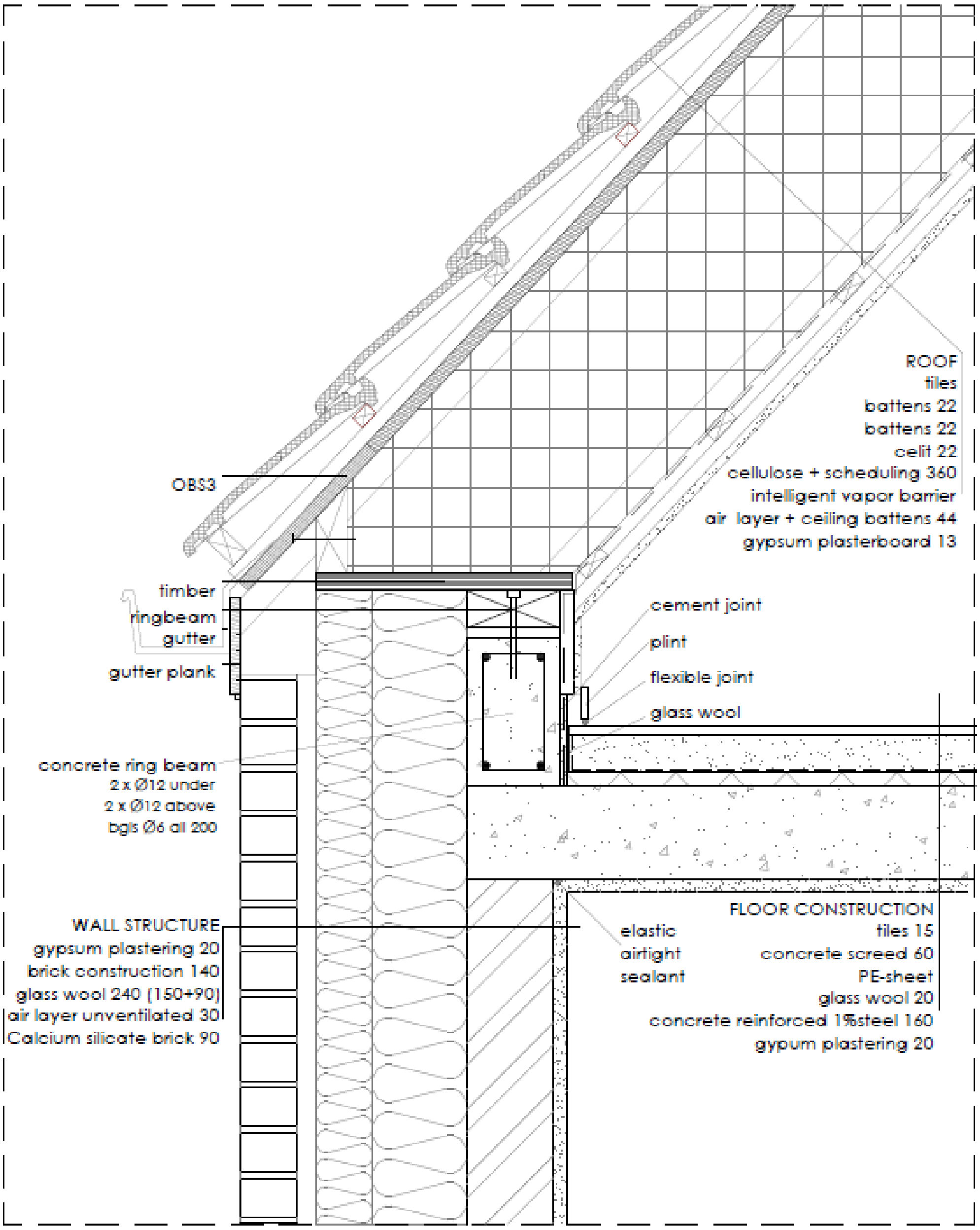


Figure 24. Materials used in detail 5.



DETAIL 6

Connection both sides of the sloping roof at the top of the building.

Figure 25. Location of detail 6.

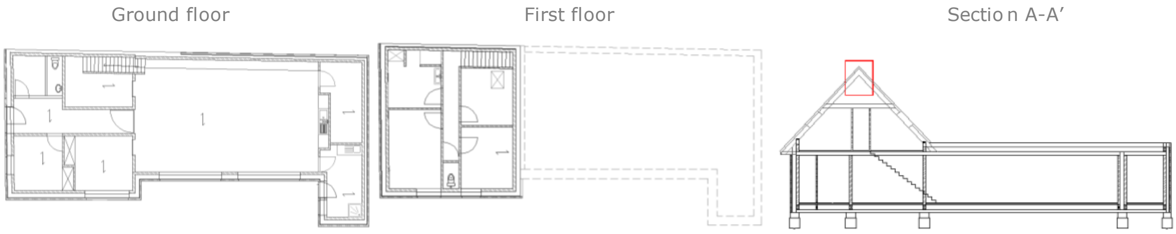
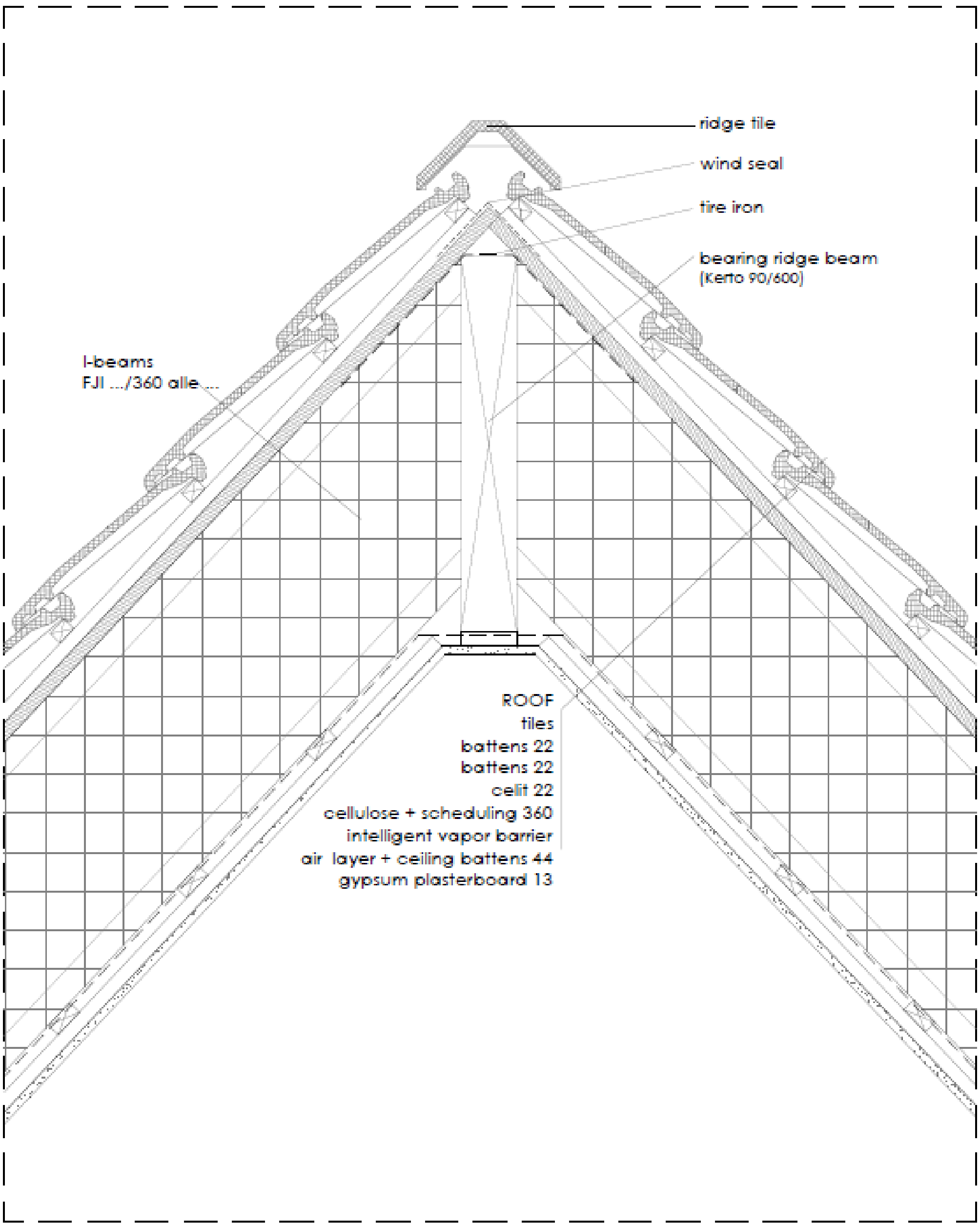


Figure 26. Materials used in detail 6.



DETAIL 7

Connection sloping roof to flat roof at the back side of the building.

Figure 27. Location of detail 7.

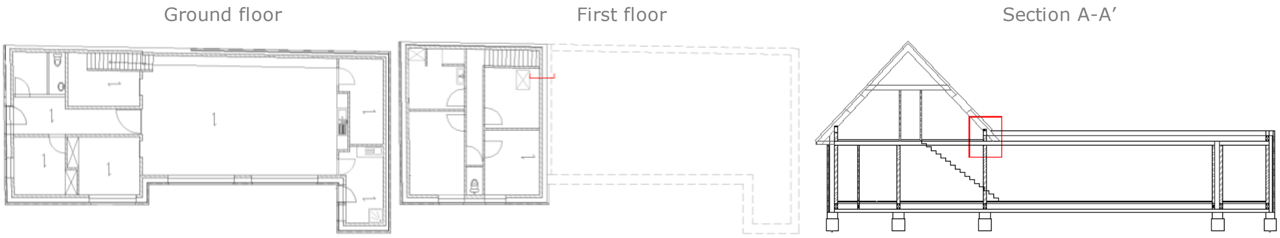
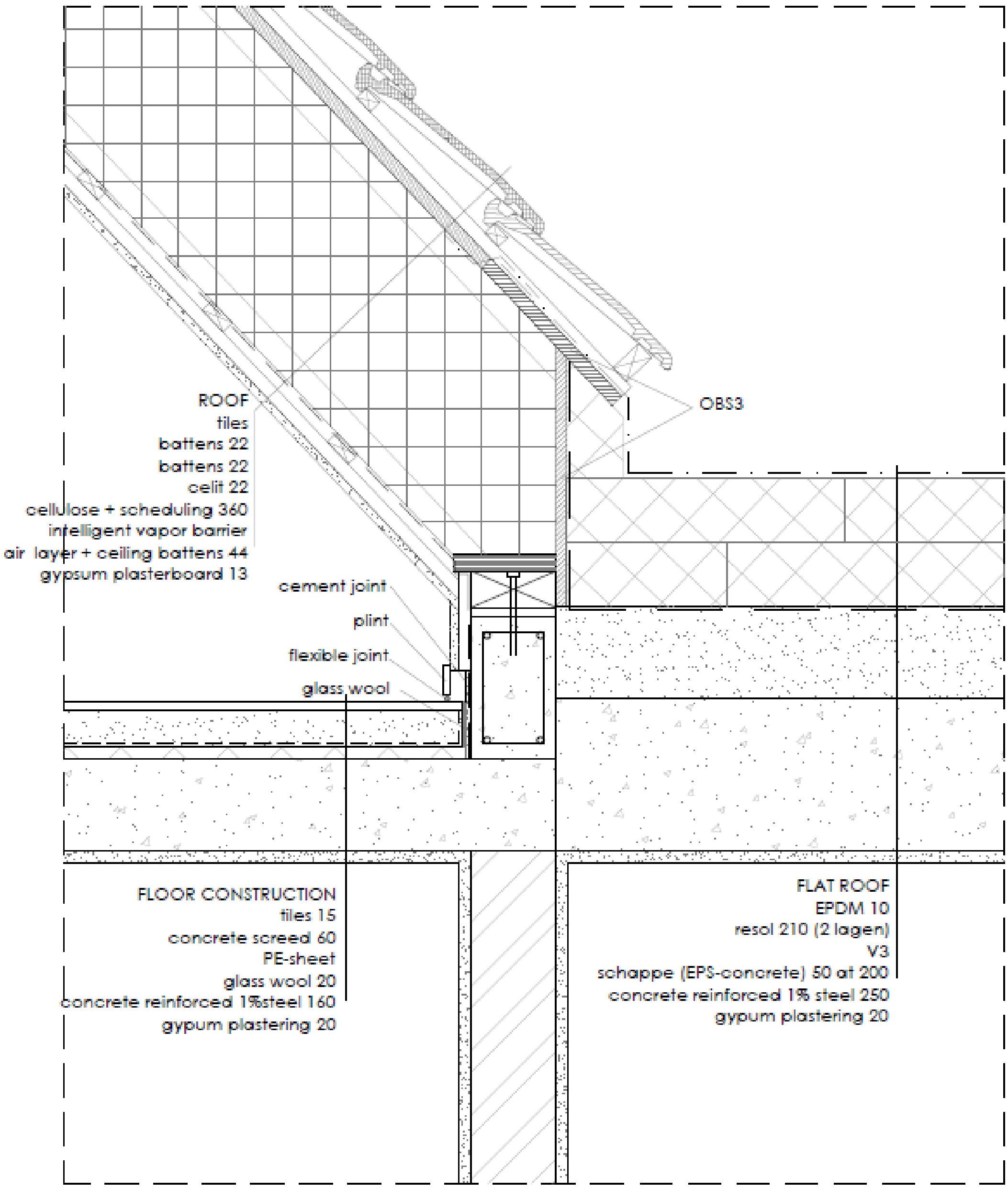


Figure 28. Materials used in detail 7.



DETAIL 8

Connection external wall to flat roof at south side of the building.

Figure 29. Location of detail 8.

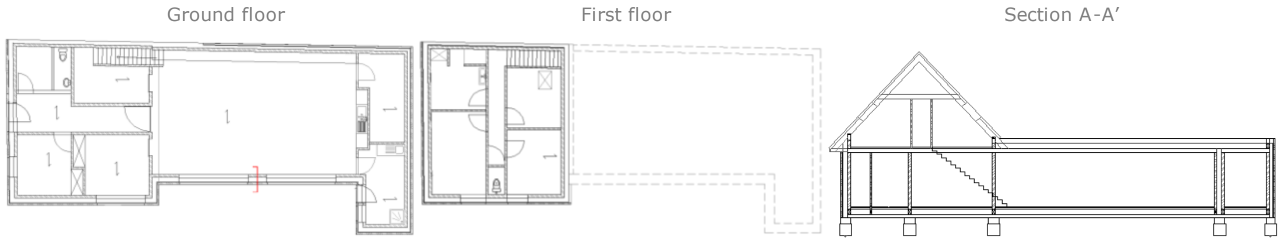
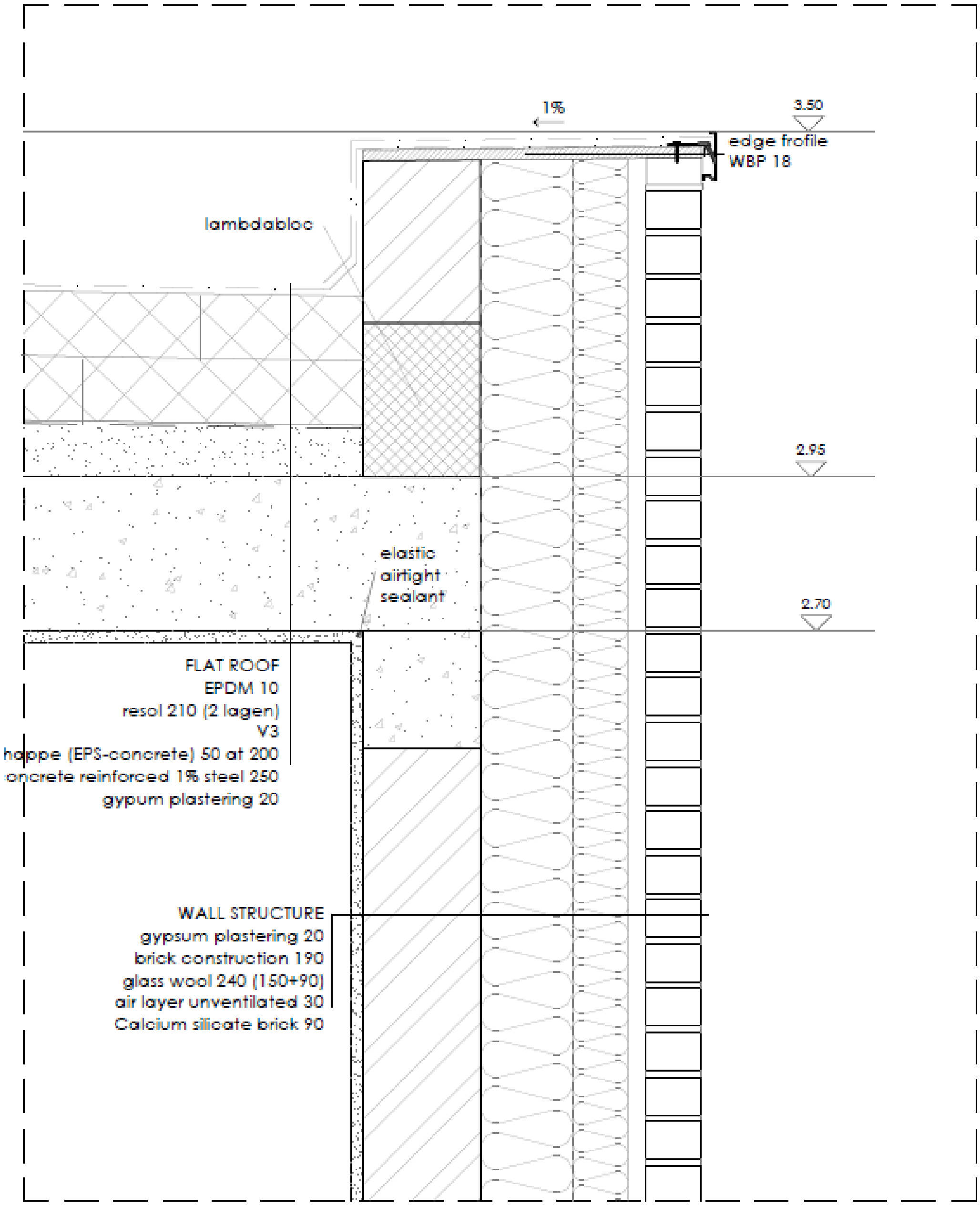


Figure 30. Materials used in detail 8.



DETAIL 9

Connection external wall to window frame on ground floor at the south side of the building (horizontal section).

Figure 31. Location of detail 9.

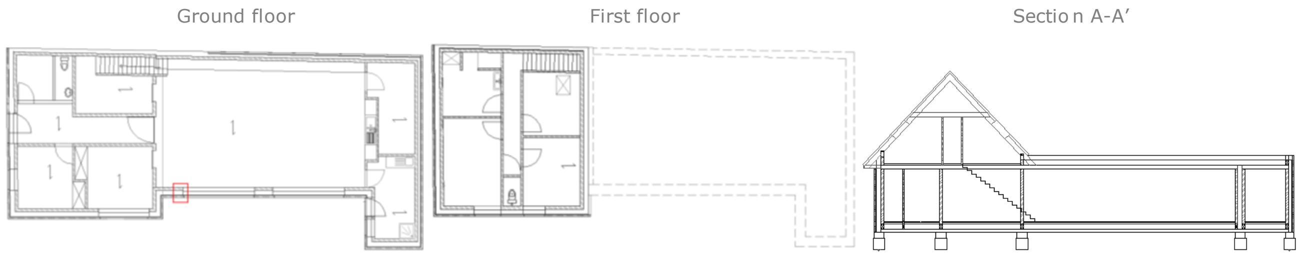
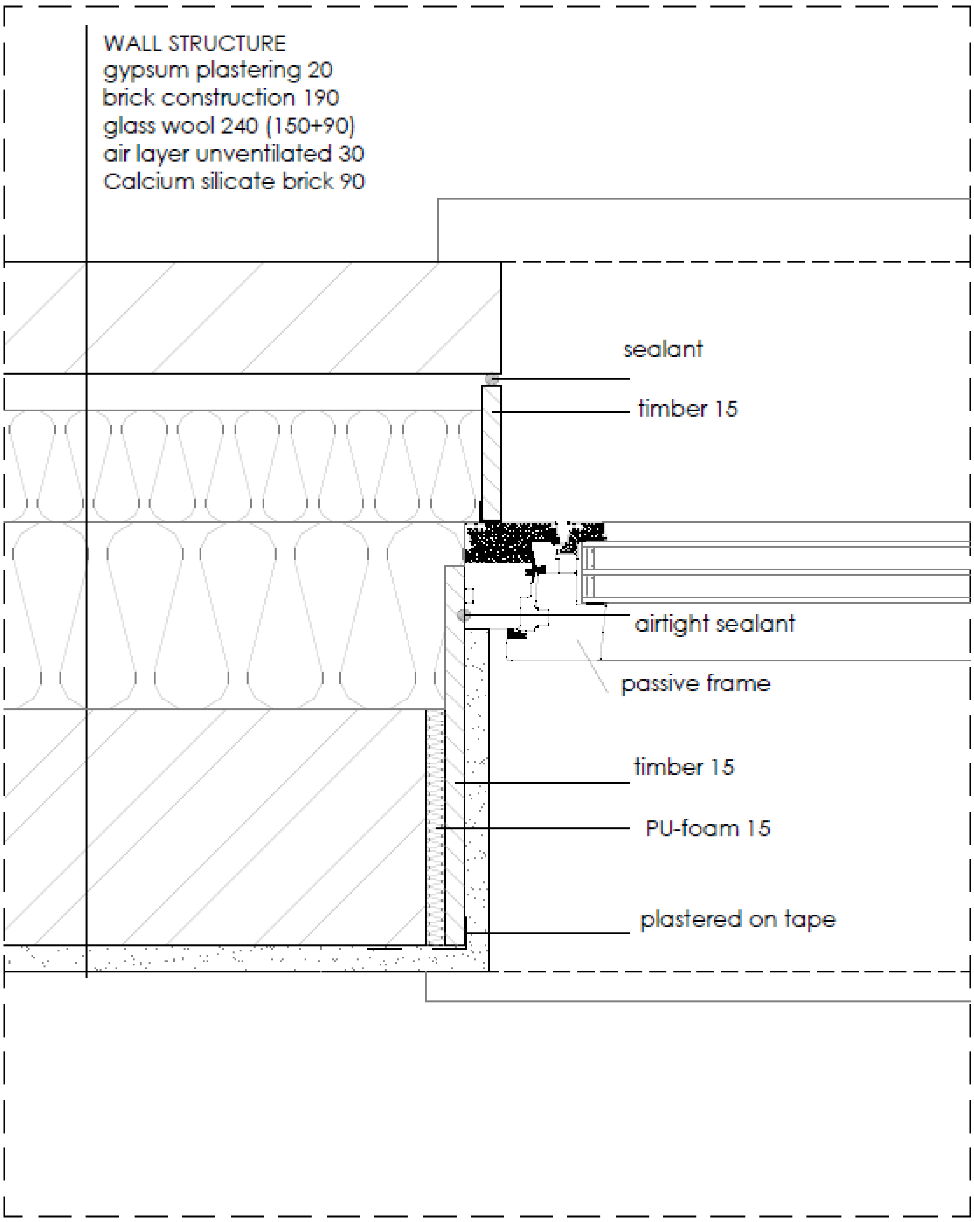


Figure 32. Materials used in detail 9.



DETAIL 10

Connection external wall to window frame with blind rail outdoor on first floor at the south side of the building (horizontal section).

Figure 33. Location of detail 10.

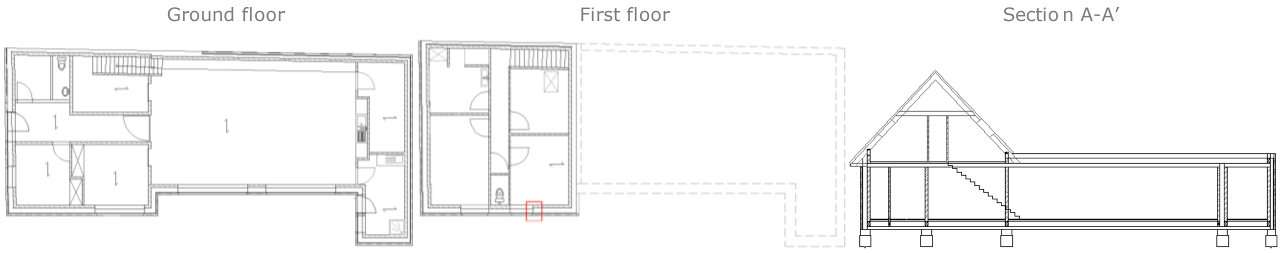
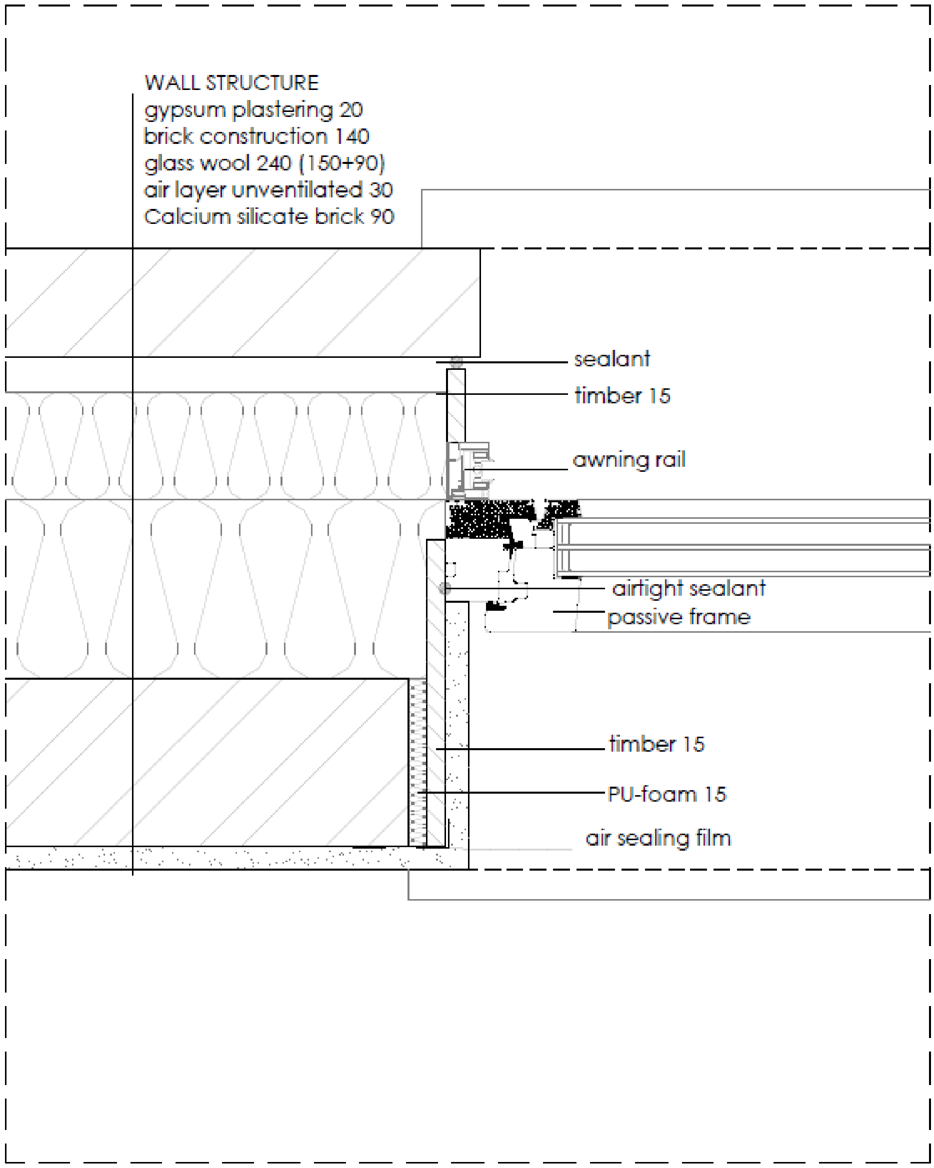


Figure 34. Materials used in detail 10.



DETAIL 11

Connection external wall to window frame on first floor at the south side of the building (vertical section).

Figure 35. Location of detail 11.

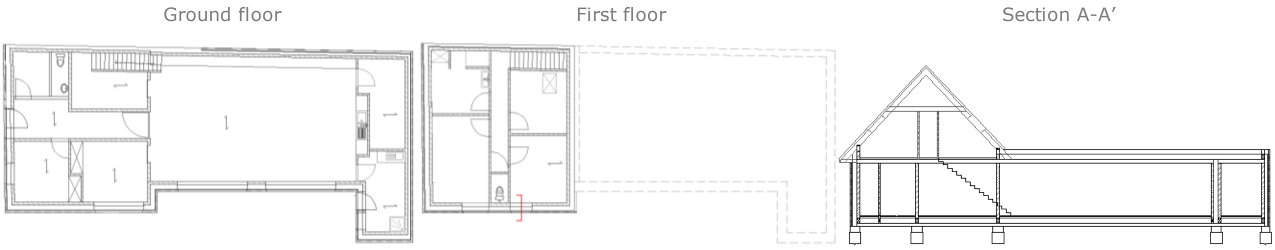
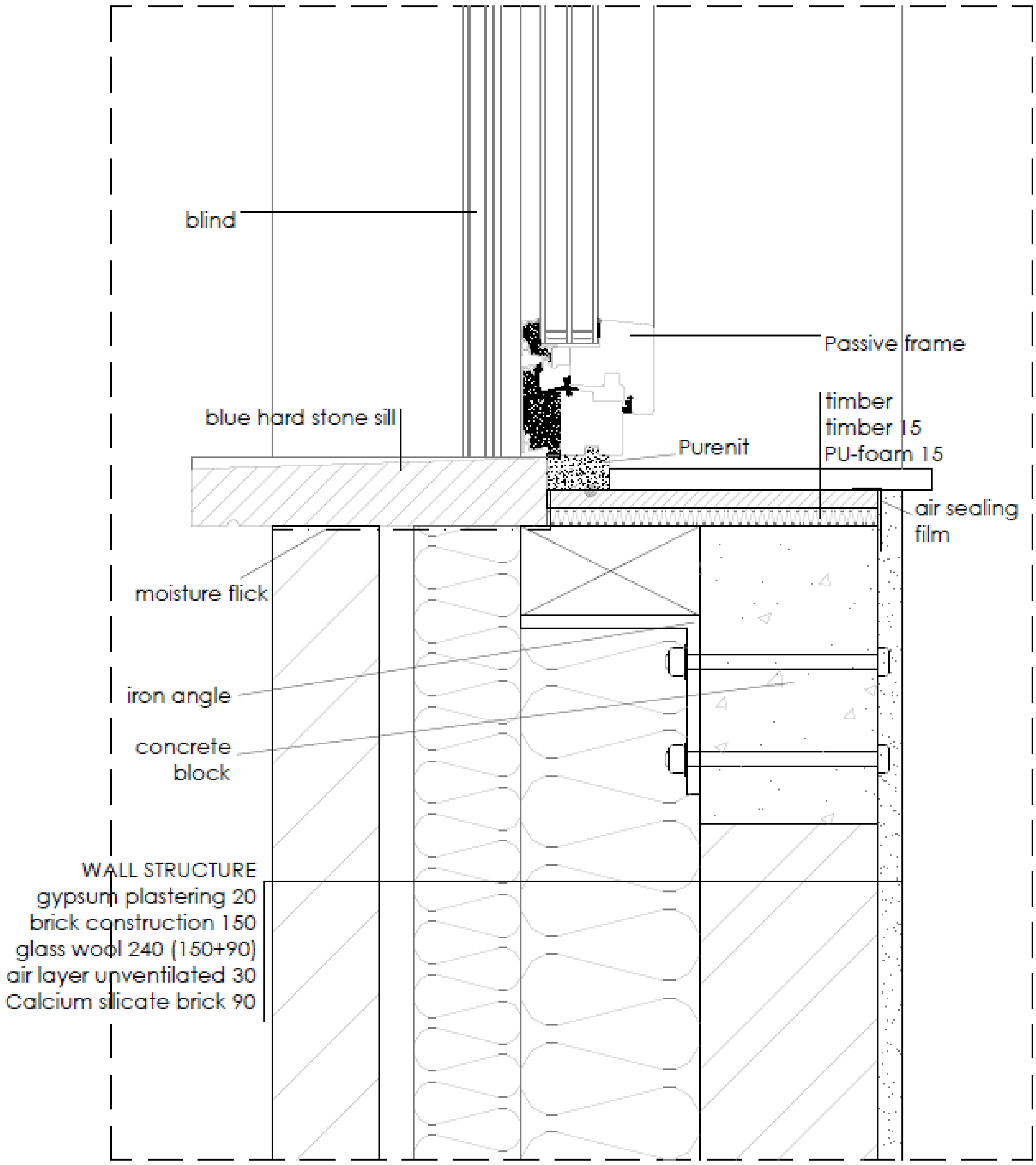


Figure 36. Materials used in detail 11.



DETAIL 12

Connection external wall to window frame with shutter box on first floor at the south side of the building (vertical section).

Figure 37. Location of detail 12.

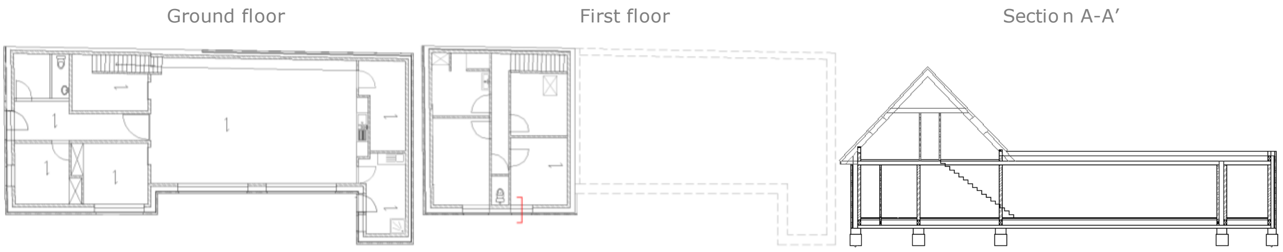
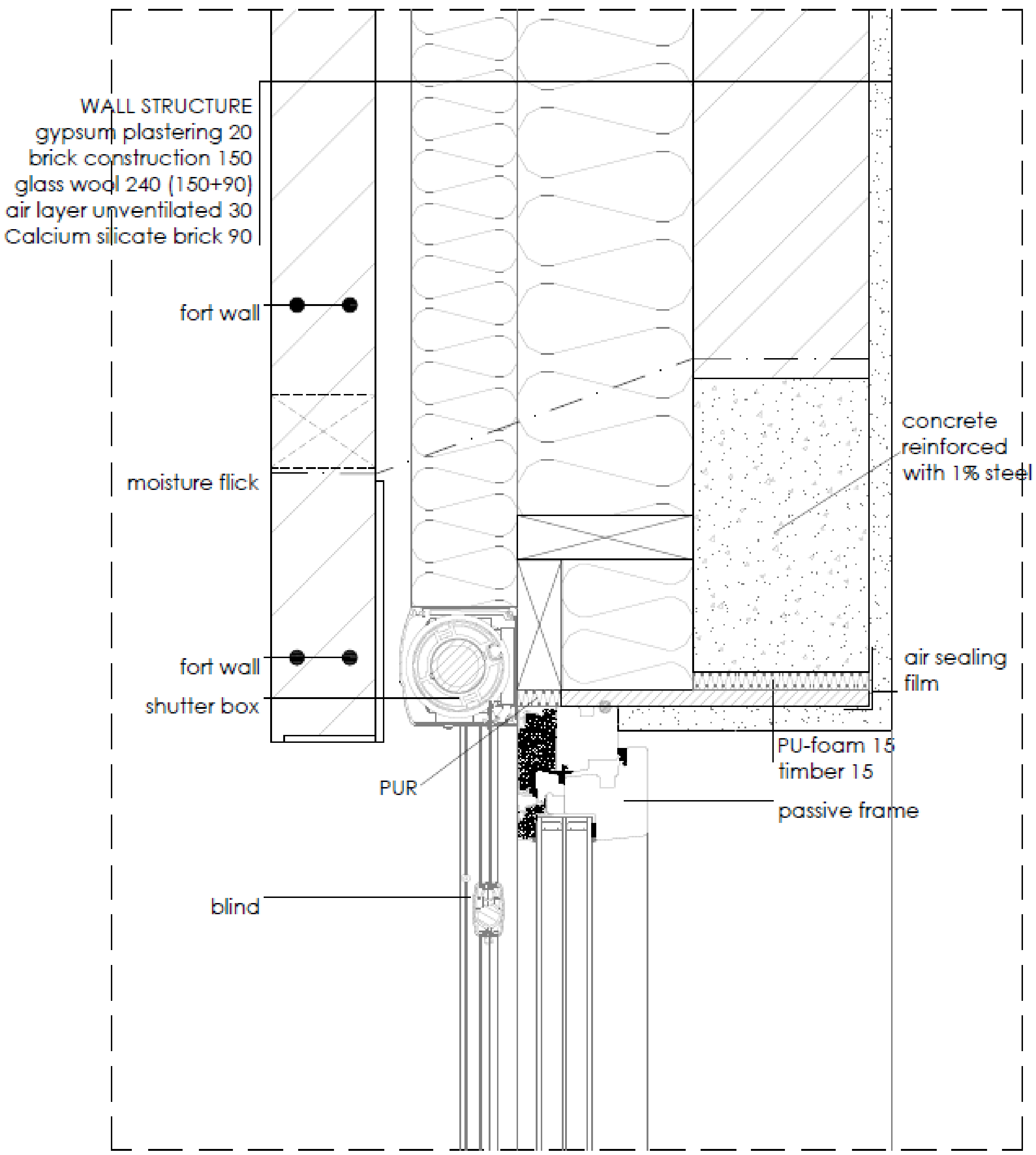


Figure 38. Materials used in detail 12.



3.3. MATERIALS AND λ-VALUES

The calculations are made using the real thermal conductivity of materials (λ-value)

Table 6 shows the materials used in constructions details, its λ-value and the standard reference.

Table 6. Thermal conductivity values of materials.

Material	Type	λ W/(m·K)	Standard reference
Unventilated air cavity	ISO	-	ISO 10077-2
Slightly ventilated air cavity	ISO	-	ISO 10077-2
Air layer unventilated	generic	0,167	ISO 6946
Concrete with 1% of steel	generic	2,30	ISO 10456
Concrete with 2% of steel	generic	2,50	ISO 10456
Screed (concrete)	generic	1,30	ISO 10456
Screed (EPB-concrete)	trademark	0,10	-
Calcium silicate brick	trademark	0,90	-
Brick construction	trademark	0,26	-
Baksteen (brick)	trademark	0,90	-
Concrete block	generic	0,14	-
PUR insulation	trademark	0,024	-
PU foam	trademark	0,023	-
Glass wool	trademark	0,032	-
Lamdablock	ploegsteert	0,16	-
Ytong kimblock (cellular concrete)	Xella	0,125	-
Cellular glass	Foamglass	0,041	-
Purenit (insulation)	Puren gmbh	0,07	DIN EN 12667
Resol (insulation)	trademark	0,023	-
Celit (wood panel)	trademark	0,05	-
OSB3	trademark	0,13	ISO 10456
Cellulose	trademark	0,039	ISO 10456
Gypsum plasterboard	generic	0,21	ISO 10456
Gypsum plastering	trademark	0,52	ISO 10456
Plaster, cement, sand	generic	1,00	ISO 10456
Sand and gravel	generic	2,00	ISO 10456
Tiles	generic	2,90	ISO 10456
Wood window frames	trademark	0,074*	-
Aluminum door frame	trademark	0,057*	-
PVC rigid	generic	0,17	ISO 10077-2
Timber 500 Kg/m³	generic	0,13	ISO 10456
Timber 700 Kg/m³	generic	0,18	ISO 10456
Limestone hard	generic	1,70	ISO 10456
Blue hard stone	generic	3,50	ISO 10456

* This λ-value is calculated according equation (3) with U-value providing by trademark. (Window frame U=0,76 W/m²·K ; door frame U=0,88 W/m²·K).

4. RESULTS & DISCUSSION

This chapter discusses the analysis results and a discussion of them. The analysis shows a summary of all results calculated with flixo program with several possibilities. It lets compare and argue them in the following step as well as extract the final conclusions shown on the chapter 5.

4.1. ANALYSIS RESULTS

4.1.1. Façade-ground floor connection

Thermal bridges in foundations are studied in this paragraph. Each figure shows the calculation model, isotherms and streamlines, total heat flux, linear transmittance Ψ and the limits in EPB-regulation and passive house standard.

The legends of the materials, boundary conditions, streamlines and isotherms are given in ANNEX A.

Figure 39 to Figure 45 show the results for detail 1, i.e. connection external wall to ground floor at the front side of the building. Three different insulated elements are tested to guarantee a continuous insulation layer: Lamdablock (see Figure 39), Ytong cellular concrete (see Figure 40) and cellular glass (see Figure 41). Moreover, the insulation thickness in the floor is varied (see from Figure 43 to Figure 45).

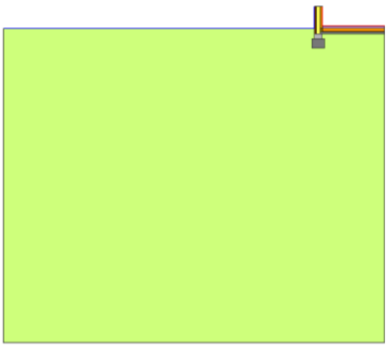
Table 7 summaries the linear transmittance of all the variations of detail 1.

This detail is modeled as explained in section 2.1 EN ISO 10211:2007 to simplify in general.

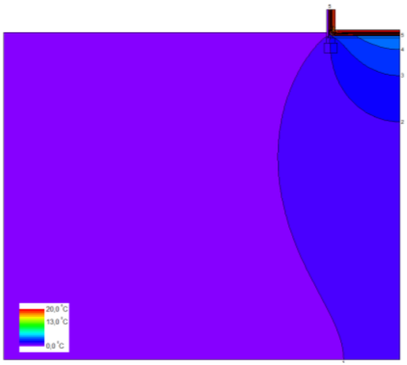
The Ψ -Value is determined according to equation (2).

Figure 39. Results of detail 1.1 (Lamdablock, d = 25 cm).

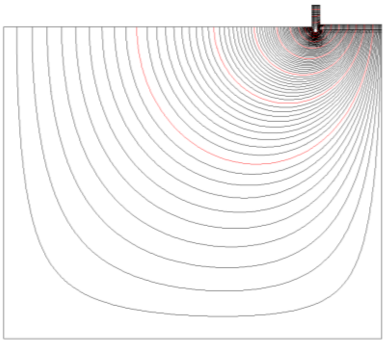
DETAIL 1.1			
	Ψ-Value calculated 0,048 W/(m·K)	Ψ -EPB regulation 0,05 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



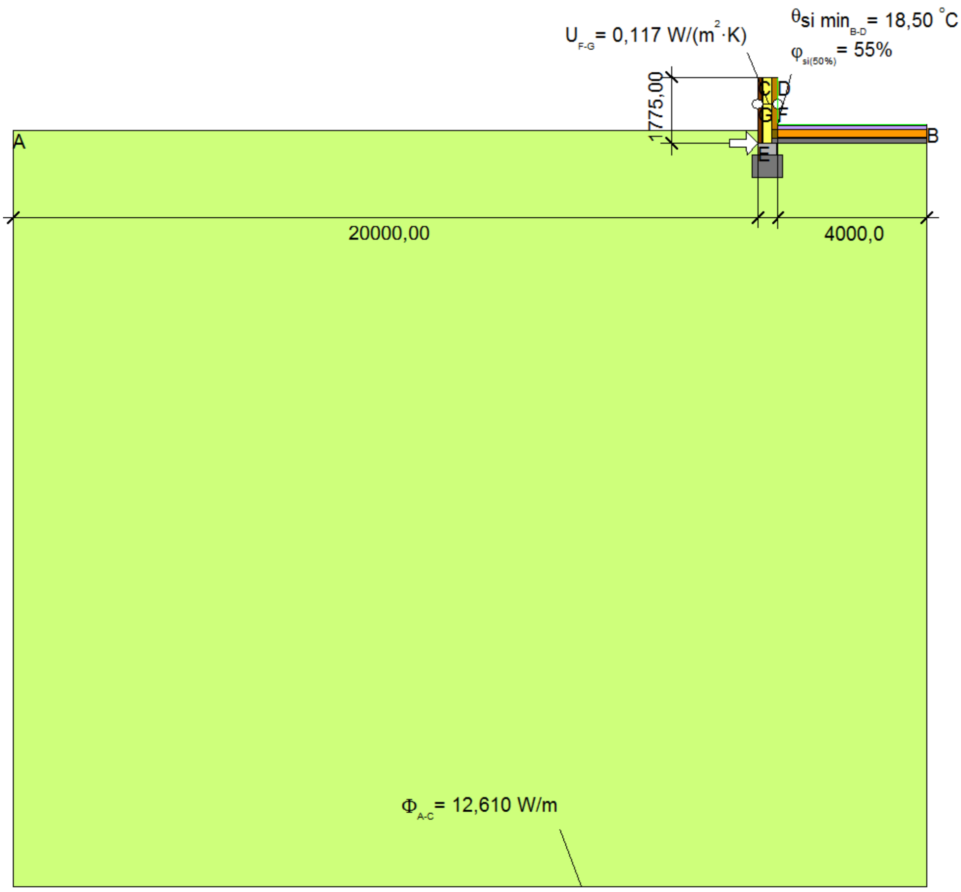
Modeled



ΔT and Isotherms

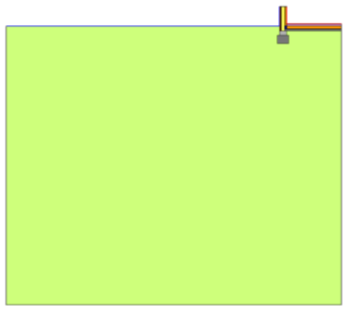
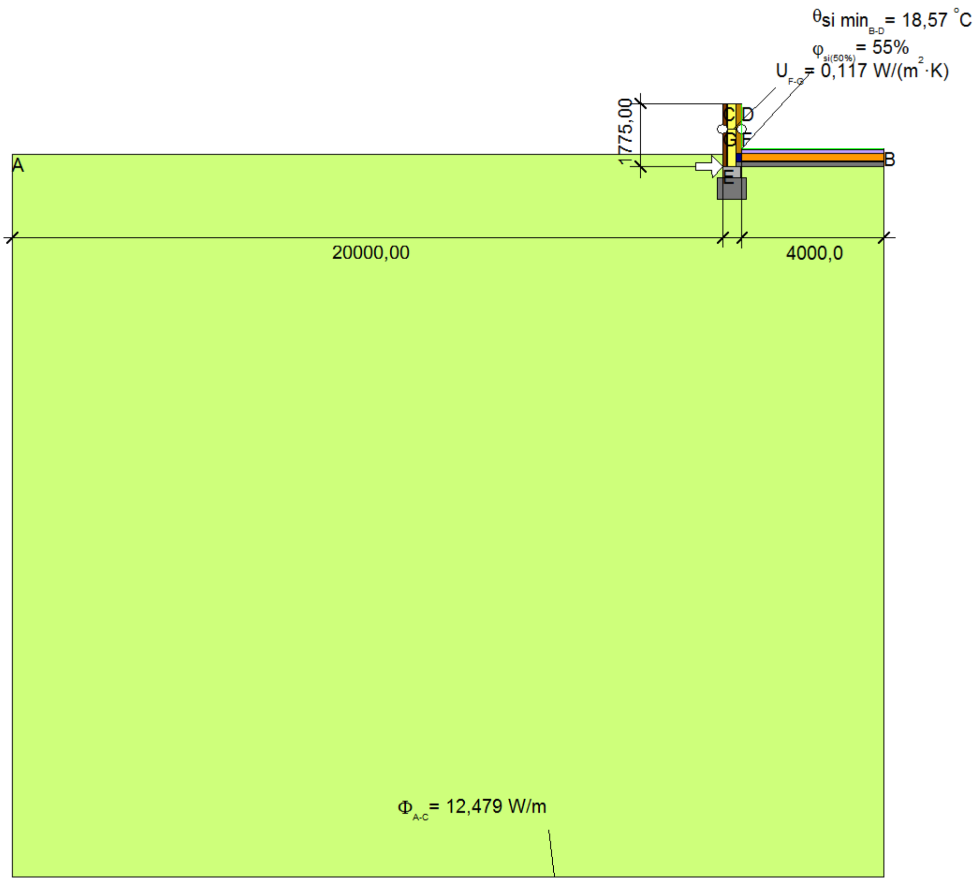


Streamlines



$$\Psi_{A-E-C,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12{,}610}{20{,}000} - \frac{7{,}500}{20{,}000} - 0{,}117 \cdot 1{,}775 = 0{,}048 \text{ W/(m·K)}$$

Figure 40. Results of detail 1.2 (Ytong-Cellular concrete, d = 25 cm).

<table>
<tr><th colspan="4">DETAIL 1.2</th></tr>
<tr><td></td><td>Ψ-Value calculated
0,041 W/(m·K)</td><td>Ψ -EPB regulation
0,05 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

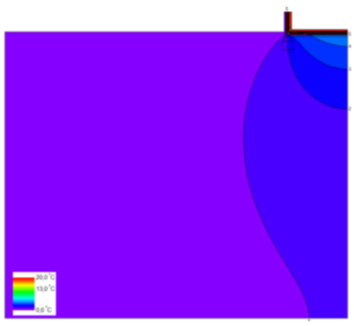
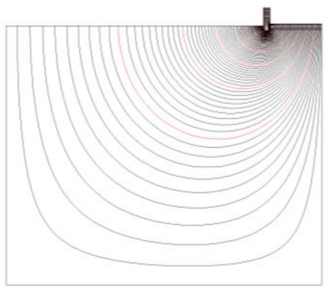
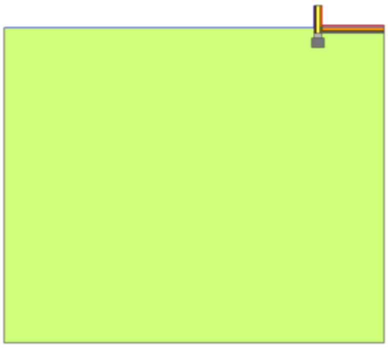
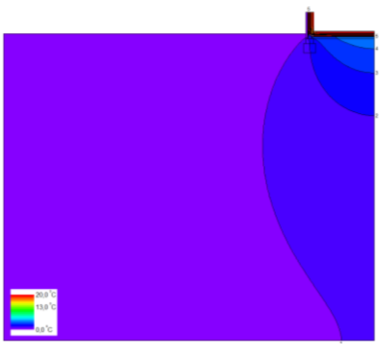
$$\psi_{A-E-C,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12,479}{20,000} - \frac{7,500}{20,000} - 0,117 \cdot 1,775 = 0,041 \text{ W/(m·K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 41. Results of detail 1.3 (Cellular glass, d = 10 cm).

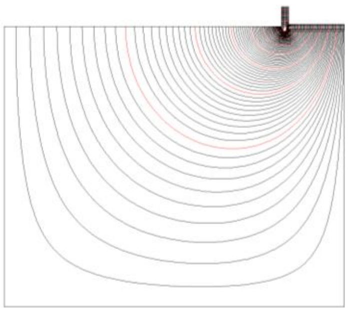
DETAIL 1.3			
	Ψ-Value calculated 0,036 W/(m·K)	Ψ -EPB regulation 0,05 W/(m·K)	ΨPassive Standard 0,01W/(m·K)



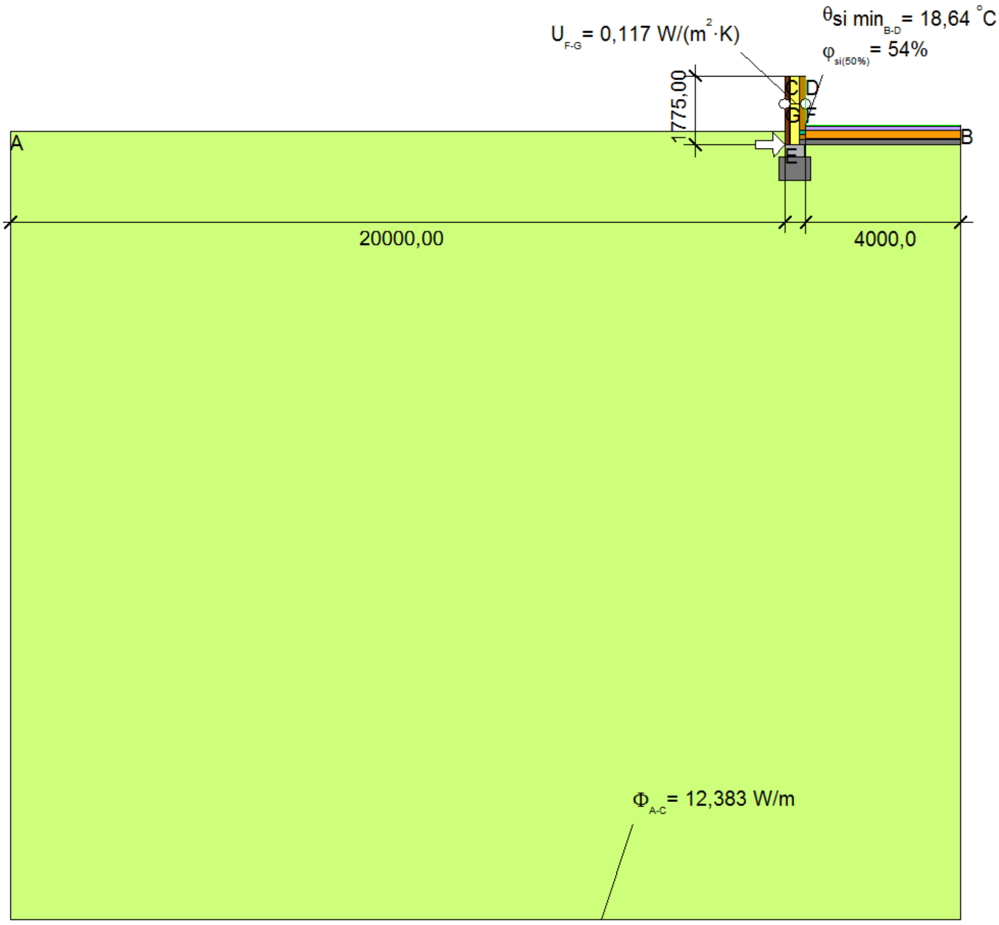
Modeled



ΔT and Isotherms



Streamlines



$$\psi_{A\text{-}E\text{-}C,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12{,}383}{20{,}000} - \frac{7{,}500}{20{,}000} - 0{,}117 \cdot 1{,}775 = 0{,}036 \text{ W/(m·K)}$$

Figure 42. Results of detail 1.4 (Without wall).

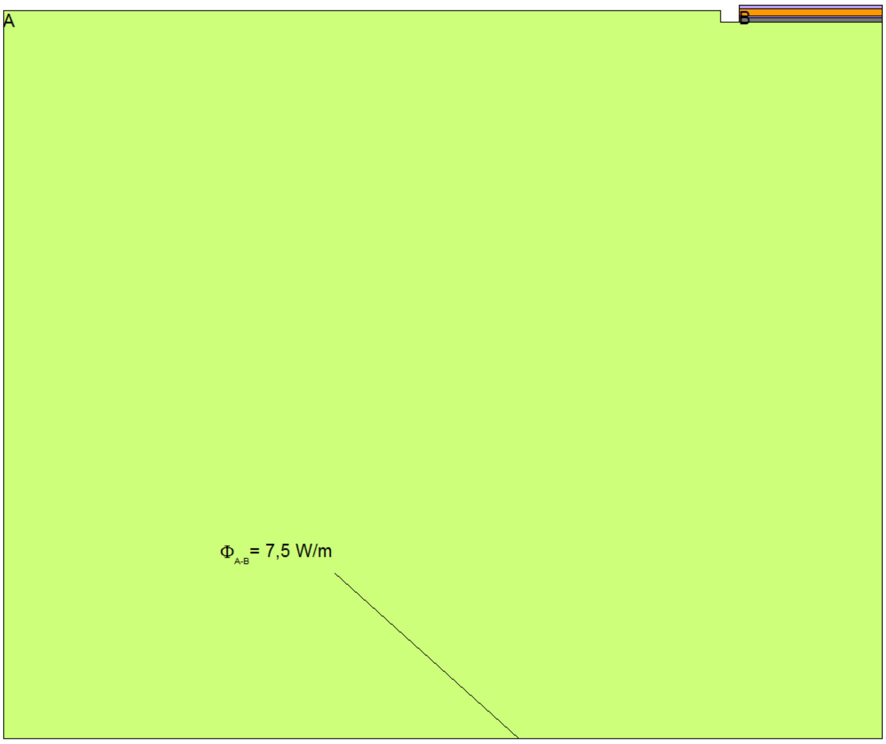
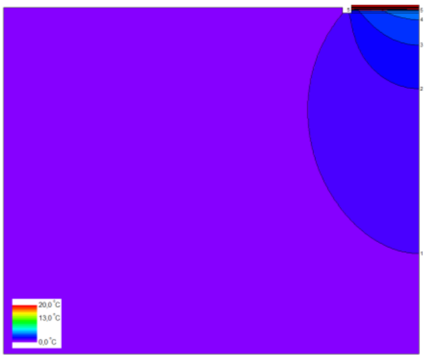
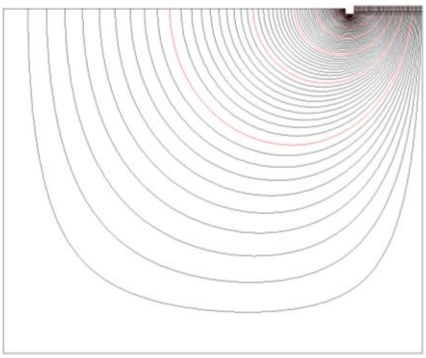
<table>
<tr><th colspan="4">DETAIL 1.4</th></tr>
<tr><td></td><td>Ψ-Value calculated
-</td><td>Ψ-EPB regulation
0,05 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">
</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 43. Results of detail 1.1.1 (Lamdablock, d = 19 cm).

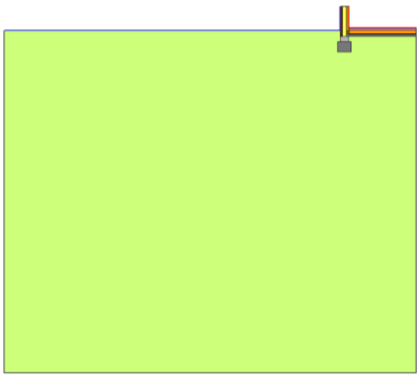
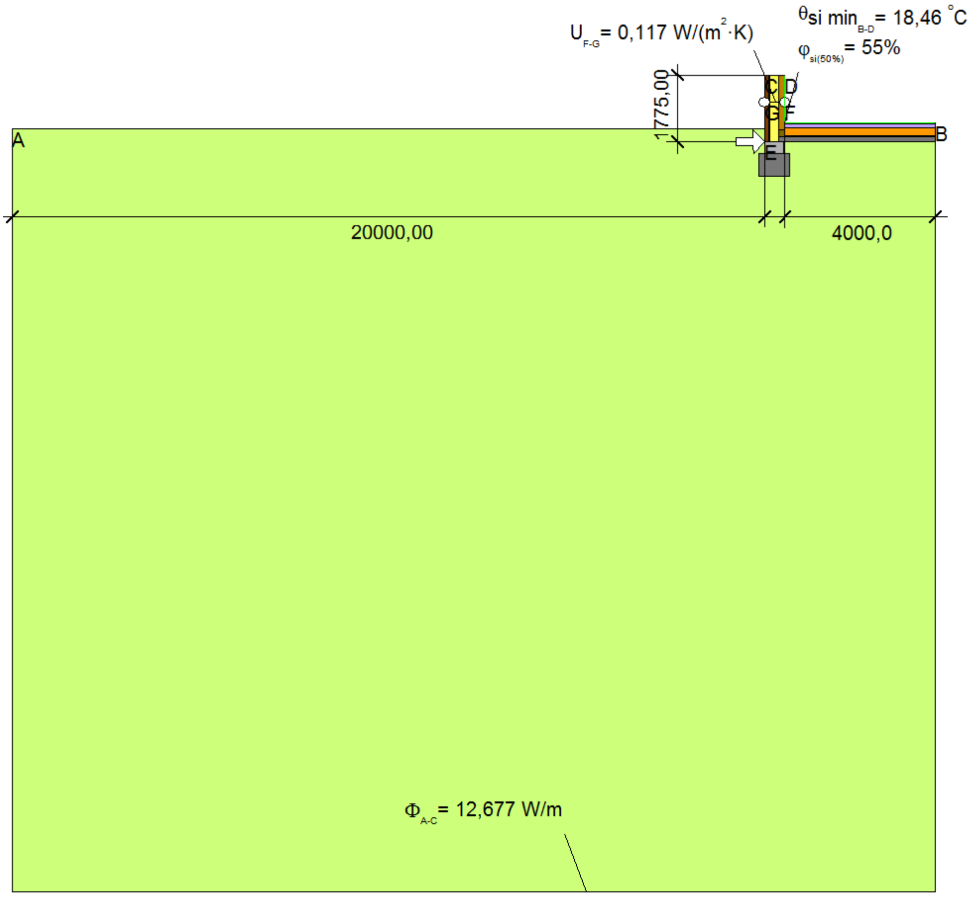
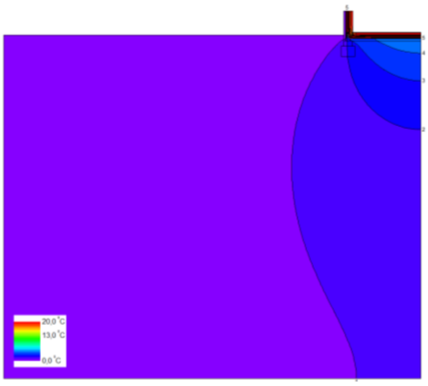
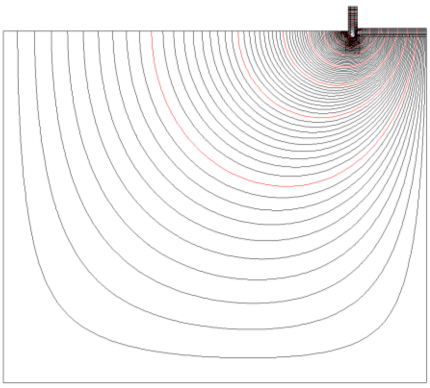
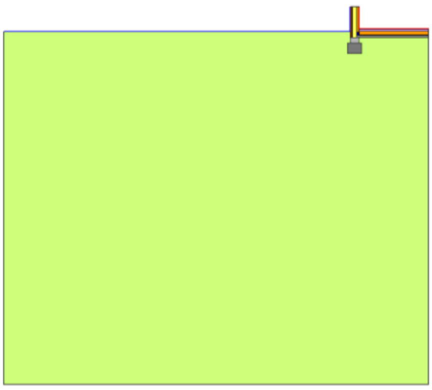
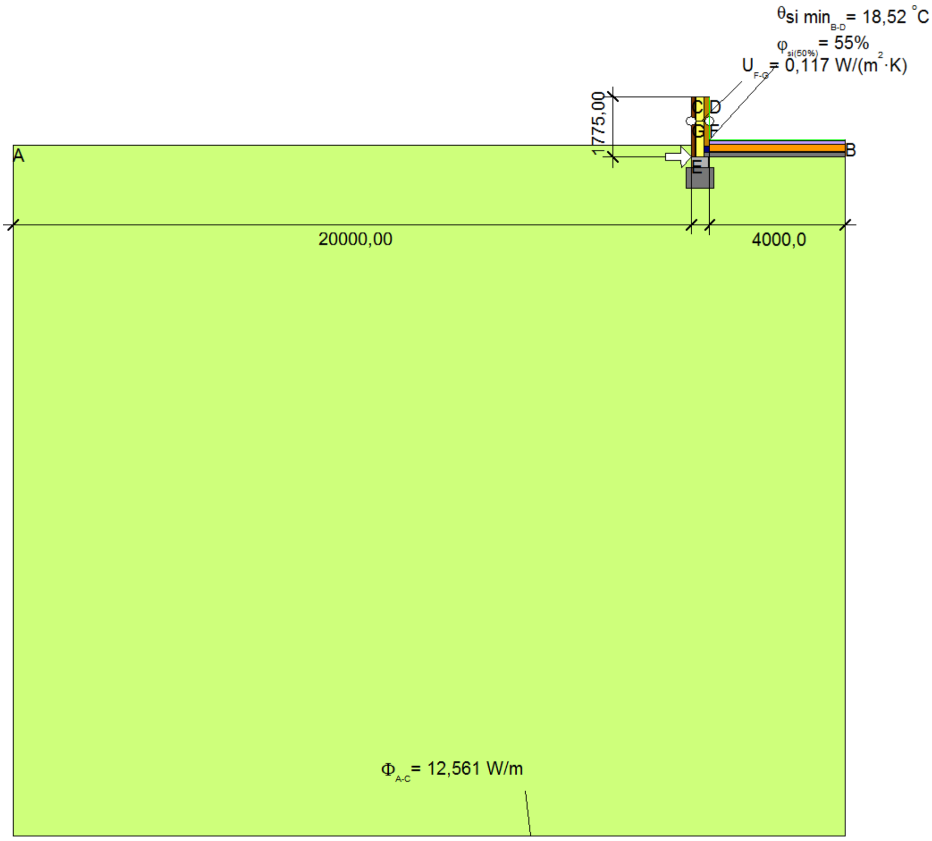
DETAIL 1.1.1			
	Ψ-Value calculated 0,051 W/(m·K)	Ψ-EPB regulation 0,05 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)
 Modeled	 $\Psi_{A-E-C,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2\cdot b_2 = \frac{12,677}{20,000} - \frac{7,500}{20,000} - 0,117\cdot 1,775 = 0,051$ W/(m·K)		
 ΔT and Isotherms			
 Streamlines			

Figure 44. Results of detail 1.2.1 (Ytong-Cellular concrete, d = 20 cm).

<table>
<tr><th colspan="4">DETAIL 1.2.1</th></tr>
<tr><td></td><td>Ψ-Value calculated
0,045 W/(m·K)</td><td>Ψ -EPB regulation
0,05 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

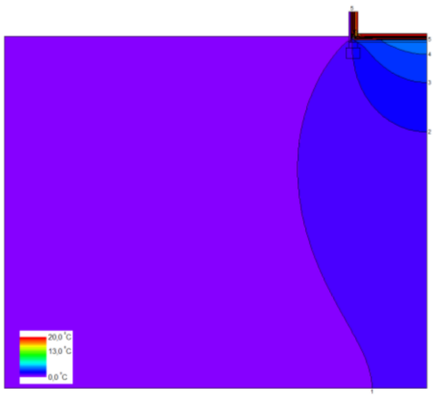
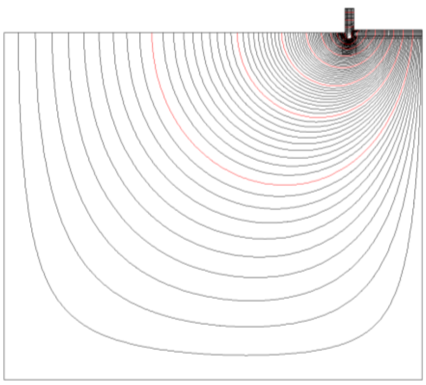
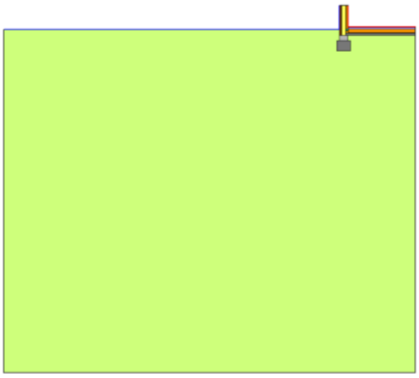
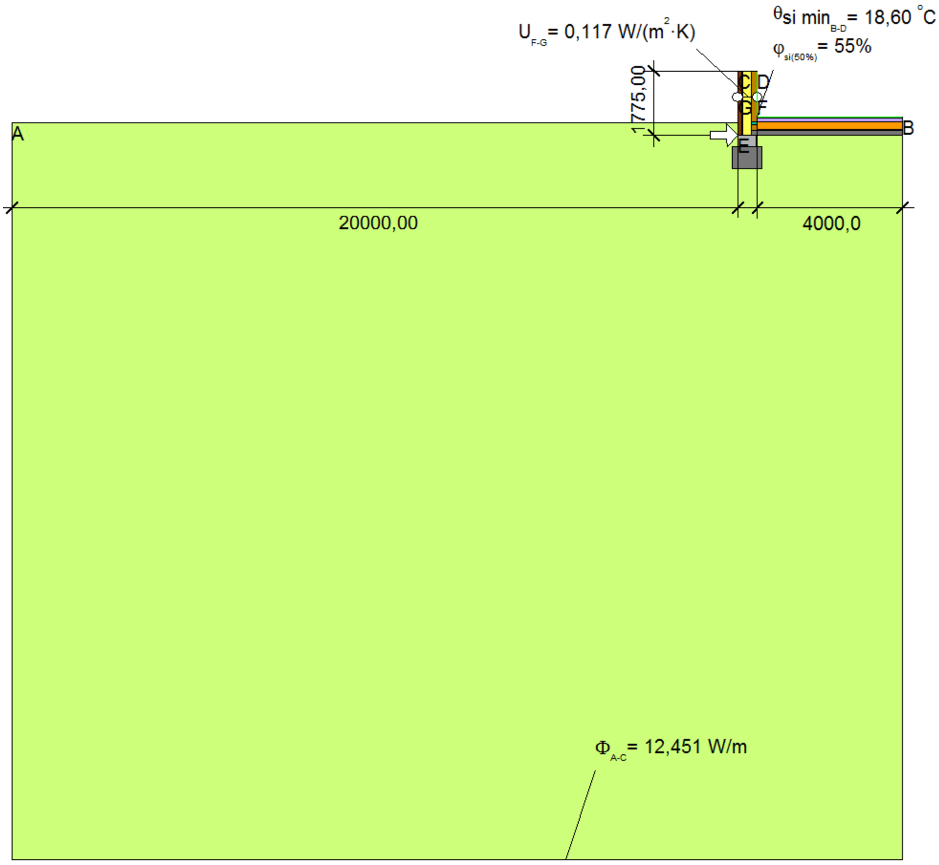
$$\psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12{,}561}{20{,}000} - \frac{7{,}500}{20{,}000} - 0{,}117 \cdot 1{,}775 = 0{,}045 \text{ W/(m·K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 45. Results of detail 1.3.1 (Cellular glass, d = 8 cm).

<table>
<tr><th colspan="4">DETAIL 1.3.1</th></tr>
<tr><td></td><td>Ψ-Value calculated
0,033 W/(m·K)</td><td>Ψ -EPB regulation
0,05 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

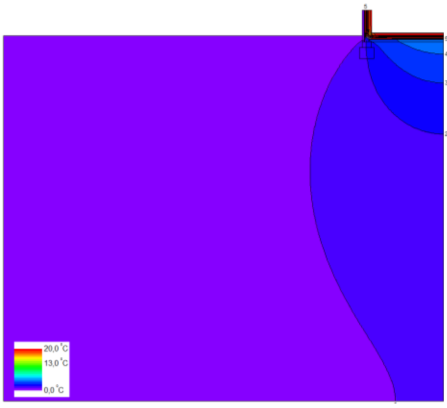
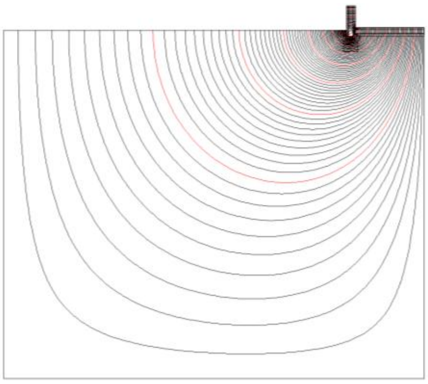
$$\Psi_{A\text{-}E\text{-}C,\cdot} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12,451}{20,000} - \frac{7,500}{20,000} - 0,117 \cdot 1,775 = 0,040 \text{ W/(m·K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Table 7. Summary of results of detail 1.

	λ-value W/(m·K)	Φ obtained W/m	Ψ obtained W/(m·K)	Ψ limit W/(m·K)
Lamdablock 25 cm	0,16	12,610	0,048	0,05
Cellular concrete 25 cm	0,125	12,479	0,041	
Cellular glass 10 cm	0,041	12,102	0,036	
Less thickness on insulation element				
Lamdablock 19 cm	0,16	12,714	0,051	0,05
Cellular concrete 20 cm	0,125	12,604	0,045	
Cellular glass 8 cm	0,041	12,315	0,040	

Detail 1 reaches the requirements of the EPB-regulation for all three insulation elements, but do not fulfill the limit for Passive House standard.

However, differences in Ψ-values depending of the material are noticed. Ψ-value of detail 1 with Lamdablock is 25 % higher than Ψ-value of detail 1 with cellular glass.

Table 7 shows that Ψ-values are 8 % higher in case of smaller insulation thickness.

Lambdablock with 19 cm of thickness seem does not fit with EPB-regulation but with the basic rule 2 of EPB-accepted construction nodes, Lamdablock meets with EPB-regulation as well as using Ytong or cellular glass. The calculation of basic rule 2 of detail 2 is shown on Table 9.

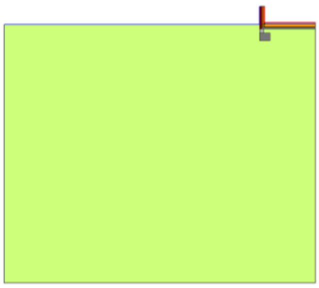
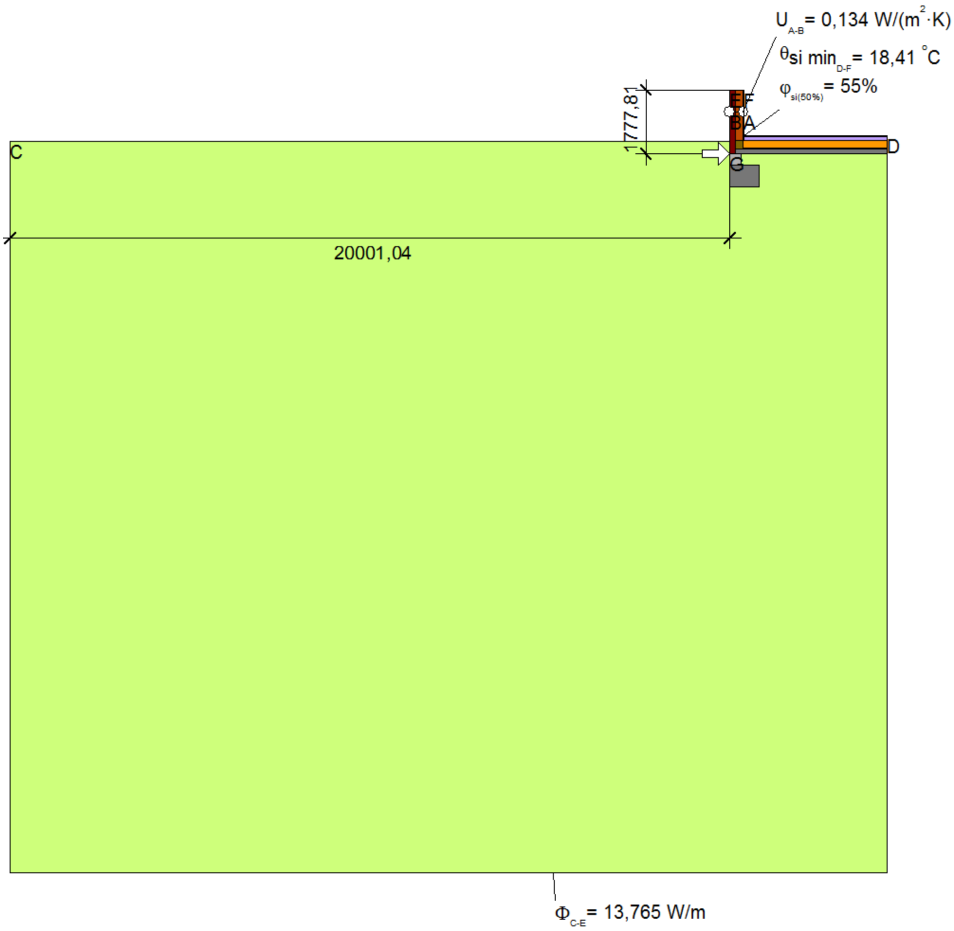
Figure 46 to Figure 51 shows the results for detail 2, i.e. connection external wall to ground floor at the north side of the building. Three different insulated elements are tested to guarantee a continuous insulation layer: Lamdablock (see Figure 46), Ytong cellular concrete (see Figure 47) and cellular glass (see Figure 48). Two possibilities are performed on the calculation: considering the two external layers (calcium silicate brick and unventilated air layer) and replacing it for external ventilated boundary condition (R_{se}= 0,13 m²·K/W)

Table 8 summaries the linear transmittance of the variations of detail 2.

This detail is modeled as explained in section 2.1 EN ISO 10211:2007 to simplify in general.

The Ψ -Value is determined according to equation (2).

Figure 46. Results of detail 2.1(Lamdablock, d=25cm-Without ext. layers).

<table>
<tr><th colspan="4">DETAIL 2.1</th></tr>
<tr><td></td><td>Ψ-Value calculated
0,073 W/(m·K)</td><td>Ψ-EPB regulation
0,05 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

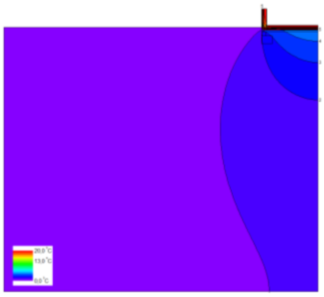
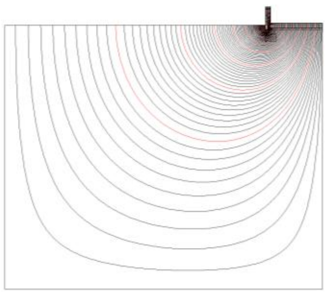
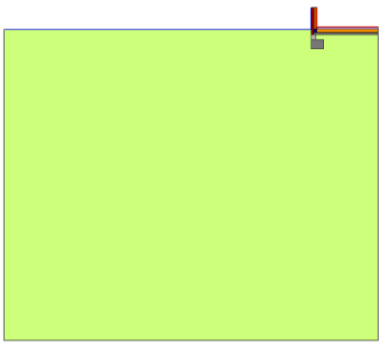
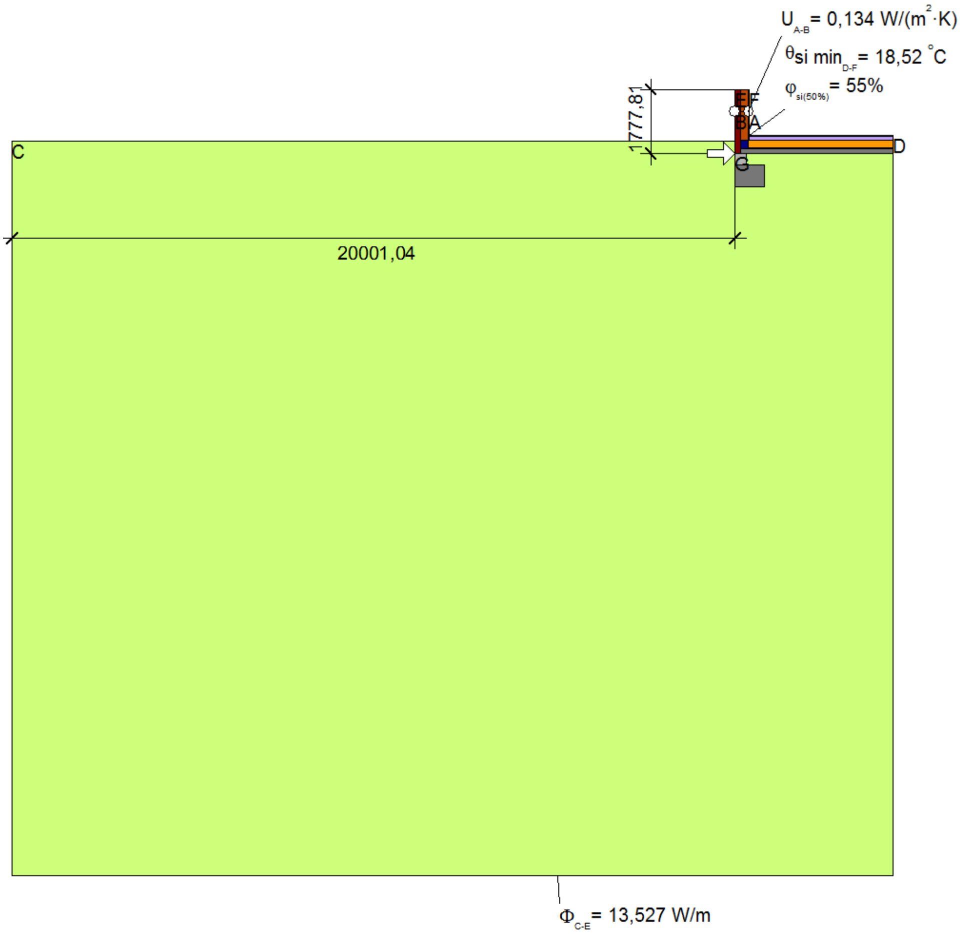
$\Psi_{C\text{-}G\text{-}E,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{13,765}{20,000} - \frac{7,500}{20,000} - 0,135 \cdot 1,778 = 0,073$ W/(m·K)</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 47. Results of detail 2.2(Cell. concrete, d=25cm-Without ext. layers).

<table>
<tr><th colspan="4">DETAIL 2.2</th></tr>
<tr><td></td><td>Ψ-Value calculated
0,061 W/(m·K)</td><td>Ψ-EPB regulation
0,05 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

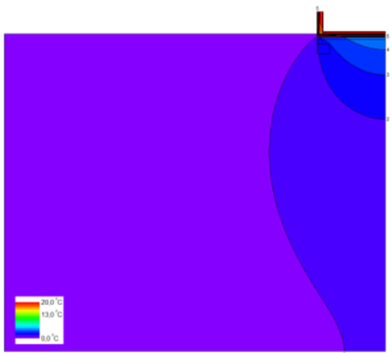
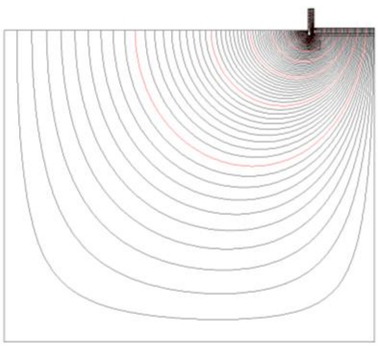
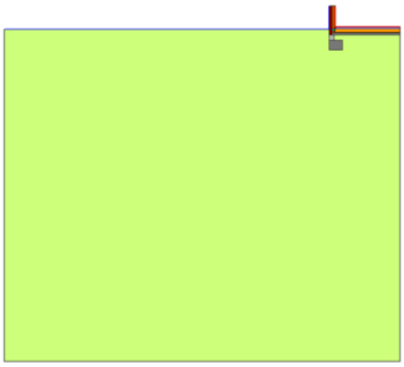
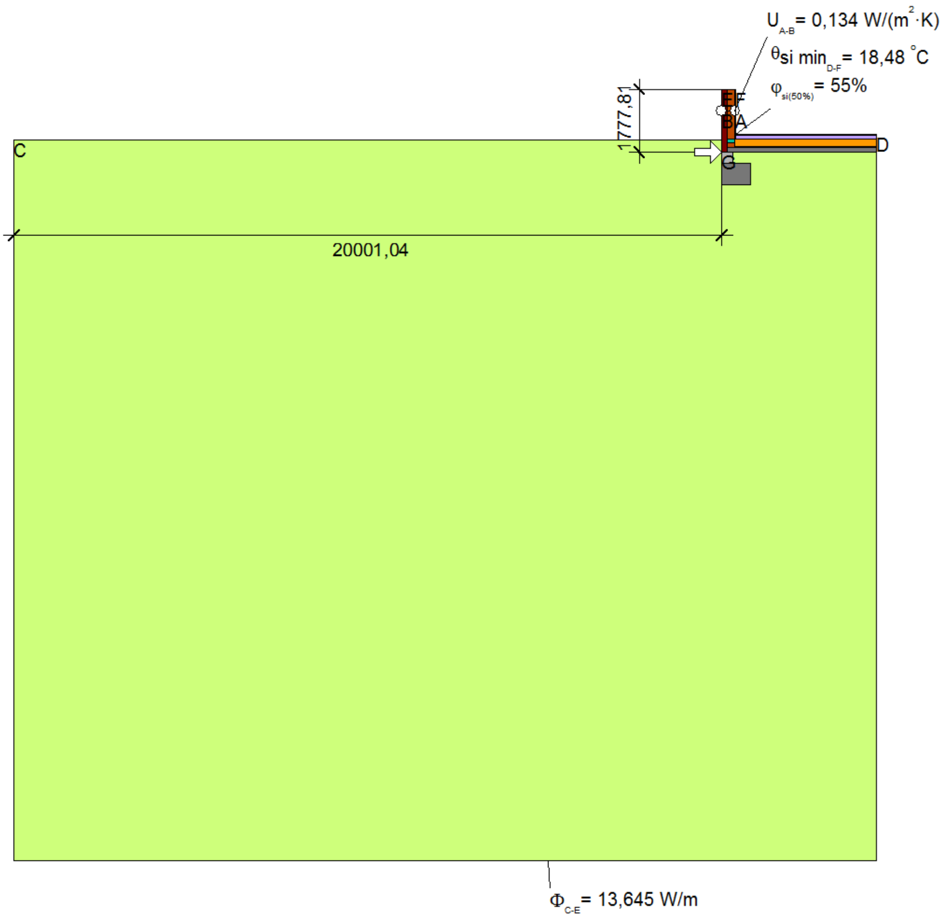
$\Psi_{C-G-E,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{13,527}{20,000} - \frac{7,500}{20,000} - 0,135 \cdot 1,778 = 0,061$ W/(m·K)</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 48. Results Detail 2.3 (Cell. glass, d=10cm-Without ext. layers).

<table>
<tr><th colspan="4">DETAIL 2.3</th></tr>
<tr><td></td><td>Ψ-Value calculated
0,067 W/(m·K)</td><td>Ψ-EPB regulation
0,05 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

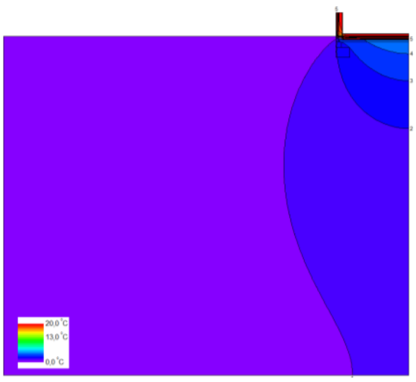
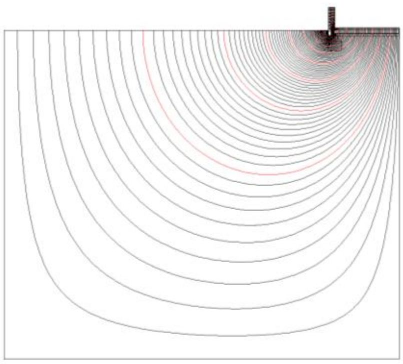
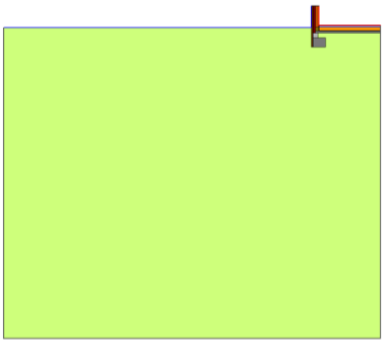
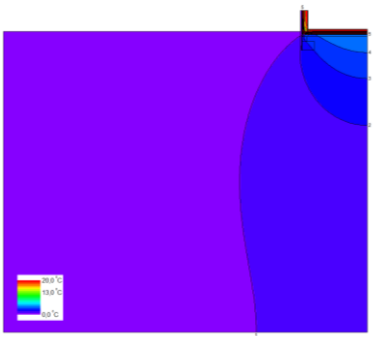
$$\psi_{C\text{-}G\text{-}E.\text{-}} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{13{,}645}{20{,}000} - \frac{7{,}500}{20{,}000} - 0{,}135 \cdot 1{,}778 = 0{,}067\ \mathrm{W/(m \cdot K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 49. Results of detail 2.1.1 (Lamdablock, d=25cm-With ext. layers).

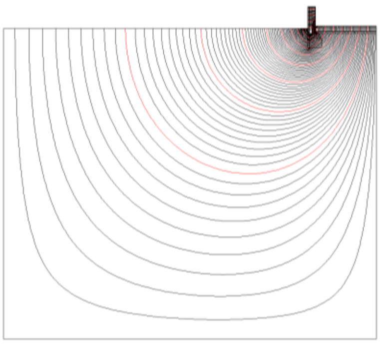
DETAIL 2.1.1			
	Ψ-Value calculated 0,064 W/(m·K)	Ψ-EPB regulation 0,05 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



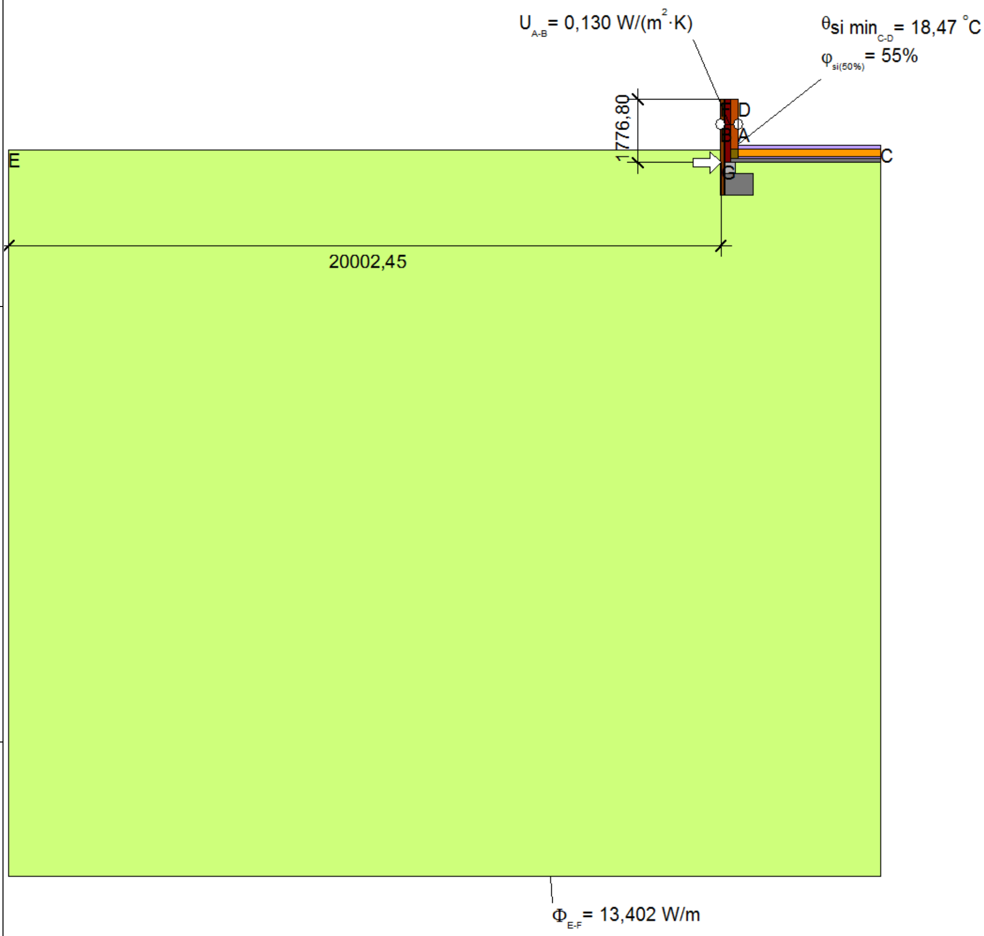
Modeled



ΔT and Isotherms



Streamlines

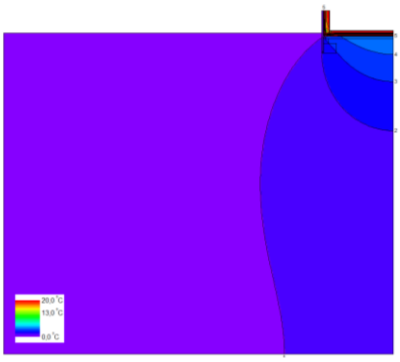


$$\Psi_{E\text{-}G\text{-}F,\text{-}} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{13,402}{20,000} - \frac{7,500}{20,000} - 0,130 \cdot 1,777 = 0,064 \text{ W/(m}\cdot\text{K)}$$

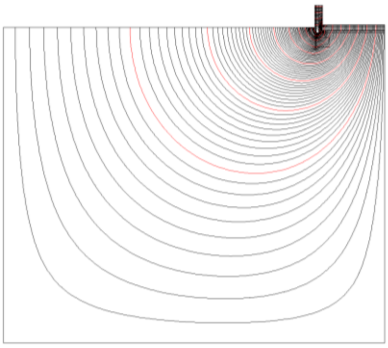
Figure 50. Results of detail 2.2.1(Cell. concrete, d=25cm-With ext. layers).

DETAIL 2.2.1			
	Ψ-Value calculated 0,053 W/(m·K)	Ψ-EPB regulation 0,05 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)

Modeled



ΔT and Isotherms



Streamlines

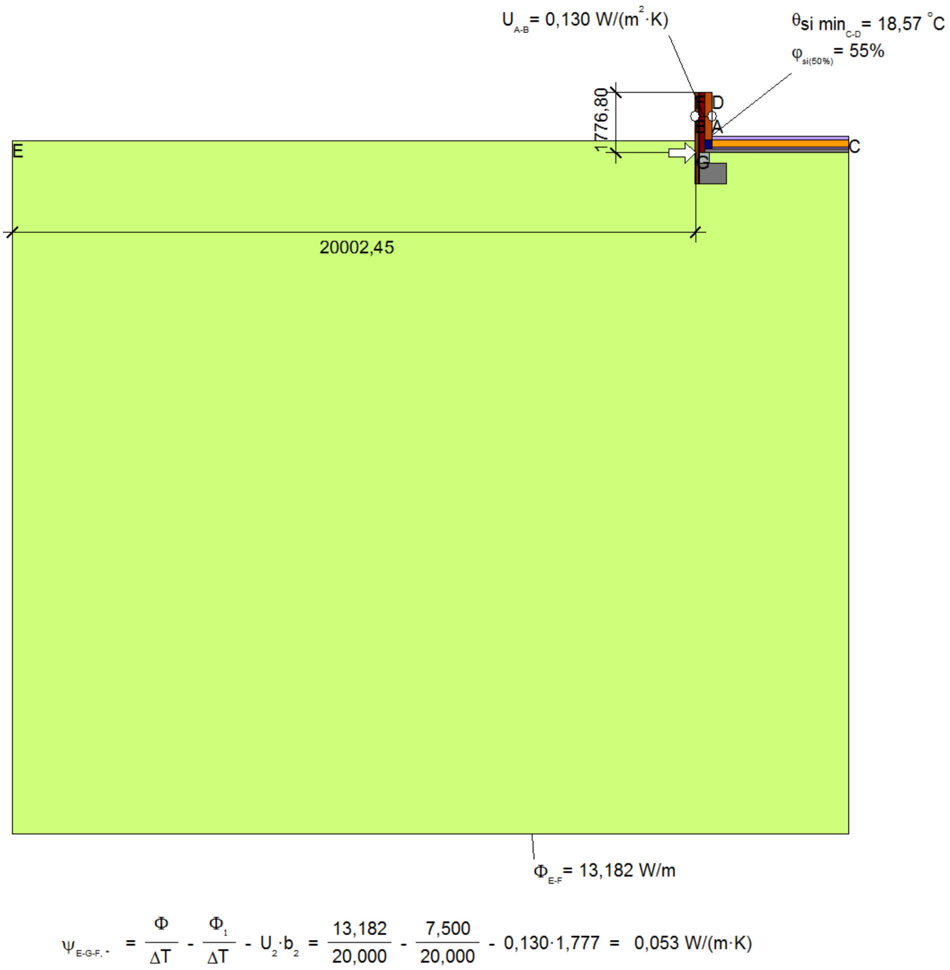
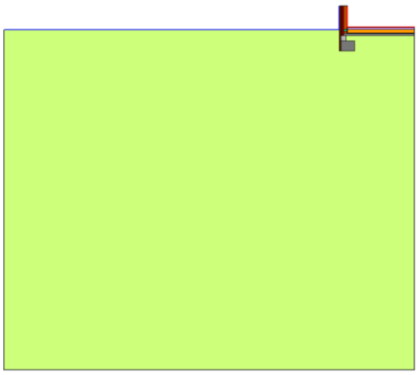
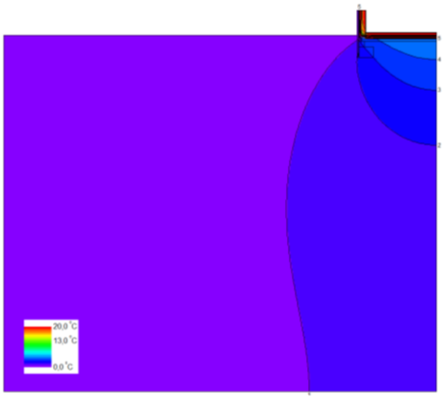


Figure 51. Results of detail 2.3.1 (Cell. glass, d=10cm-With ext. layers).

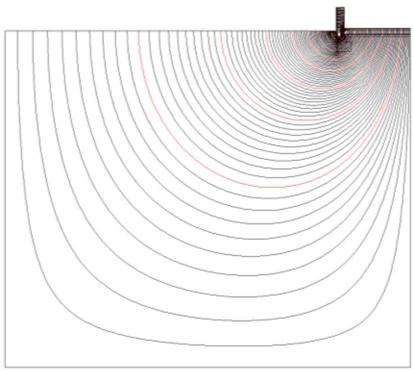
DETAIL 2.3.1			
	Ψ-Value calculated 0,057 W/(m·K)	Ψ-EPB regulation 0,05 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



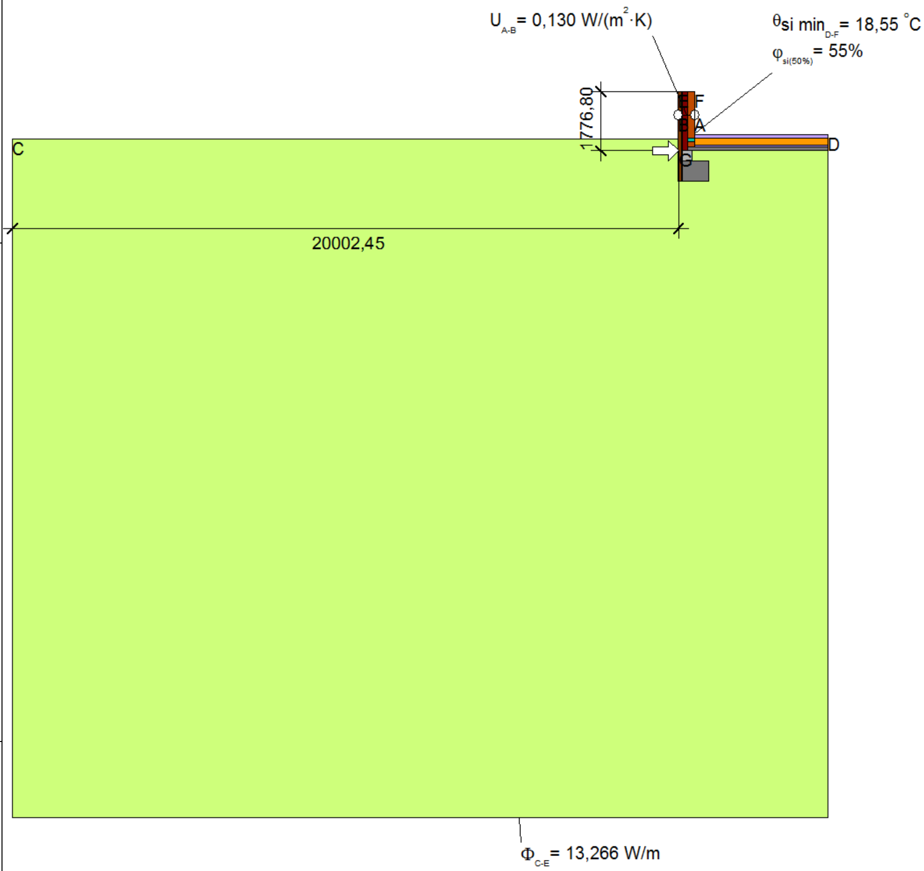
Modeled



ΔT and Isotherms



Streamlines



$$\Psi_{C-G-E,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{13,266}{20,000} - \frac{7,500}{20,000} - 0,130 \cdot 1,777 = 0,057 \text{ W/(m·K)}$$

Table 8. Summary of results of detail 2.

	λ -value W/(m·K)	Φ obtained W/m	Ψ obtained W/(m·K)	Ψ limit W/(m·K)
WITHOUT consider external layers (U = 0,134 W/m²·K)				
Lamdablock 25 cm	0,160	13,765	0,073	0,05
Cellular concrete 25 cm	0,125	13,527	0,061	
Cellular glass 10 cm	0,041	12,866	0,067	
Considering external layers (U = 0,130 W/m²·K)				
Lamdablock 25 cm	0,160	13,402	0,064	0,05
Cellular concrete 25 cm	0,125	13,182	0,053	
Cellular glass 10 cm	0,041	12,561	0,057	

Detail 2 reaches the requirements of the EPB-regulation for all three insulation elements, despite of apparently it may not seem, but no one fulfills the limit for Passive House standard.

However, differences in Ψ-values depending of the material are noticed. Ψ-value of detail 2 with Lamdablock is 10 % higher than Ψ-value of detail 2 with cellular glass.

Table 8 shows that Ψ-values are 15 % lower in case to consider the outer two layers.

It seems like no one's fits with EPB-regulation but with the basic rule 2 (insertion of insulating element) of EPB-accepted construction nodes, all the three insulation elements meet with EPB-regulation.

Table 9 shows the results of apply the basic rule 2.

To obtain thermal resistance:

$$R = d_{\text{insulation}} / \lambda_{\text{insulation}} \ (m^2 \cdot K/W)$$

Table 9. R-value obtained.

	d insulation (m)	λ - Value (W/mK)	R-value (m²K/W)
Resol (R1)	0,16	0,023	7
PUR (R2)	0,20	0,024	8,3
Kind of insulating material used			
Lamdablock	0,25	0,160	1,56
Cellular concrete	0,25	0,125	2

Cellular glass	0,10	0,041	2,44

$$R_{\text{intermediate element}} \geq \min (R_1/2, R_2/2, 2) \geq \min (7/2, 8'3/2, 2)$$

$$R\text{-value} \geq 2 \ m^2{\cdot}K/W$$

At first sight it seems as Lambdablock not-EPB-accepted nodes is accepted as the R-value ≥ 2 m²·K/W. This is one of the important conditions of the EPB-accepted construction nodes (basic rule 2, insertion of insulating elements).

Comparing with Ytong with R=2 m²·K/W it complies narrowly and with cellular glass (R= 2,44 m²·K/W) it fulfill highly.

However, the EPB regulation provides an exception: if the P_{si} value of building node calculated in detail is smaller than the limit value (Table 2), the thermal bridge is accepted.

According the calculation made by Ploegsteert with Trisco (validated program to calculate P_{si}), the P_{si}-values obtained are greatly lower than the limit value, in this case 0,05 W/mK to foundations (see ANNEX B).

The Lambdablock is included on EPB accepted, but for each building should check this one node.

Figure 52 to Figure 54 shows the results for detail 3, i.e. connection window frame to ground floor at the south side of the building. Three different insulated elements are tested to guarantee a continuous insulation layer: Lamdablock (see Figure 52), Ytong cellular concrete (see Figure 53) and cellular glass (see Figure 54).

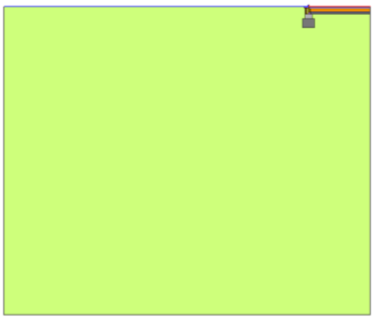
Table 10 summaries the linear transmittance of all the variations of detail 3.

This detail is modeled as explained in section 2.1 EN ISO 10211:2007 to simplify in general.

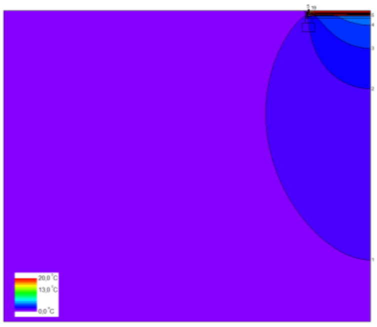
The Ψ -Value is determined according to equation (2).

Figure 52. Results of detail 3.1 (Lamdablock, d = 25 cm).

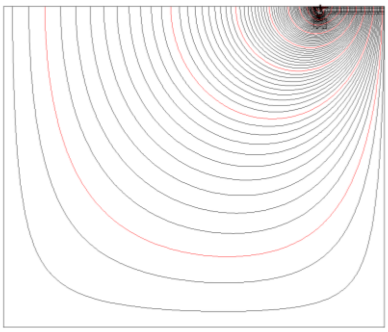
DETAIL 3.1			
	Ψ -Value calculated 0,165 W/(m·K)	Ψ -EPB regulation 0,15 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



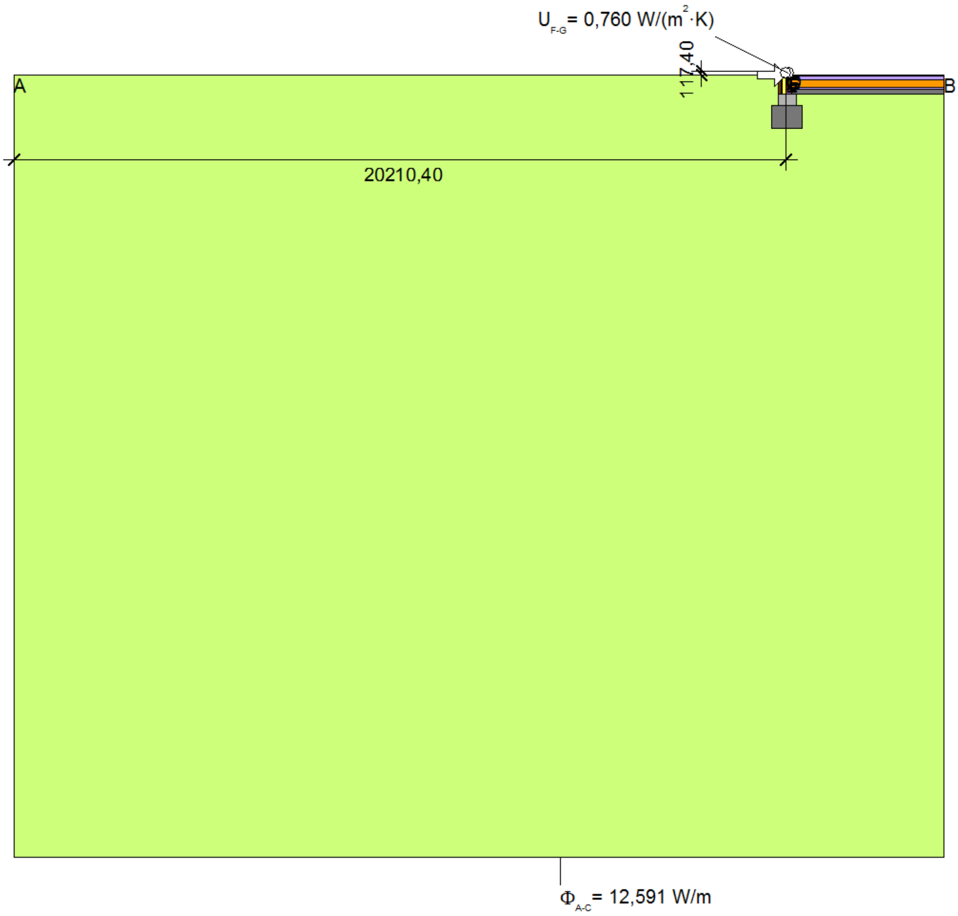
Modeled



ΔT and Isotherms

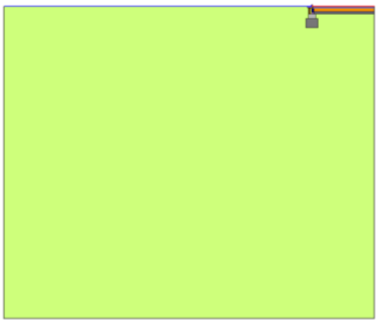
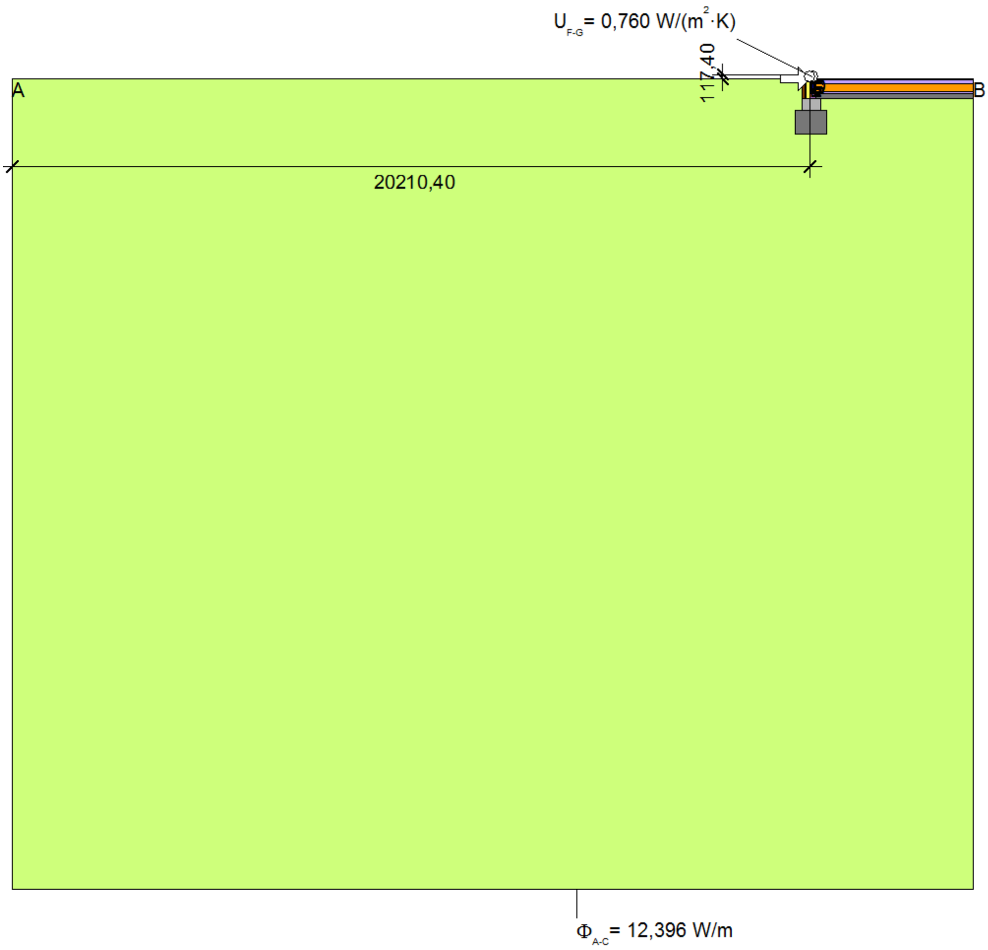


Streamlines



$$\Psi_{A-E-C} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12,591}{20,000} - \frac{7,500}{20,000} - 0,760 \cdot 0,117 = 0,165 \text{ W/(m·K)}$$

Figure 53. Results of detail 3.2 (Ytong Cellular concrete, d = 25 cm).

<table>
<tr><th colspan="4">DETAIL 3.2</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,156 W/(m·K)</td><td>Ψ -EPB regulation
0,15 W/(m·K)</td><td>Ψ Passive Standard
0,01 W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

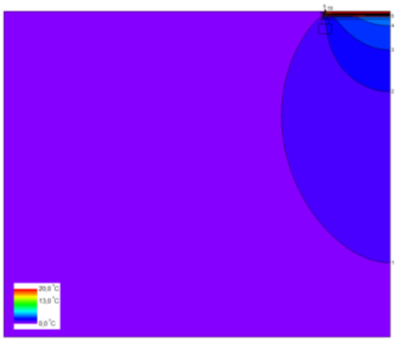
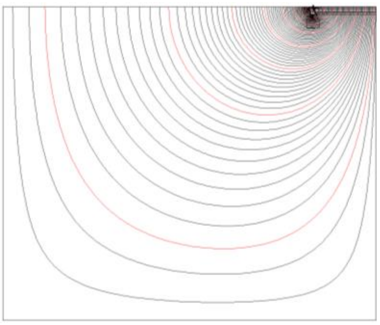
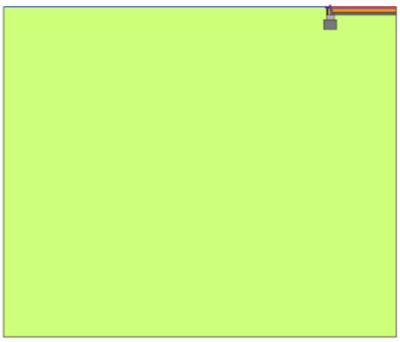
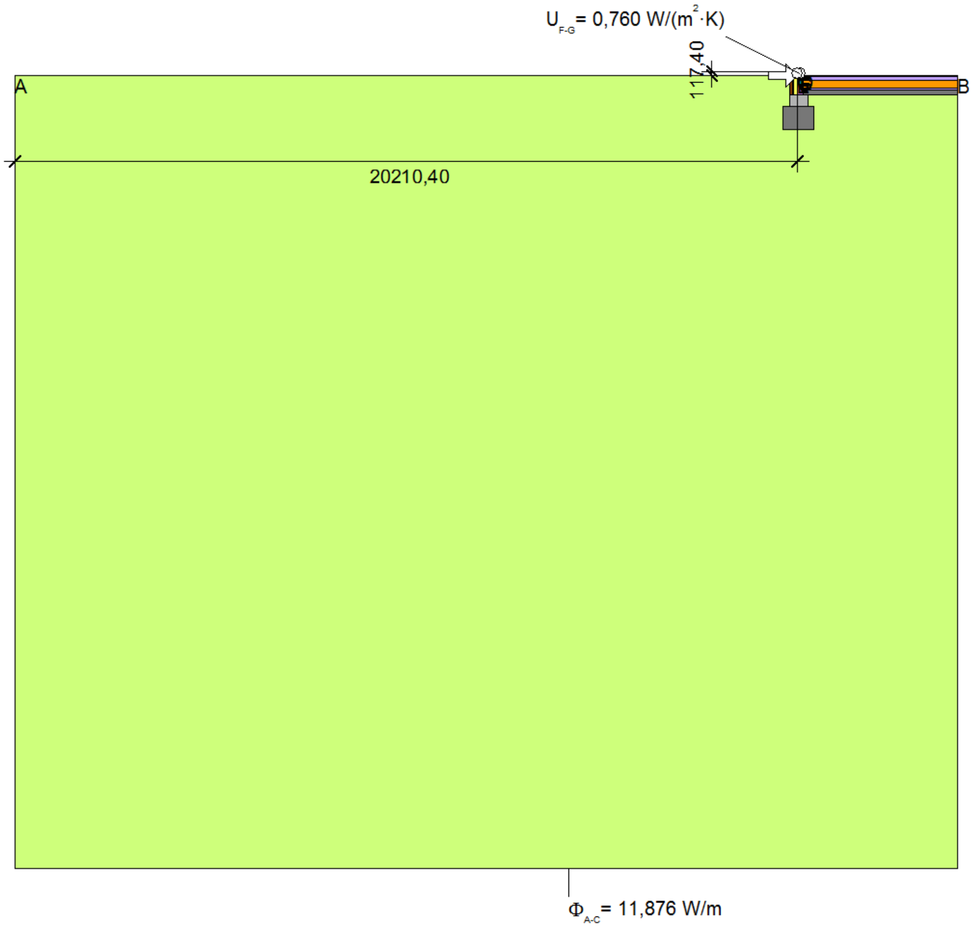
$$\Psi_{A-E-C,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12,396}{20,000} - \frac{7,500}{20,000} - 0,760 \cdot 0,117 = 0,156 \text{ W/(m·K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 54. Results of detail 3.3 (Cellular glass, d = 10 cm).

<table>
<tr><th colspan="4">DETAIL 3.3</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,13 W/(m·K)</td><td>Ψ -EPB regulation
0,15 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

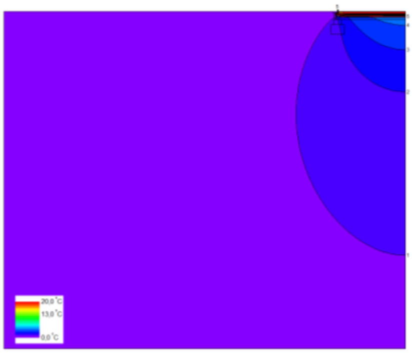
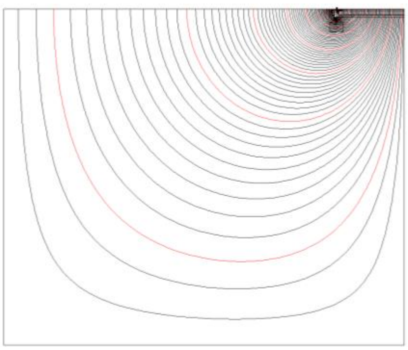
$$\Psi_{A\text{-}E\text{-}C,\,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{11,876}{20,000} - \frac{7,500}{20,000} - 0,760 \cdot 0,117 = 0,130 \text{ W/(m·K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Table 10. Summary of results of detail 3.

	λ -value W/(m·K)	Φ obtained W/m	Ψ obtained W/(m·K)	Ψ limit W/(m·K)
Blue hard stone sill (λ= 3,5 W/(m·K))				
Lamdablock 25 cm	0,160	12,591	0,165	0,15
Cellular concrete 25 cm	0,125	12,396	0,156	
Cellular glass 10 cm	0,041	11,876	0,13	

Detail 3 reaches the requirements of the EPB-regulation for all three insulation elements, despite of apparently Lamdablock and cellular concrete do not seem it, but no one fulfill the limit for Passive House standard.

However, differences in Ψ-values depending of the material are noticed. Ψ-value of detail 3 with Lamdablock is 27 % higher than Ψ-value of detail 3 with cellular glass.

With the basic rule 2 (insertion of insulating element) of EPB-accepted construction nodes, Lamdablock and cellular concrete meets with EPB-regulation.

Table 11 shows the results of apply the basic rule 2.

Table 11. R-value obtained.

	d insulation (m)	λ - Value (W/mK)	R-value (m^2K/W)
PUR (R1)	0,20	0,024	8,3
Kind of insulating material used			
Lamdablock	0,25	0,160	1,56
Cellular concrete	0,25	0,125	2
Cellular glass	0,10	0,041	2,44

$$R_{\text{intermediate element}} \geq \min (R_1/2,\ 1.5) \geq \min (8'3/2,\ 1.5)$$

$$R\text{-value} \geq 1.5\ m^2{\cdot}K/W$$

The Lambdablock and cellular concrete are included on EPB-accepted nodes ($R_{\text{lamdablock}}$ = 1,56 $m^2{\cdot}K/W$ and $R_{\text{Ytong kimblock}}$ = 2 $m^2{\cdot}K/W$ > 1,5 $m^2{\cdot}K/W$).

Figure 55 to Figure 57 shows the results for detail 4, i.e. connection door frame to ground floor at the front side of the building. Three different insulated elements are tested to guarantee a continuous insulation layer: Lamdablock (Figure 55), Ytong cellular concrete (see Figure 56) and cellular glass (see Figure 57).

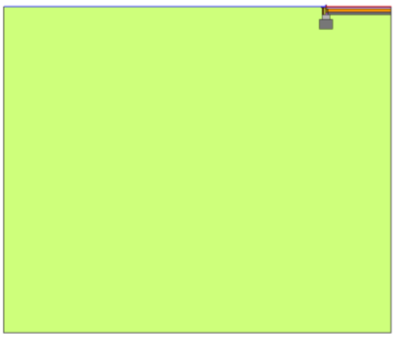
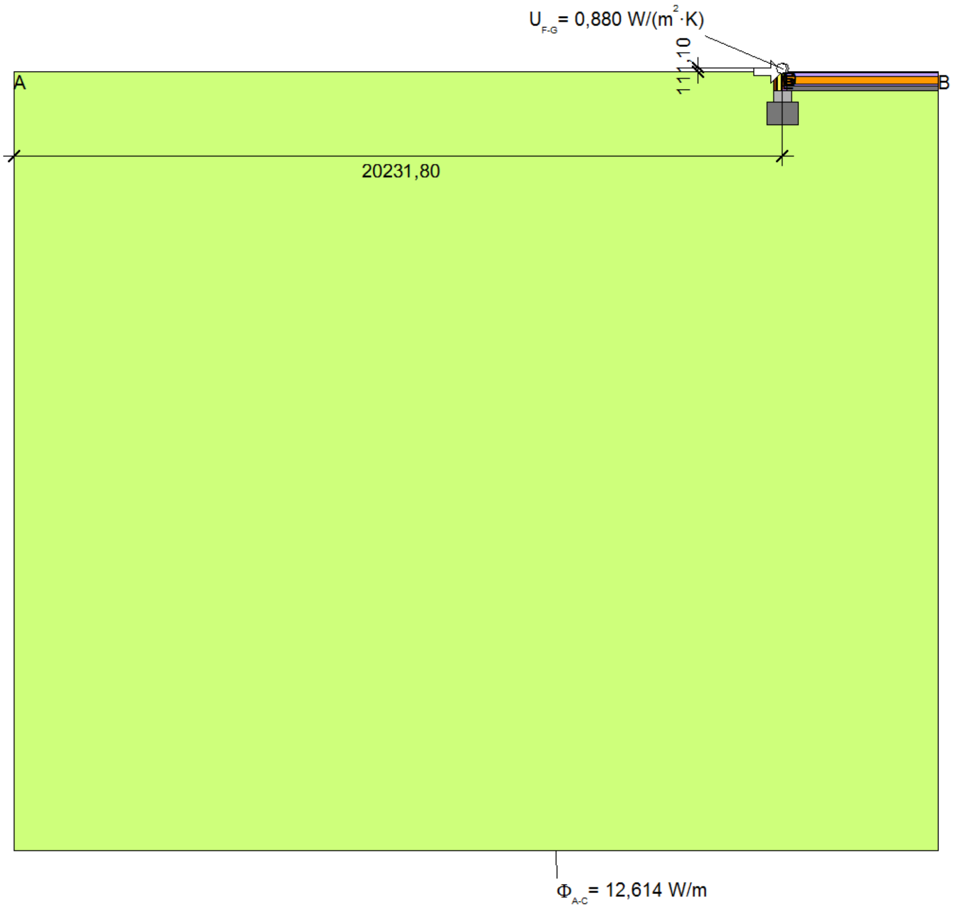
The construction elements are the same than detail 3 but changing the kind of frame (λ-window frame = 0,075 W/mK and λ-door frame = 0,057 W/mK).

Table 12 summaries the linear transmittance of all the variations of detail 4 and of detail 3 to compare them.

This detail is modeled as explained in section 2.1 EN ISO 10211:2007 to simplify in general.

The Ψ -Value is determined according to equation (2).

Figure 55. Results of detail 4.1 (Lamdablock, d = 25 cm).

<table>
<tr><th colspan="4">DETAIL 4.1</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,158 W/(m·K)</td><td>Ψ-EPB regulation
0,15 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

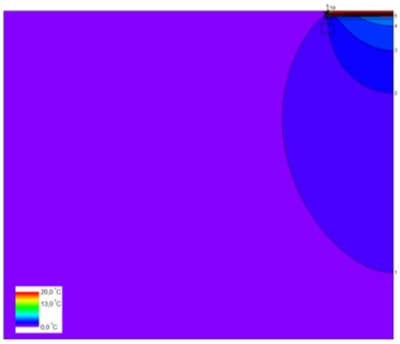
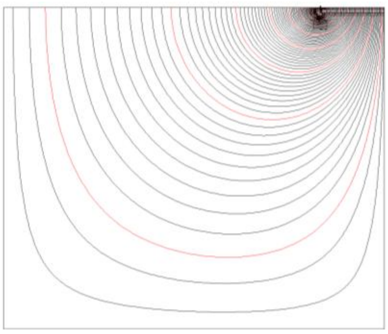
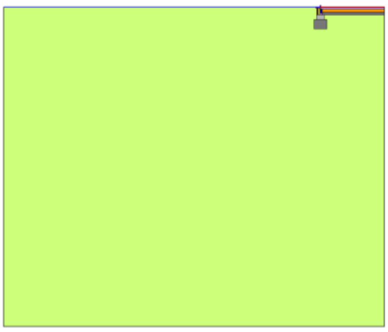
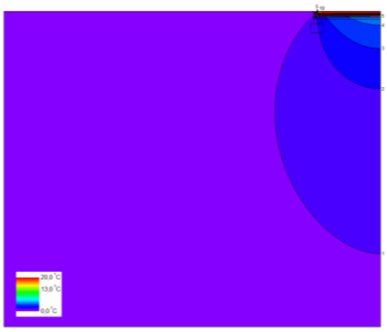
$$\psi_{A\text{-}E\text{-}C,\text{-}} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12{,}614}{20{,}000} - \frac{7{,}500}{20{,}000} - 0{,}880 \cdot 0{,}111 = 0{,}158 \text{ W/(m·K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 56. Results of detail 4.2 (Ytong-cellular concrete, d = 25 cm).

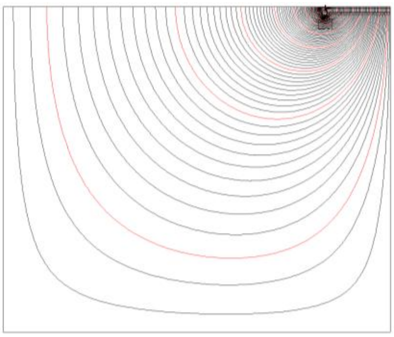
DETAIL 4.2			
	Ψ -Value calculated 0,148 W/(m·K)	Ψ -EPB regulation 0,15 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



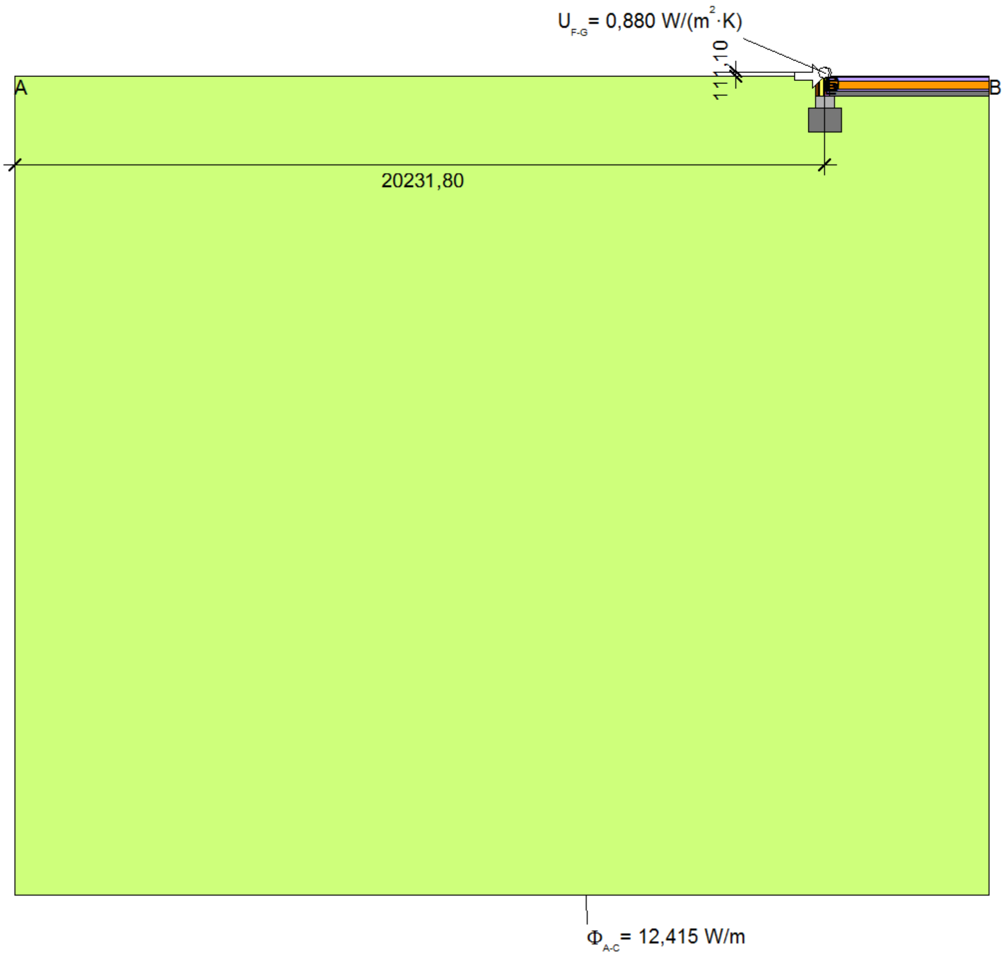
Modeled



ΔT and Isotherms



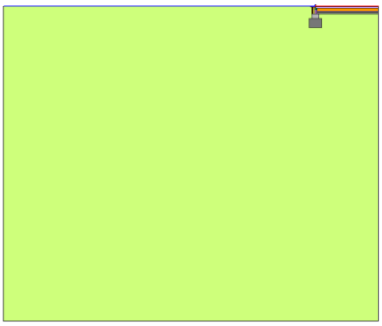
Streamlines



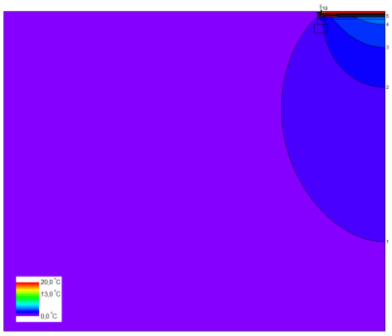
$$\Psi_{A\text{-}E\text{-}C,-} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{12,415}{20,000} - \frac{7,500}{20,000} - 0,880 \cdot 0,111 = 0,148 \text{ W/(m·K)}$$

Figure 57. Results of detail 4.3 (Cellular glass, d = 10 cm).

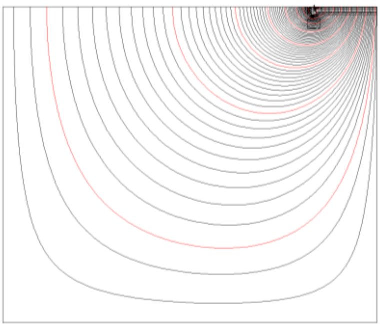
DETAIL 4.3			
	Ψ -Value calculated 0,122 W/(m·K)	Ψ -EPB regulation 0,15 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



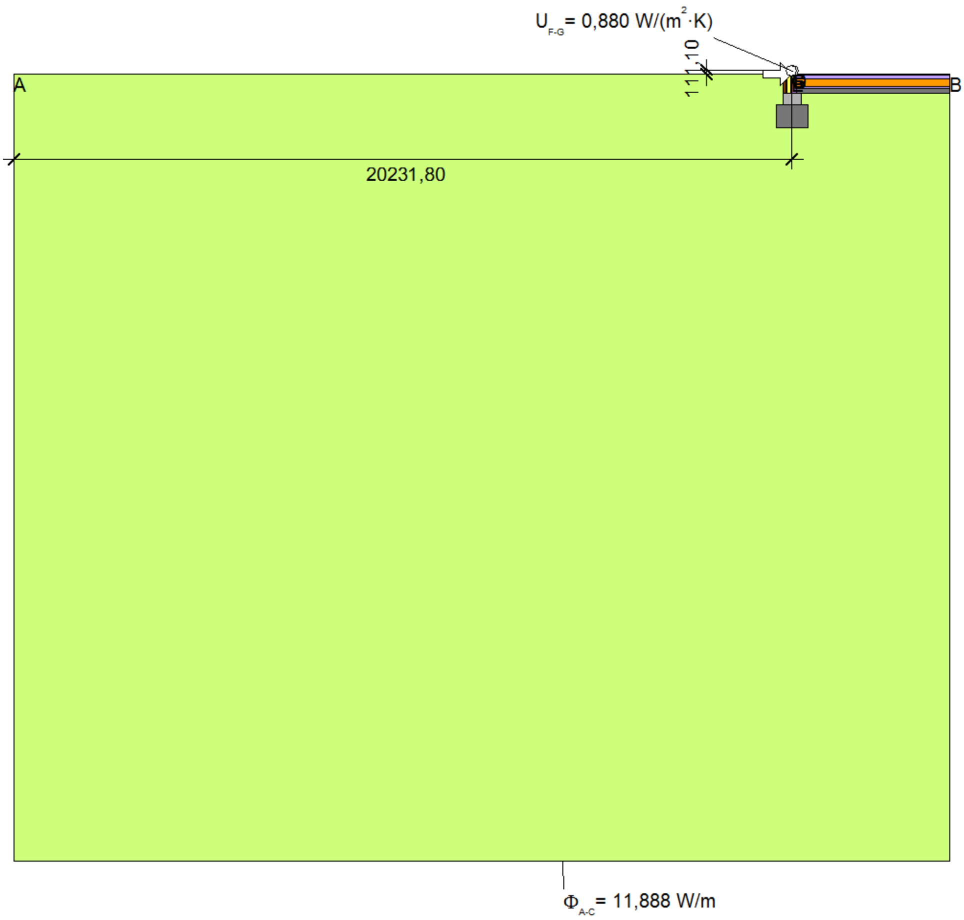
Modeled



ΔT and Isotherms



Streamlines



$$\Psi_{A\text{-}E\text{-}C,\text{-}} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{11{,}888}{20{,}000} - \frac{7{,}500}{20{,}000} - 0{,}880 \cdot 0{,}111 = 0{,}122 \text{ W/(m·K)}$$

Table 12. Summary of results of detail 4 (Comparing results with detail 3).

	λ -value W/(m·K)	Φ obtained W/m	Ψ obtained W/(m·K)	Ψ limit W/(m·K)
D.4 λ door frame = 0,057 W/(m·K)) → U = 0,88 W/m²·K				
Lamdablock 25 cm	0,160	12,614	0,158	0,15
Cellular concrete 25 cm	0,125	12,415	0,148	
Cellular glass 10 cm	0,041	11,888	0,122	
D.3 λ window frame = 0,075 W/(m·K)) → U = 0,76 W/m²·K				
Lamdablock 25 cm	0,160	12,591	0,165	0,15
Cellular concrete 25 cm	0,125	12,396	0,156	
Cellular glass 10 cm	0,041	11,876	0,13	

Detail 4 reaches the requirements of the EPB-regulation for all three insulation elements, despite of apparently lamdablock does not seem it, but no one fulfill the limit for Passive House standard.

However, differences in Ψ-values depending of the material are noticed. Ψ-value of detail 4 with Lamdablock is 28 % higher than Ψ-value of detail 4 with cellular glass.

Table 12 shows that Ψ-values are 5 % higher on detail 3 which U-frame is lower than U-frame of detail 4.

With the basic rule 2 (insertion of insulating element) of EPB-accepted construction nodes, Lamdablock meets with EPB-regulation.

Table 11 shows the results of apply the basic rule 2.

The Lambdablock is included on EPB-accepted nodes ($R_{\text{lamdablock}}$ = 1,56 m²·K/W > 1,5 m²·K/W).

4.1.2. Roof connections

Thermal bridges in the roof are studied in this paragraph. Each figure shows the calculation model, isotherms and streamlines, total heat flux, linear transmittance Ψ and the limits in EPB-regulation and passive house standard.

The legends of the materials, boundary conditions, streamlines and isotherms are given in ANNEX A.

Figure 59 and Figure 60 show the results for detail 5, i.e. connection external wall to sloping roof at the front side of the building. Timber is used to guarantee a continuous insulation layer. Considering the first floor and replacing it by interior, section boundary conditions are tested.

Figure 58. Detail 5 (location cut off of first floor).

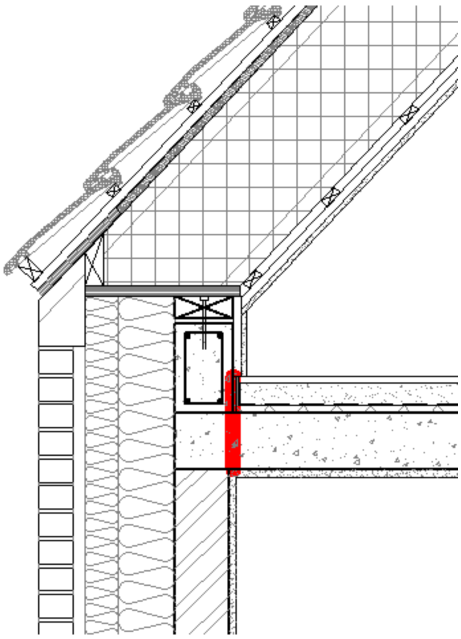


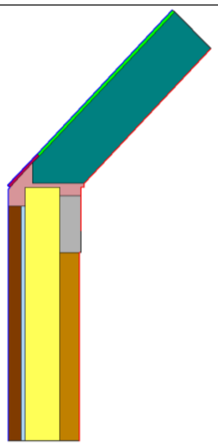
Table 13 summaries the linear transmittance of detail 5. It shows there is practically no relevance on both calculation possibilities as the two sides of the first floor (up and down) are indoors (see Figure 60).

This detail is modeled as explained in section 2.1 EN ISO 10211:2007 to simplify in general and section 2.2 ISO 6946:2007 to simplify the sloping roof.

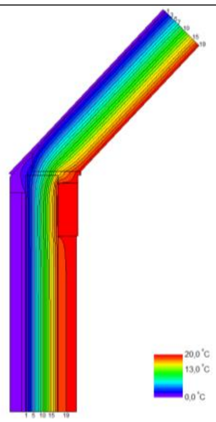
The Ψ -Value is determined according to equation (1).

Figure 59. Results of detail 5 (Simplified).

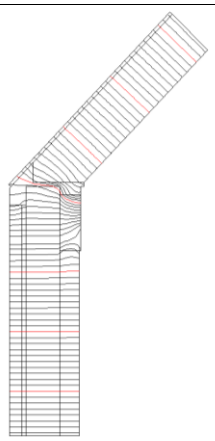
DETAIL 5			
	Ψ -Value calculated -0,004 W/(m·K)	Ψ -EPB regulation 0,00W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



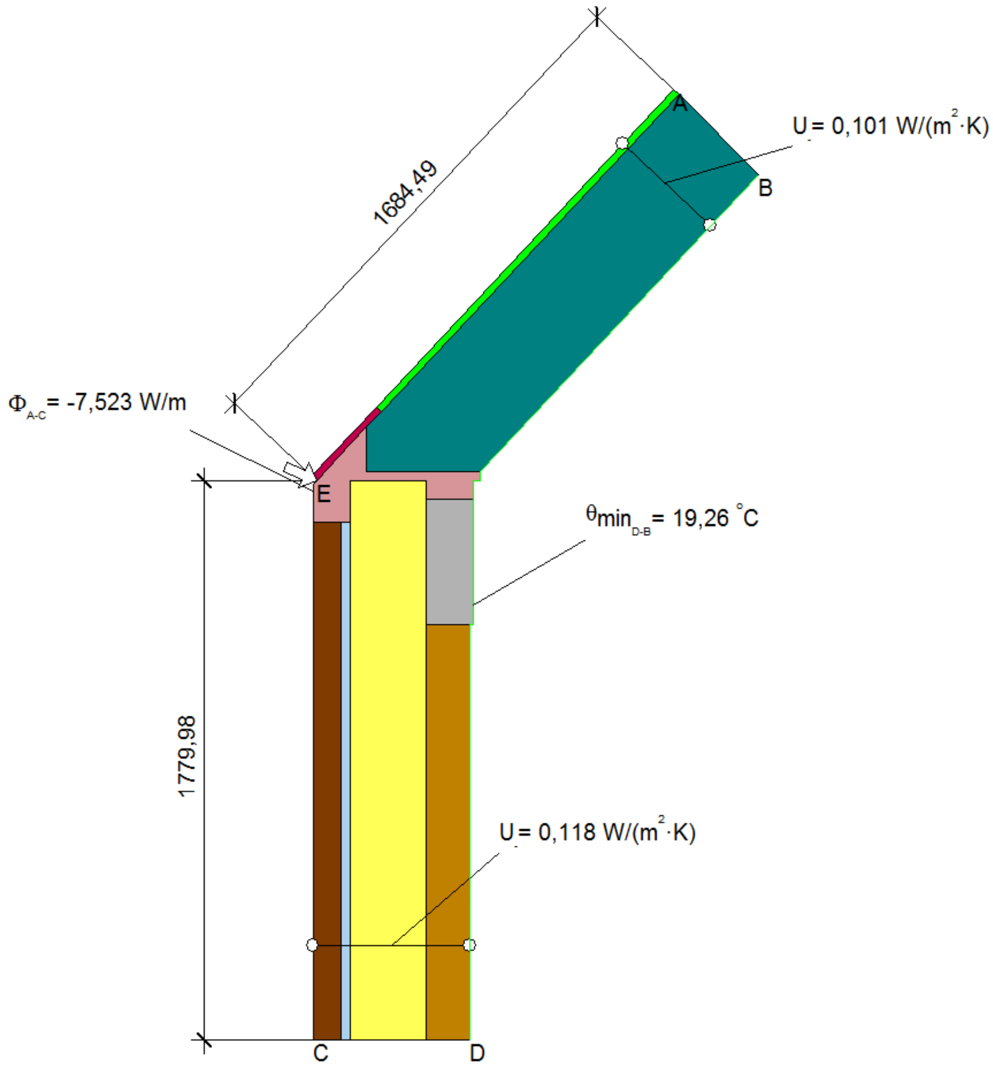
Modeled



ΔT and Isotherms

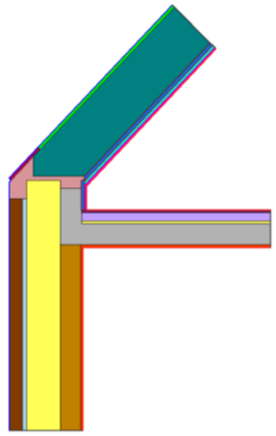
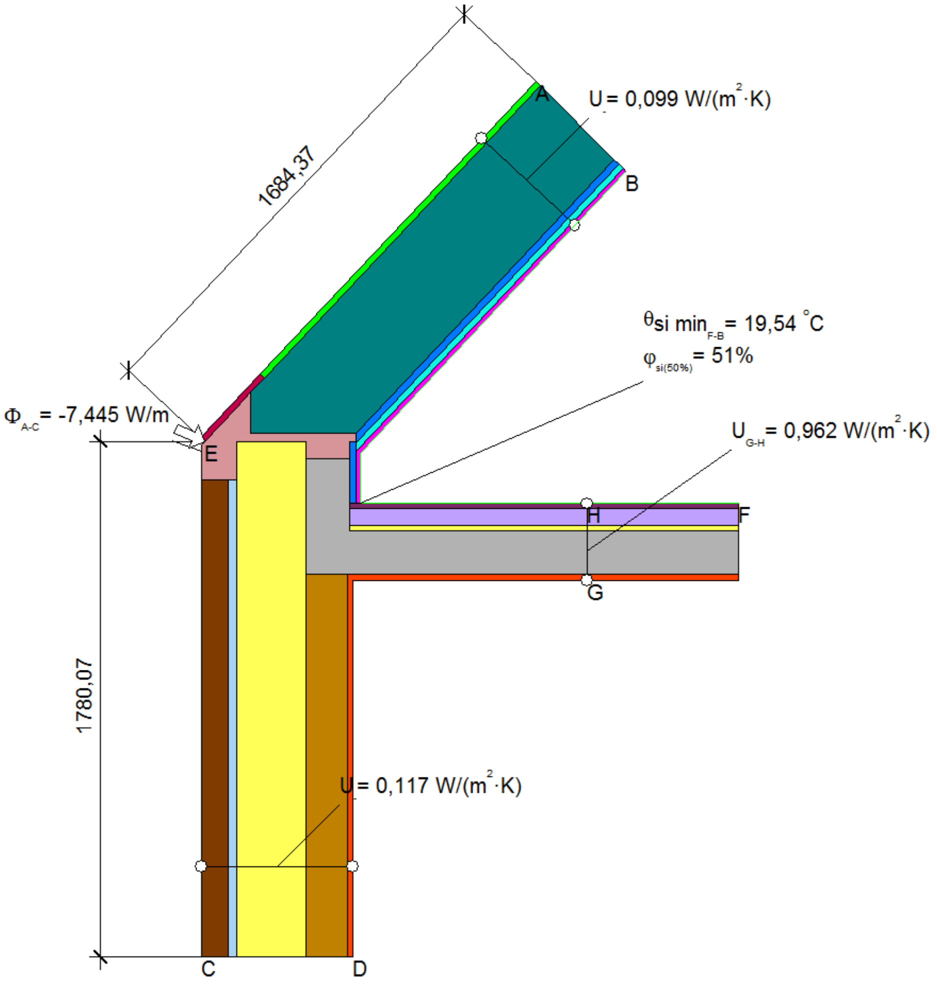


Streamlines



$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{7{,}523}{20{,}000} - 0{,}101 \cdot 1{,}684 - 0{,}118 \cdot 1{,}780 = -0{,}004 \text{ W/(m·K)}$$

Figure 60. Results Detail 5.1 (Considering first floor).

<table>
<tr><th colspan="4">DETAIL 5.1</th></tr>
<tr><td></td><td>Ψ -Value calculated
-0,003 W/(m·K)</td><td>Ψ -EPB regulation
0,00W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

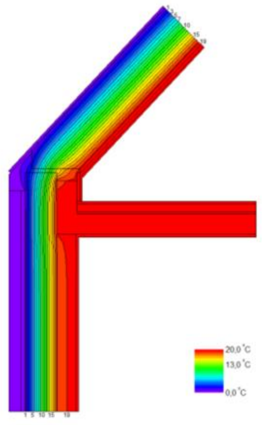
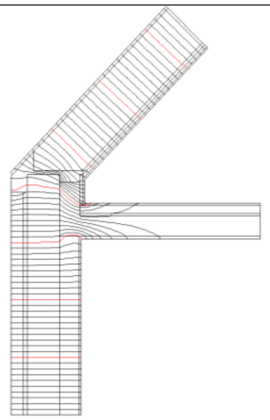
$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1\cdot b_1 - U_2\cdot b_2 = \frac{7,445}{20,000} - 0,099\cdot 1,684 - 0,117\cdot 1,780 = -0,003 \text{ W/(m·K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Table 13. Summary of results of detail 5.

	U-wall W/(m²K)	U-roof W/(m²K)	Φ obtained W/m	Ψ obtained W/(mK)	Ψ limit W/(mK)
D.5 Simplified	0,118	0,101	7,523	-0,004	0,00
D.5.1 Considering first floor	0,117	0,099	7,445	-0,003	

Detail 5 reaches the requirements of the EPB-regulation and the limit for Passive House standard.

Table 13 shows that Ψ-values are negatives. It is due to choose the most external option to determining the linear thermal transmittance according EPB-regulation point 7. *Berekening van U- en X-waarden.*

Glass wool with λ-value =0,032 W/(mK) and cellulose with λ -value =0,039 W/(mK) give the good result of Ψ-value obtained.

Figure 61 shows the results for detail 6, i.e. connection both sides of the sloping roof at the top of the building.

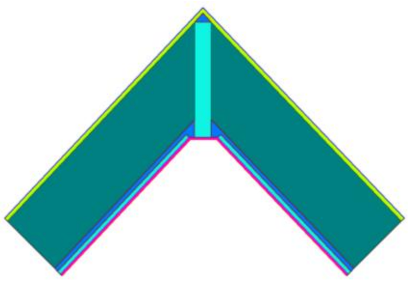
This detail is modeled as explained in section 2.1 EN ISO 10211:2007 to simplify in general and section 2.2 ISO 6946:2007 to simplify the sloping roof.

The roof tiles are replaced by exterior ventilated boundary condition (R_{se}= 0,13 m²·K/W). Indoor is considered as interior, heat flux, upwards instead of AOR due the roof of first floor has not insulating material so R_{si}= 0,10 m²·K/W, the same than inside of the room.

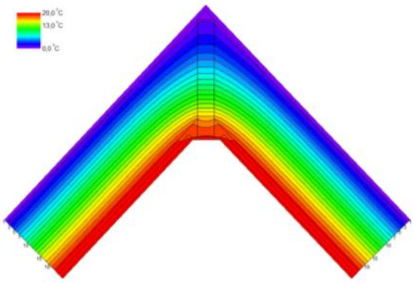
The Ψ -Value is determined according to equation (1).

Figure 61. Results of detail 6.

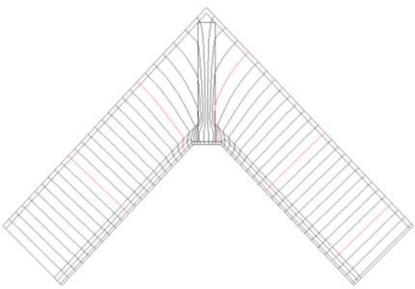
DETAIL 6			
	Ψ -Value calculated -0,043 W/(m·K)	Ψ -EPB regulation 0,00 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



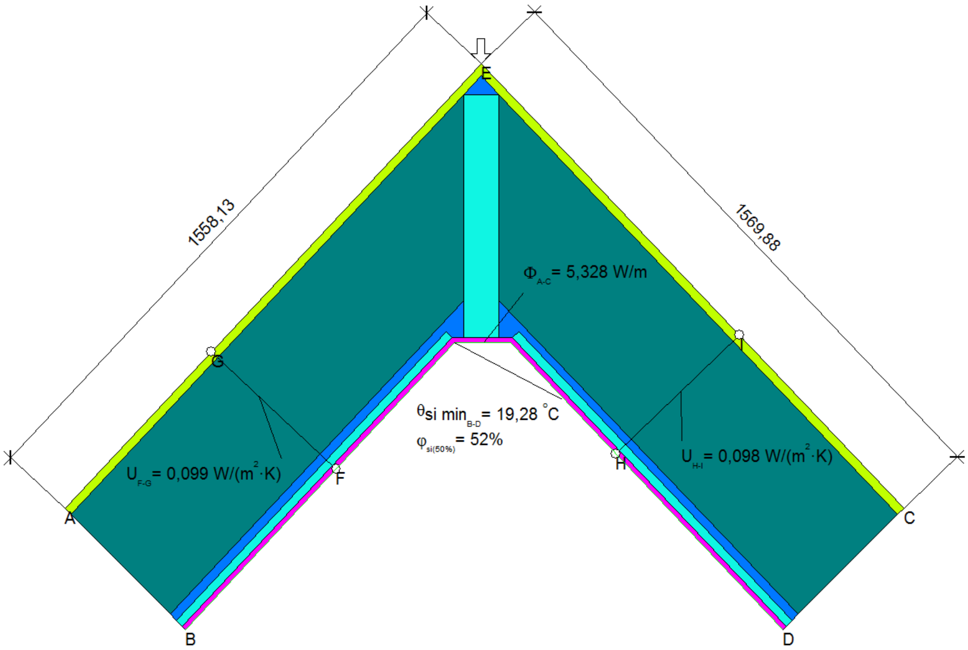
Modeled



ΔT and Isotherms



Streamlines



$$\Psi_{A\text{-}E\text{-}C,\,-} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{5{,}328}{20{,}000} - 0{,}099 \cdot 1{,}558 - 0{,}099 \cdot 1{,}570 = -0{,}043 \text{ W/(m·K)}$$

Detail 6 reaches loosely the requirements of the EPB-regulation and the limit for Passive House standard.

Timber with λ-value = 0,18 W/(mK) used to guarantee a continuous insulated layer together with cellulose with λ = 0,039 W/(m·K) used as insulation material on the roof, let obtain a really low Ψ-value.

Figure 63 and Figure 64 show the results for detail 7, i.e. connection sloping roof to flat roof at the back side of the building. Considering first floor and replacing it by interior, section boundary conditions are tested as in detail 5.

Figure 62. Detail 7 (location cut off of first floor and interior partition).

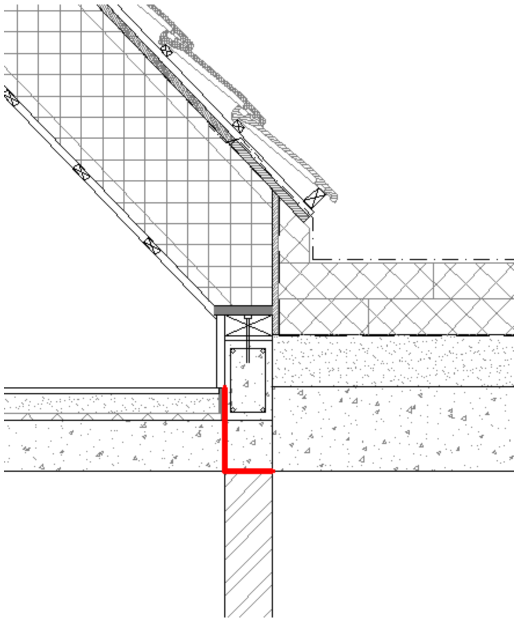


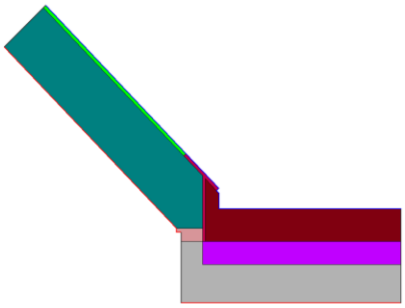
Table 14 summaries the linear transmittance of detail 7. It shows there is no relevance on both calculation possibilities as the two sides of the first floor (up and down) are indoors (see Figure 64).

This detail is modeled as explained in section in section 2.1 EN ISO 10211:2007 to simplify in general and section 2.2 ISO 6946:2007 to simplify the sloping roof.

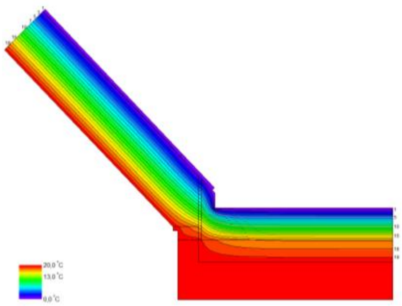
The Ψ -Value is determined according to equation (1).

Figure 63. Results of detail 7 (Simplified).

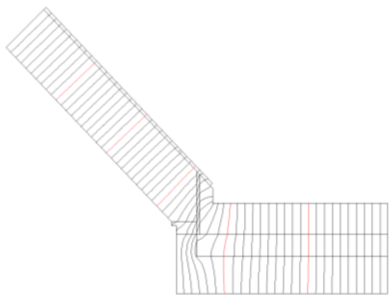
DETAIL 7			
	Ψ -Value calculated 0,023 W/(m·K)	Ψ -EPB regulation 0,15 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



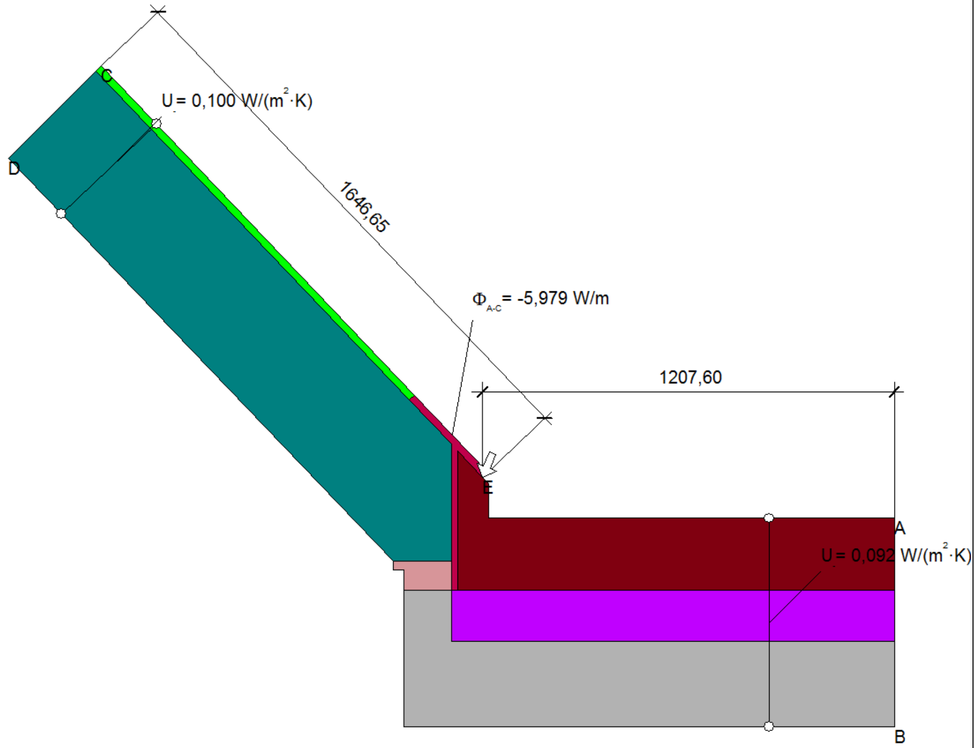
Modeled



ΔT and Isotherms

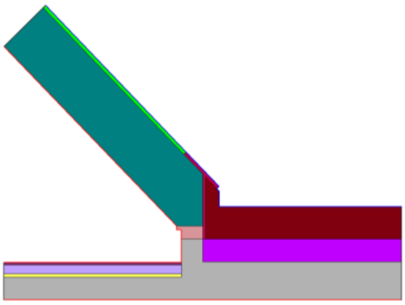
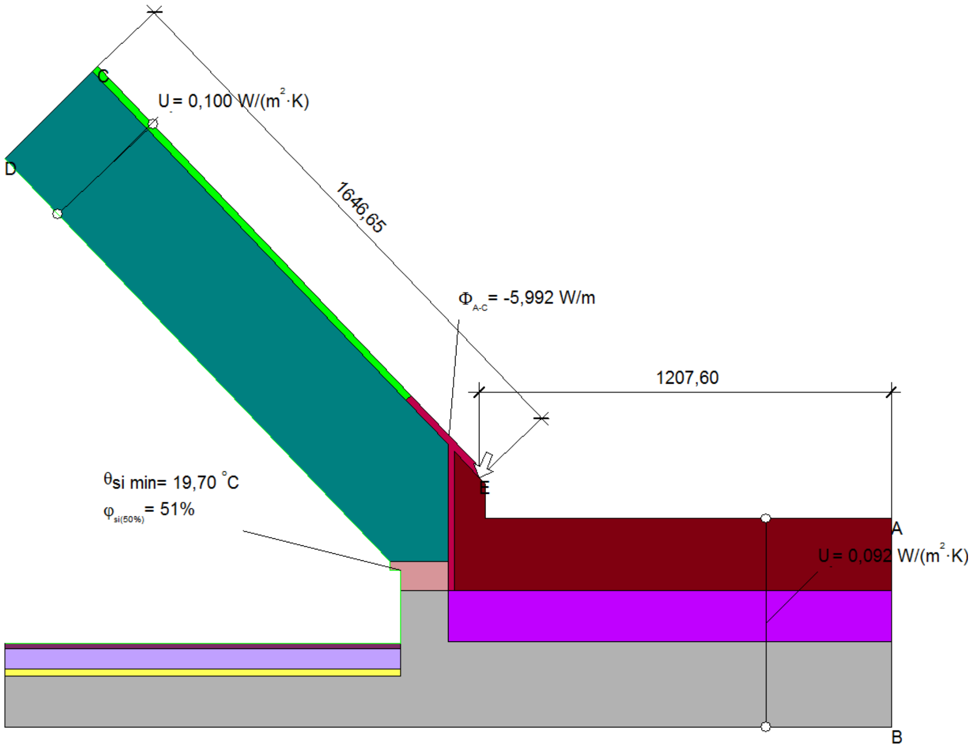


Streamlines



$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{5{,}979}{20{,}000} - 0{,}092 \cdot 1{,}208 - 0{,}100 \cdot 1{,}647 = 0{,}023 \text{ W/(m·K)}$$

Figure 64. Results of detail 7.1 (Considering first floor).

<table>
<tr><th colspan="4">DETAIL 7.1</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,023 W/(m·K)</td><td>Ψ -EPB regulation
0,15 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

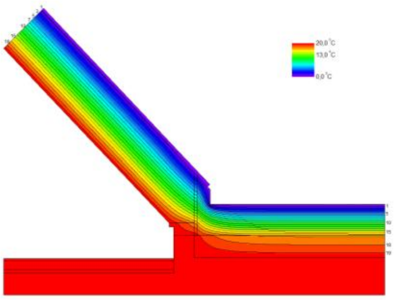
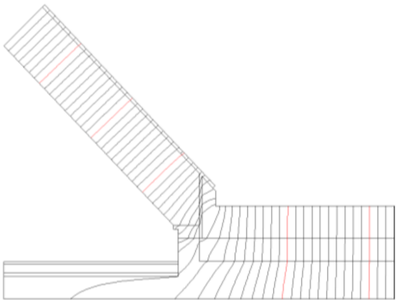
$\Psi_{A-E-C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{5,992}{20,000} - 0,092 \cdot 1,208 - 0,100 \cdot 1,647 = 0,023$ W/(m·K)</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Table 14. Summary of results of detail 7.

	U-sloping roof W/(m²·K)	U-flat roof W/(m²·K)	Φ obtained W/m	Ψ obtained W/(m·K)	Ψ limit W/(m·K)
Simplified D.7	0,100	0,092	5,979	0,023	0,15
Considering first floor D.7.1	0,100	0,092	5,992	0,023	

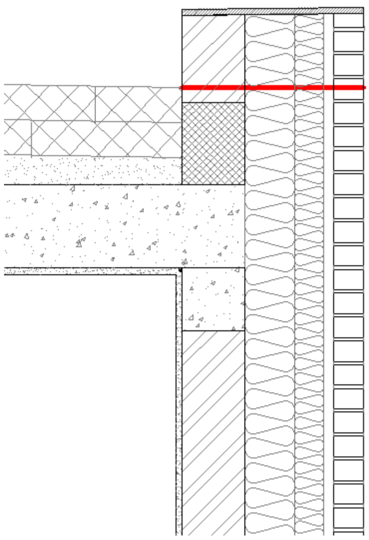
Detail 7 reaches the requirements of the EPB-regulation but not the limit for Passive House standard.

OSB3 with low λ-value (0,13 W/(m·K) is used to guarantee a continuous insulation layer. The two insulation materials used, cellulose on the sloping roof and resol on the flat roof, let obtain a good Ψ-value, despite of it does not fulfill the Passive House standards.

Figure 66 shows the results for detail 8, i.e. connection external wall to flat roof at south side of the building.

The sill roof has been replaced for a section boundary as it has not relevance on the calculation because both sides of the sill are outdoors.

Figure 65. Results of detail 8 (location cut off of sill roof).

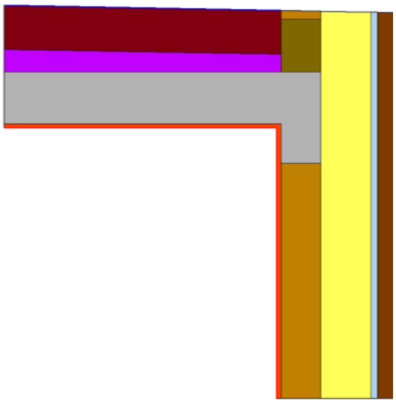


The detail is modeled as explained in section in section 2.1 EN ISO 10211:2007 to simplify in general and section 2.2 ISO 6946:2007 to simplify the sloping roof.

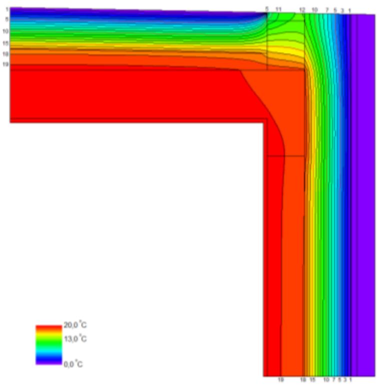
The Ψ -Value is determined according to equation (1).

Figure 66. Results of detail 8.

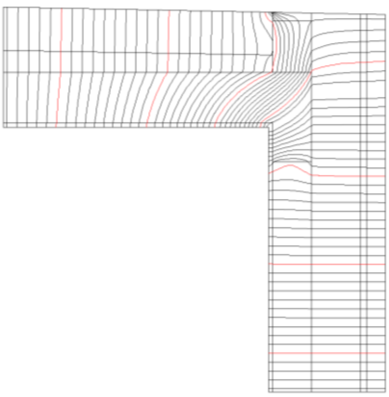
DETAIL 8			
	Ψ -Value calculated -0,005 W/(m·K)	Ψ -EPB regulation 0,00 W/(m·K)	Ψ Passive Standard 0,01W/(m·K)



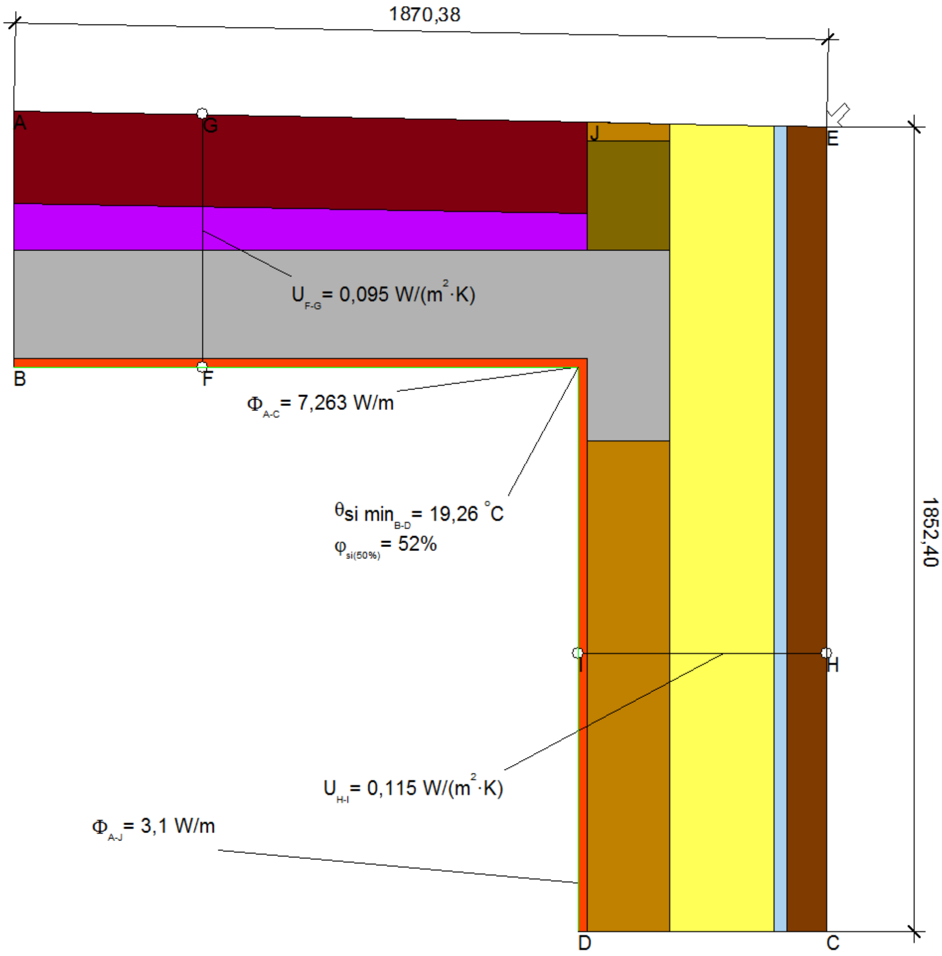
Modeled



ΔT and Isotherms



Streamlines



$$\Psi_{A\text{-}E\text{-}C,} = \frac{\Phi}{\Delta T} - \frac{\Phi_1}{\Delta T} - U_2 \cdot b_2 = \frac{7,263}{20,000} - \frac{3,100}{20,000} - 0,115 \cdot 1,852 = -0,005 \text{ W/(m·K)}$$

Detail 8 reaches the requirements of the EPB-regulation and the limit for Passive House standard.

Lamdablock with 25 cm of thickness is used to guarantee a continuous insulation layer. It together the two insulation materials used, resol on the flat roof and glass wool on the external wall, let obtain a low Ψ-value meeting with both standards.

4.1.3. Façade-window frame connection

Thermal bridges in windows frame are studied in this paragraph. Each figure shows the calculation model, isotherms and streamlines, total heat flux, linear transmittance Ψ and the limits in EPB-regulation and passive house standard.

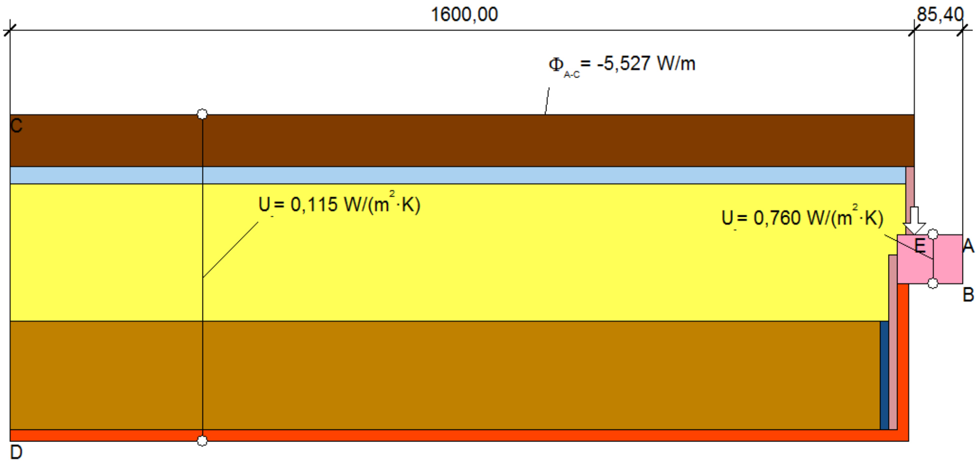
The legends of the materials, boundary conditions, streamlines and isotherms are given in ANNEX A.

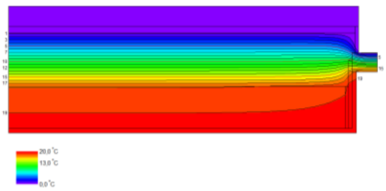
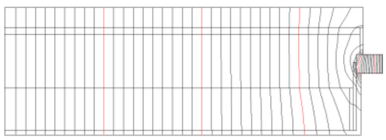
Figure 67 shows the results for detail 9, i.e. connection external wall to window frame on ground floor at the south side of the building (horizontal section). Timber is used to guarantee a continuous insulation layer.

This detail is modeled as explained in section 2.3 ISO 10077-1 and section 2.4 ISO 10077-1 to simplify windows frame.

The Ψ -Value is determined according to equation (1).

Figure 67. Results of detail 9.

<table>
<tr><th colspan="4">DETAIL 9</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,028 W/(m·K)</td><td>Ψ -EPB regulation
0,10 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{5{,}527}{20{,}000} - 0{,}760 \cdot 0{,}085 - 0{,}115 \cdot 1{,}600 = 0{,}028\ W/(m \cdot K)$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Detail 9 reaches the requirements of the EPB-regulation, but does not fulfill the limit for Passive House standard.

However, the great features that window frame presents are an important improvement that combines wood and thermal insulated providing excellent thermal comfort even near the window with U-value = 0,76 W/(m²·K) < 0,80 W/(m²·K), one of the requirements of Passive House standard.

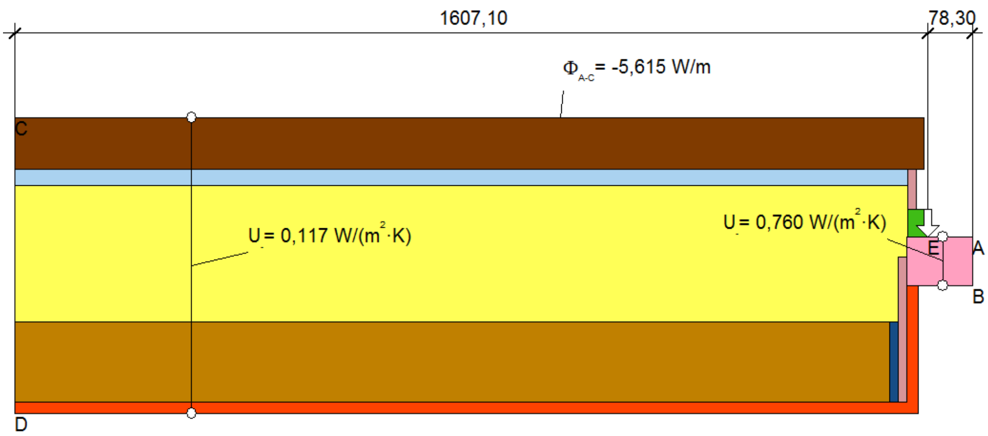
Figure 68 shows the results for detail 10, i.e. connection external wall to window frame with blind rail outdoor on first floor at the south side of the building (horizontal section). It is the same than detail 9 just adding the blind rail outdoor. Timber is used to guarantee a continuous insulation layer.

Table 15 summaries the linear transmittance of detail 10 and detail 9 to compare the results obtained.

This detail is modeled as explained in section 2.3 ISO 10077-1 and section 2.4 ISO 10077-1 to simplify windows frame.

The Ψ -Value is determined according to equation (1).

Figure 68. Results of detail 10.

<table>
<tr><th colspan="4">DETAIL 10</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,033 W/(m·K)</td><td>Ψ -EPB regulation
0,10 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

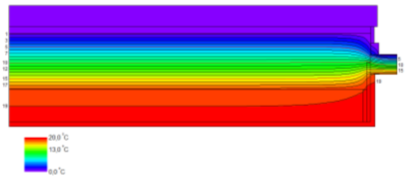
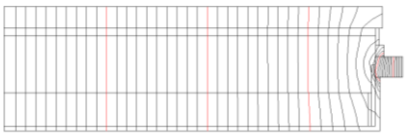
$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{5,615}{20,000} - 0,760 \cdot 0,078 - 0,117 \cdot 1,607 = 0,033 \text{ W/(m·K)}$$</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Table 15. Summary of results of detail 9 and detail 10.

DETAIL	U-wall W/(m²·K)	Φ obtained W/m	Ψ obtained W/(m·K)	Ψ limit W/(m·K)
9	0,115	5,527	0,028	0,10
10 (blind rail)	0,117	5,615	0,033	

Detail 10 reaches the requirements of the EPB-regulation, but does not fulfill the limit for Passive House standard.

Table 15 shows that Ψ-values are 15 % higher in case of add blind rail and basically there is no difference on U-value of external wall.

Figure 69 shows the results for detail 11, i.e. connection external wall to window frame on first floor at the south side of the building (vertical section).

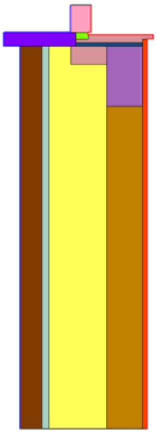
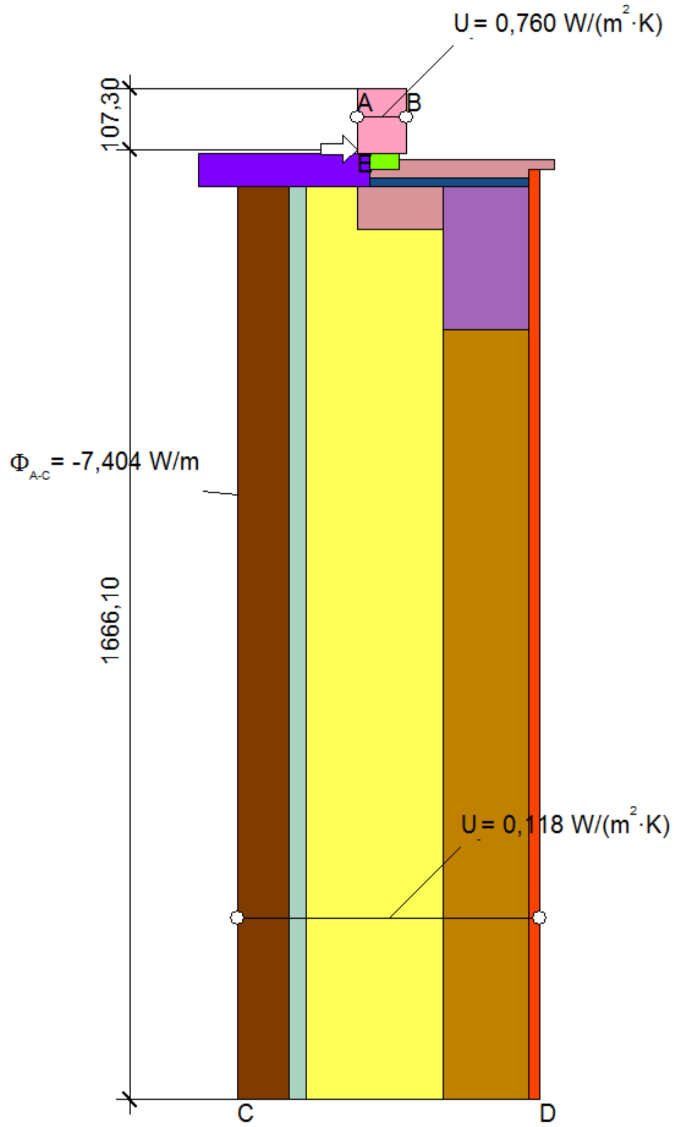
Purenit with λ= 0,07 W/(m·k) is used as insulated material to guarantee a continuous insulation layer. The insulation thickness is varied (from d=2,8 cm to d=4,3 cm on Figure 70)

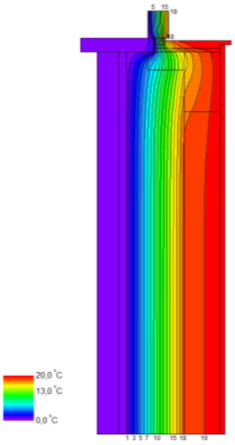
Table 16 summaries the linear transmittance of the variations of detail 11.

This detail is modeled as explained in section 2.3 ISO 10077-1 and section 2.4 ISO 10077-1 to simplify windows frame.

The Ψ -Value is determined according to equation (1).

Figure 69. Results of detail 11.

<table>
<tr><th colspan="4">DETAIL 11</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,092 W/(m·K)</td><td>Ψ -EPB regulation
0,10 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{7{,}404}{20{,}000} - 0{,}760 \cdot 0{,}107 - 0{,}118 \cdot 1{,}666 = 0{,}092 \text{ W/(m·K)}$$
</td></tr>
<tr><td>

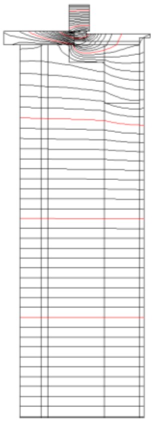
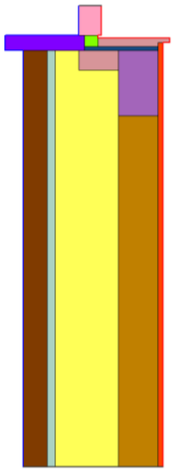
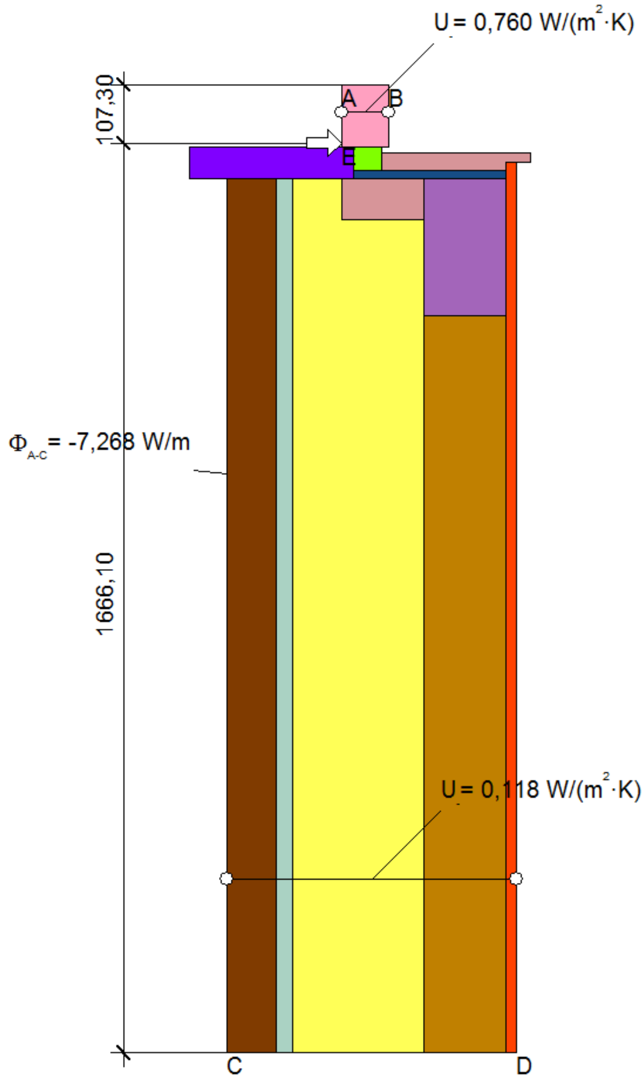
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 70. Results of detail 11.1.

<table>
<tr><th colspan="4">DETAIL 11.1</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,085 W/(m·K)</td><td>Ψ -EPB regulation
0,10 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

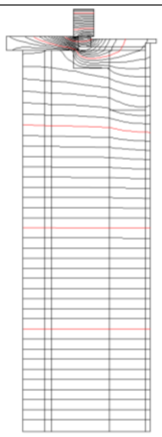
$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{7,268}{20,000} - 0,760 \cdot 0,107 - 0,118 \cdot 1,666 = 0,085 \text{ W/(m·K)}$$
</td></tr>
<tr><td>
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Table 16. Summary of results of detail 11 (Comparing thickness of Purenit).

	Tickness of Purenit	U-wall W/(m²·K)	Φ obtained W/m	Ψ obtained W/(m·K)	Ψ limit W/(m·K)
D.11	**2,8cm**	0,118	7,404	0,092	0,10
D.11.1	**4,3 cm**	0,118	7,268	0,085	

Detail 11 reaches the requirements of the EPB-regulation but does not fulfill the limit for Passive House standard.

Table 16 shows that Ψ-values are 8 % lower, increasing 50 % the Purenit thickness.

Figure 71 shows the results for detail 12, i.e. connection external wall to window frame with shutter box on first floor at the south side of the building (vertical section). It is the same than detail 11 but it is the top of the window, the lintel of first floor with shutter box.

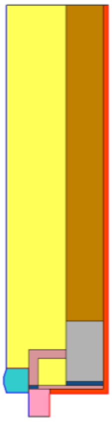
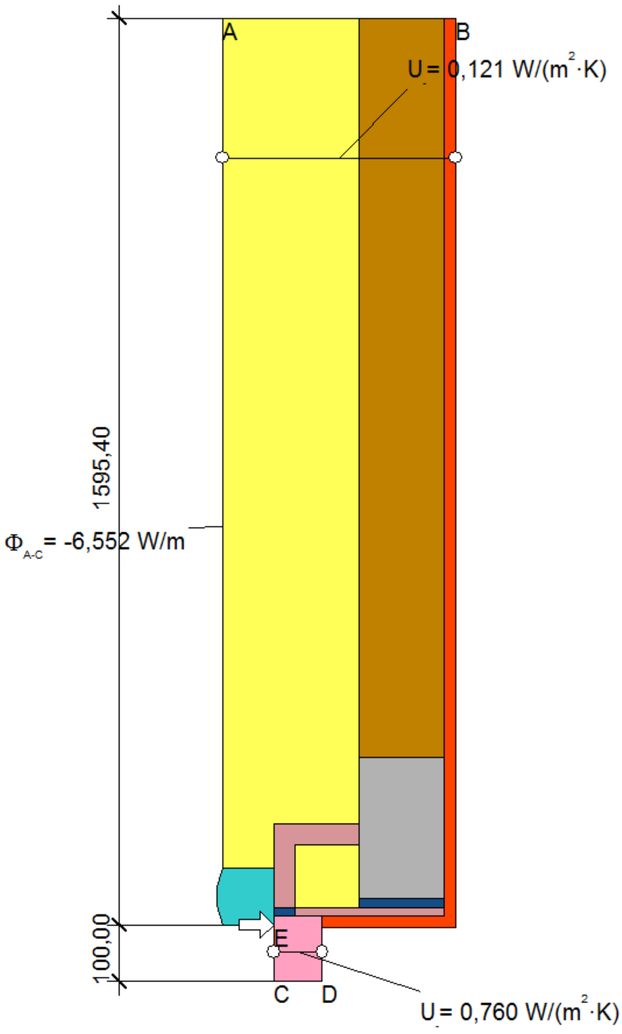
Disregarding the two external layers and replacing it by an external surface resistance R_{se}= 0,13 (m²·K)/W is tested. Considering these layers is calculated too, to confirm that it has not influence on the results.

Table 8 summaries the linear transmittance of the variations of detail 12.

This detail is modeled as explained in section 2.3 ISO 10077-1 and section 2.4 ISO 10077-2 to simplify windows frame.

The Ψ -Value is determined according to equation (1).

Figure 71. Results of detail 12 (Simplified).

<table>
<tr><th colspan="4">DETAIL 12</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,059 W/(m·K)</td><td>Ψ -EPB regulation
0,10 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{6{,}552}{20{,}000} - 0{,}121 \cdot 1{,}595 - 0{,}760 \cdot 0{,}100 = 0{,}059 \text{ W/(m·K)}$$</td></tr>
<tr><td>

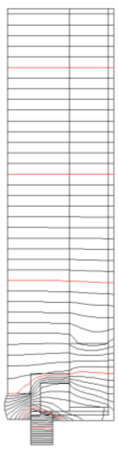
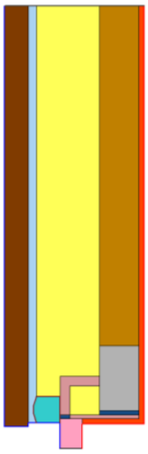
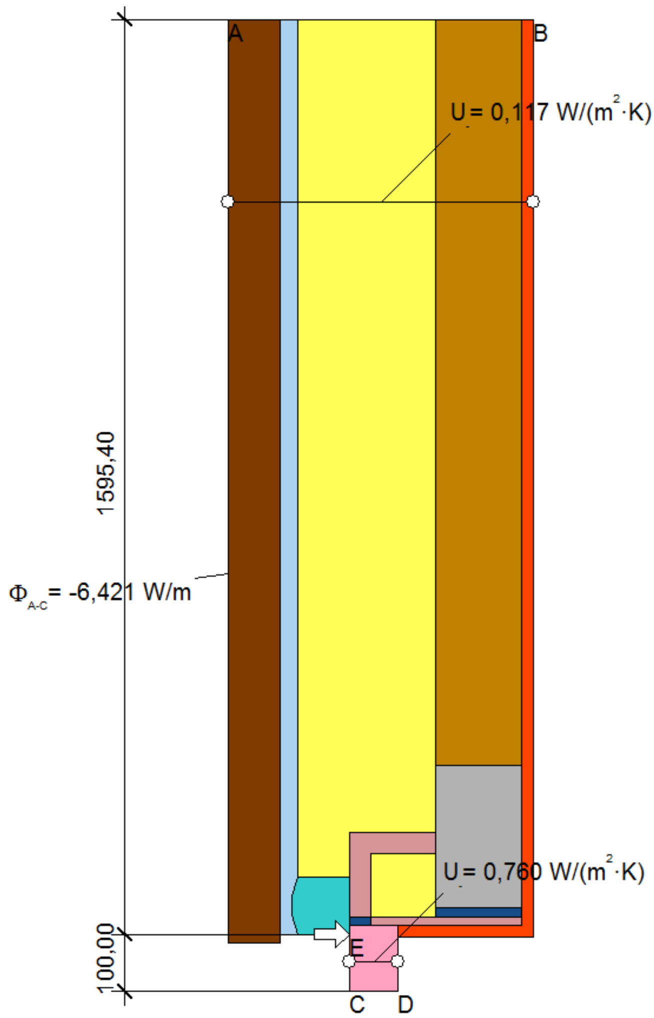
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Figure 72. Results of detail 12.1 (Considering external layers).

<table>
<tr><th colspan="4">DETAIL 12.1</th></tr>
<tr><td></td><td>Ψ -Value calculated
0,059 W/(m·K)</td><td>Ψ -EPB regulation
0,10 W/(m·K)</td><td>Ψ Passive Standard
0,01W/(m·K)</td></tr>
<tr><td>
Modeled</td><td colspan="3" rowspan="3">

$$\Psi_{A\text{-}E\text{-}C} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{6,421}{20,000} - 0,117 \cdot 1,595 - 0,760 \cdot 0,100 = 0,059 \text{ W/(m·K)}$$</td></tr>
<tr><td>

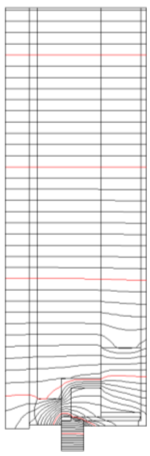
ΔT and Isotherms</td></tr>
<tr><td>
Streamlines</td></tr>
</table>

Table 17. Summary of results of detail 12.

	U-wall W/(m²·K)	Φ obtained W/m	Ψ obtained W/(m·K)	Ψ limit W/(m·K)
D.12 Simplified	0,121	6,552	0,059	0,10
D.12.1 Considering layers	0,117	6,421	0,059	

Detail 12 reaches the requirements of the EPB-regulation but does not the limit for Passive House standard despite the low Ψ-value obtained.

4.2. RESULTS DISCUSSION

This paragraph argues and discusses the obtained results on the analysis.

Table 17 shows a summary of all details with the boundary conditions imposed, the lineal transmittance Ψ and the limits in EPB-regulation and passive house standard.

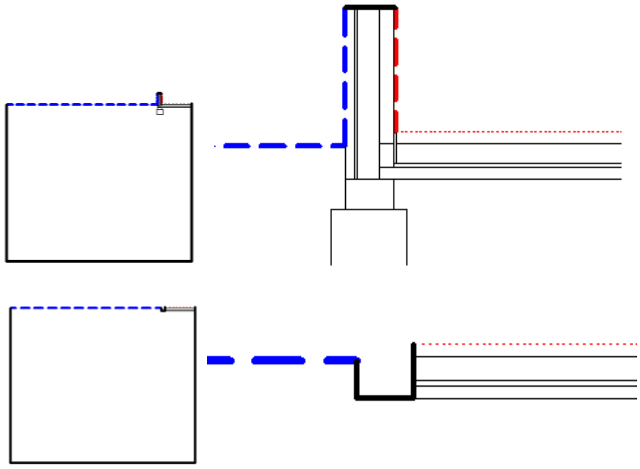
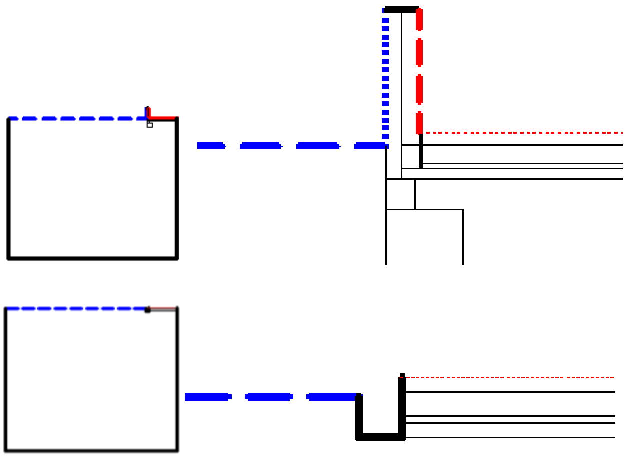
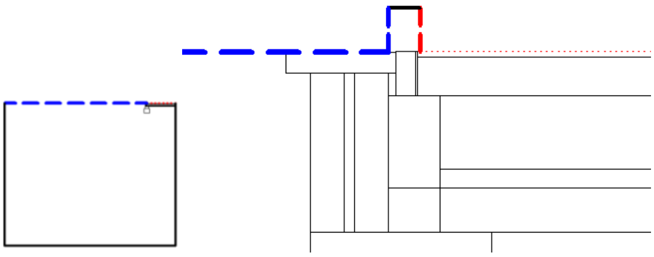
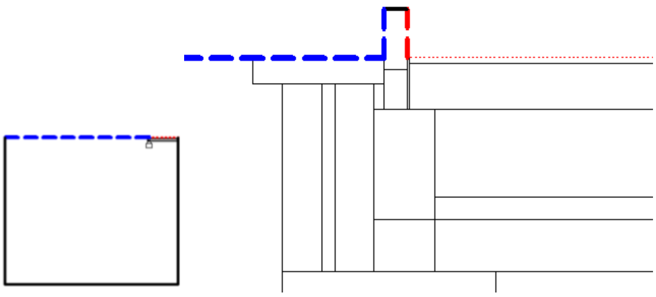
The legends of boundary conditions are given in annex A.

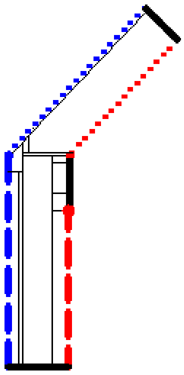
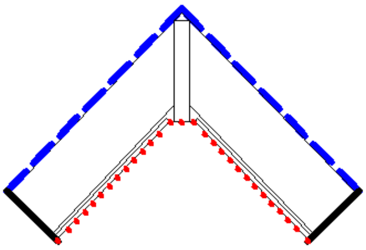
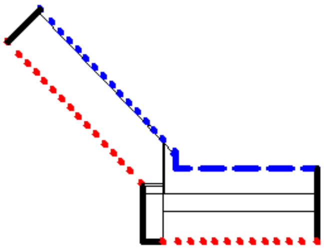
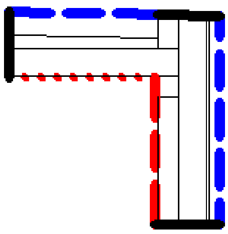
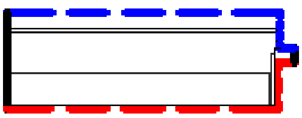
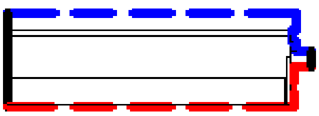
The lineal transmittance Ψ of detail 1 to 4 is shown on section 4.1.1. Façade-ground floor connection with the results of all the variations performed but the boundary conditions of them is shown on table 17 in both considerations to realize the calculation, considering the wall and replacing it by a section boundary condition.

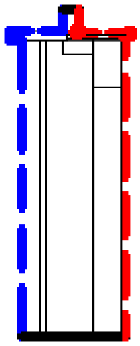
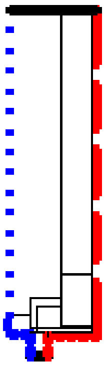
A discussion of the results obtained is given comparing to the limits, to other details and other materials. Comparing starts with the details that involve roof connections following with façade-windows frame connection and ending with details of façade-ground floor connection.

Furthermore, some details are compared with Passive House details. There is compared the λ-values of insulated materials used on the floor, wall and roof and the U-value obtained on each element. All of them are designed and built virtually identical.

Table 18. Summary of results of all details.

DETAIL	Type	Ψ-Obtained W/(m·K)	Ψ-EPB W/(m·K)	Ψ-Passive House W/(m·K)
1		-	0,05	0,01
2		-	0,05	0,01
3		-	0,15	0,01
4		-	0,15	0,01

5		-0,004	0,00	0,01
6		-0,043	0,00	0,01
7		0,023	0,15	0,01
8		-0,005	0,00	0,01
9		0,028	0,10	0,01
10		0,033	0,10	0,01

11		0,092	0,10	0,01
12		0,059	0,10	0,01

All details reach the Flemish EPB-regulations, but just three of them fulfill with Passive House standards.

These are detail 5, 6 and 8 which involve the sloping roof. The tiles with R_{se} = 0,04 m²·K/W are replaced by R_{se} = 0,13 m²·K/W, getting a lower Ψ -value.

Detail 7 is the joint between sloping roof and flat roof. Despite of it presents the same features on the sloping roof, does not reach Passive House standard but the Ψ obtained is low good too.

Table 19 shows the comparison of details 5 and 8 with the passive house details. It shows the λ-values of insulated element used and U-values obtained on the wall and on the roof. There are practically no differences on the results obtained.

Table 19. Comparing details with Passive House details.

	λ -wall insulation W/(m·K)	λ -roof insulation W/(m·K)	U-wall W/(m²·K)	U-roof W/(m²·K)
		Detail 5		
D. Analyzed	0,032	0,039	0,117	0,101
D. Passive House	0,035	0,030	0,14	0,122
		Detail 8		
D. Analyzed	0,032	0,023	0,115	0,095
D. Passive House	0,035	0,030	0,14	0,144

Details 9 to 12 are the external wall-windows frame connection.

All of them reach the Flemish EPB-regulations, but do not fulfill with Passive House standards.

However, comparing these details with Passive House details, there are insignificant differences on U-values of wall and on λ-value of insulated material used on the wall (see Table 19. same values than detail 5).

The Ψ -values obtained are really low. On detail 11 it is higher (Ψ = 0,092 W/(m·K)) due it involves the sill with high λ-value (3,5 W/(m·K)). It shows the influence of the materials used.

Lower Ψ -value is obtained with lower λ–value of material used as well as using higher thickness of the insulation element to guarantee a continuous insulation layer (see Table 16).

Purenit, used as insulation element with λ =0,07 W/m·K, has a high mechanical load capacity, excellent adhesive properties and can be covered with a wide range of top coating layers. Even constant exposure to moisture results in practically no swelling. It is economical and easy to work.

Windows frame used, made with timber and insulating in one of its parts, have a low U-value of 0,76 W/(m²·K) < 0,80 W/(m²·K), one of the requirements of the Passive house standard [16].

Using this materials is possible obtain a great Ψ–values.

Details 1 to 4 involve the foundation and they are ones of the most important.

All of them reach the Flemish EPB-regulations, but do not fulfill with Passive House standards.

However, comparing details 1 and 4 with Passive House details, insignificant differences on λ-value and U-values are detected (see Table 20).

But depending of the insulated element material differences in Ψ-values are noticed. Ψ-value of these details with Lamdablock is around 25 % higher than Ψ-value of these details with cellular glass (see Table 7).

Table 20. Comparing details with Passive House details.

	λ -wall insulation W/(m·K)	λ -floor insulation W/(m·K)	U-wall W/(m²·K)	U-floor W/(m²·K)
Detail 1 (wall-ground connection)				
D. Analyzed	0,032	0,024	0,117	0,116
D. Passive House	0,035	0,035	0,140	0,150
Detail 4 (frame-ground connection)				
D. Analyzed	-	0,024	-	0,095
D. Passive House	-	0,035	-	0,144

5. CONCLUSIONS

The study of representative thermal bridges of the building envelope applying the requirements of standards on the calculation and comparing the results shows the following conclusions:

- Despite of using lamdablock Ψ-values are 25 % higher than Ψ-values with cellular glass, the results obtained with lamdablock fulfill with Flemish EPB-regulation.
- The basic rule 2 of EPB-node accepted and the exception using lamdablock, allows accept the thermal bridges with lamdablock as insulated element. It is the best option from economic standpoint.
- Great improvement where there is a well ventilate cavity that it allows to move R_{se} from 0,04 m^2K/W to 0,13 m^2K/W.
- Window/door frame with lower U-value to fulfill the requirements to Passive house, allows get a really good lineal thermal transmittance value in details which involves them, meeting with Flemish EPB-regulation.
- The insulated material with lower λ-value (resol, cellulose, glass wool instead of concrete reinforced with 1% or 2% of steel with highest λ-value) on construction elements, allows get great results of lineal thermal transmittance reaching even the Passive House standards in some cases.
- Lower λ-value of material used let obtain lower U-value, better insulation parts, and consequently lower results of Ψ-value obtained.
- Despite of all details not fulfill with Passive house standards, the construction of them is identically to Passive House details and the-value of the insulated material used is nearly the same too.

Thereby, reminding the main objective of this master thesis, it is the analysis of thermal bridges to optimize the heat losses, stand out that due to use these materials with greatest thermal features specially which ones involve the envelope surface, how all details are designed according the correspond standard and the geometry and material chosen are a set of measures that allows meeting loosely with Flemish EPB-regulation and nearly reach the Passive House standards.

Despite of not reach Passive house standards, the annual net energy need for heating is 13,8 $KWh/m^2 < 15$ KWh/m^2 per year, one of the passive house requirements.

Apart from the improved heating demands of studied building, there are two further benefits to be considered, namely the not negligible environmental impact and the reduction of the building's running costs.

To sum up and in view of the results, this house can be considered an example to follow to reach Passive house using renewable materials and applying the regulatory standards.

Moreover, say that the sector provides the second largest untapped and cost-effective potential for energy savings after the energy sector itself. There are also important co-benefits from making buildings more energy efficient, including job creation, fuel poverty alleviation, health improvements, and better energy security and industrial competitiveness.

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ANNEXES

ANNEX A

Table 21. Legend of materials.

	Material	λ-value W/(m·K)
	Unventilated air cavity	-
	Slightly ventilated air cavity	-
	Air layer unventilated	0,167
	Concrete with 1% of steel	2,30
	Concrete with 2% of steel	2,50
	Screed (concrete)	1,30
	Screed (EPB-concrete)	0,10
	Calcium silicate brick	0,90
	Brick construction	0,26
	Baksteen (brick)	0,90
	Concrete block	0,14
	PUR insulation	0,024
	PU foam	0,023
	Glass wool	0,032
	Lamdablock (brick)	0,16
	Ytong kimblock (cellular concrete)	0,125
	Cellular glass	0,041
	Purenit (insulation)	0,07
	Resol (insulation)	0,023
	Celit (wood panel)	0,05
	OSB3	0,13
	Cellulose	0,039
	Gypsum plasterboard	0,21
	Gypsum plastering	0,52
	Plaster, cement, sand	1,00

	Sand and gravel	2,00
	Tiles	2,90
	Wood window frames	0,074
	Aluminum door frame	0,057
	PVC rigid	0,17
	Timber 500 Kg/m^3	0,13
	Timber 700 Kg/m^3	0,18
	Limestone hard	1,70
	Blue hard stone	3,50

Table 22. Legend of boundary conditions.

	Type	Temperature ºC	Rsi, Rse $(m^2 \cdot K/W)$
	Exterior, normal	0	0,04
	Exterior, ventilated	0	0,13
	Interior, normal, horizontal	20	0,13
	Interior, heat flux, upwards	20	0,10
	Interior, heat flux, downwards	20	0,17
	AOR, unheated room	0	0,13
	Adiabatic	-	-

Table 23. Legend of isotherms and streamlines.

Isotherms	Streamlines
$\Delta T = 1ºK$ $\Delta T = 5ºK$	$\Delta \Phi = 0{,}1 W/m$ $\Delta \Phi = 1{,}0 W/m$

ANNEX B

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The new building tradition.

Bouwknopen oplossen met Lambdabloc: methode Ploegsteert

1 Inrekenen van bouwknopen in het K-peil:

Om bouwknopen in rekening te brengen bij het vaststellen van het K-peil van een gebouw zijn er drie mogelijke opties:

Optie A: de *gedetailleerde methode* genoemd. Daarbij wordt voor een volledige woning elke bouwknoop uitgerekend en afzonderlijk in rekening gebracht voor de bepaling van het K-peil.

Optie B: de *EPB aanvaarde bouwknopen*. Deze methode veroorzaakt slechts een beperkte verhoging van het K-peil met 3 punten. Bij deze methode worden de bouwknopen door middel van het volgen van enkele basisregels 'EPB-aanvaardbaar' gemaakt. Er kan eveneens geverifieerd worden of de bouwknoop voldoet aan een 'psi-limiet' waarde. ($\psi_e \leq \psi_{lim}$). Zulke beter presterende bouwknopen zullen dan leiden tot een daling met een variabel aantal K-peil punten.

Optie C: men houdt geen rekening met de bouwknopen bij het vaststellen van het K-peil. Deze methode wordt afgestraft met een *forfaitaire toeslag* van 10 K-peil punten. Door strengere EPB-eisen wordt deze methode steeds minder toegepast.

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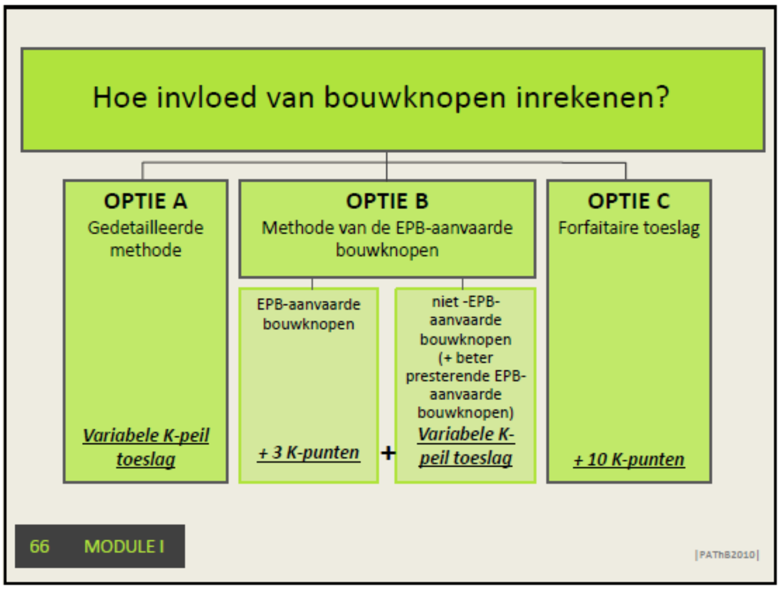
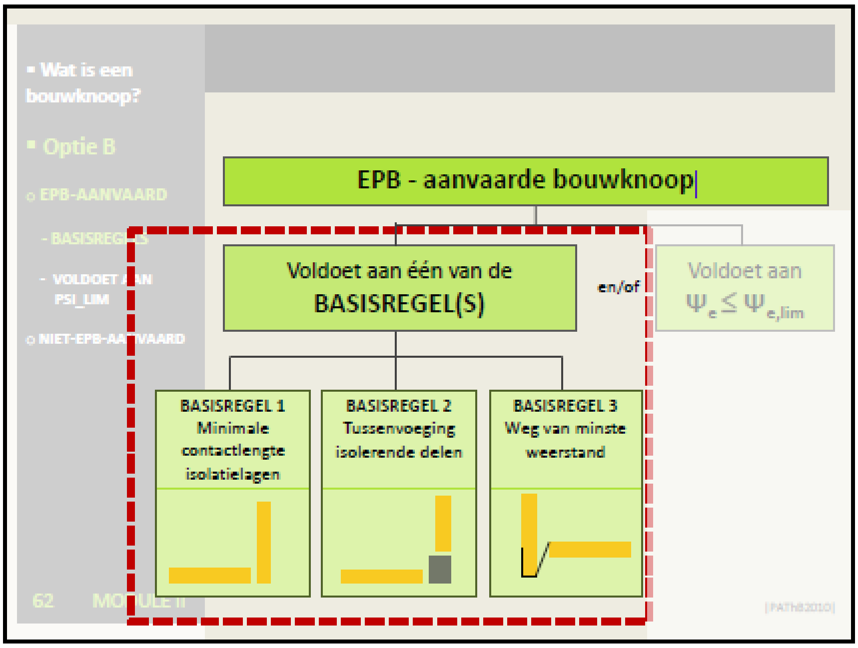
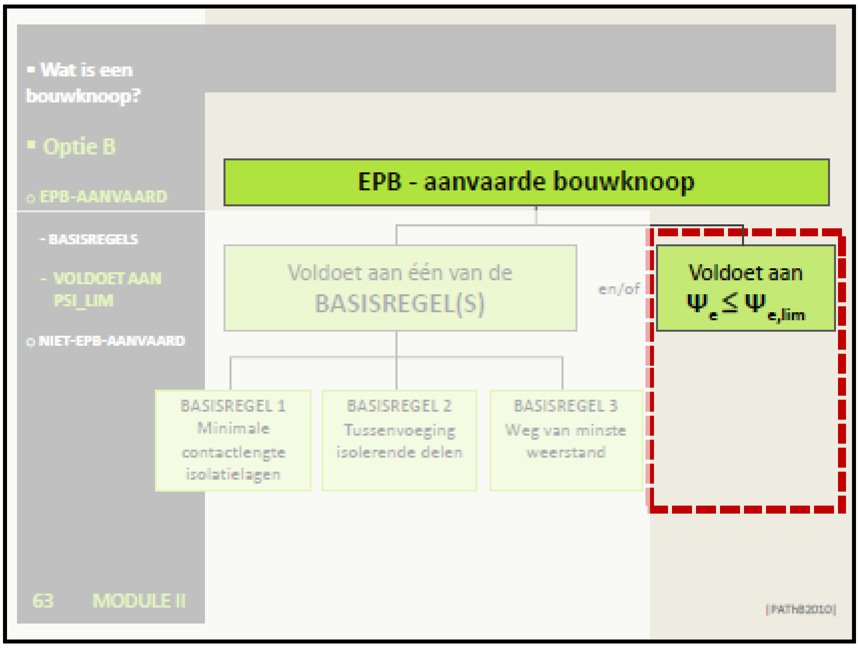


2 De EPB-aanvaarde bouwknoop:



Of een bouwknoop voldoet aan de basisregels kan eenvoudig bepaald worden. Hierbij wordt de Lambdabloc gebruikt als isolerend deel. Echter daar stoppen de mogelijkheden voor een architect, ingenieur of EPB-verslaggever niet.



De methode van de EPB-aanvaarde bouwknopen laat eveneens toe om ‘psi-waarde’ (ψ_e) uit te rekenen en te verifiëren of deze voldoet aan de limietwaarde. De psi-waarde van een bouwknoop is de warmtedoorgangscoëfficiënt van deze bouwknoop (W/mK). De psi-waarde kan voor elke bouwknoop, op basis van een detailtekening, berekend worden. Die psi-waarde wordt dan vermenigvuldigd met het aantal meter dat deze bouwknoop zich voordoet. Het resultaat wordt vervolgens verrekend in het K-peil. De invloed op het K-peil kan dus zowel positief als negatief zijn naar gelang de bouwknoop goed of slecht wordt opgelost.

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GRENSWAARDEN voor Ψ_e

IN FUNCTIE VAN TYPE BOUWKNOOP

	$\Psi_{e,lim}$
1. BUITENHOEKEN (1) (2) • 2 muren • Andere buitenhoeken	 -0.10 W/m.K 0.00 W/m.K
2. BINNENHOEKEN (3)	0.15 W/m.K
3. VENSTER- en DEURAANSLUITINGEN	0.10 W/m.K
4. FUNDERINGSAANZETTEN	0.05 W/m.K
5. BALKONS	0.10 W/m.K
6. AANSLUITINGEN VAN EEN SCHEIDINGSCONSTRUCTIE BINNEN EENZELFDE BESCHERMD VOLUME OF TUSSEN 2 VERSCHILLENDE BESCHERMDE VOLUMES OP EEN SCHEIDINGSCONSTRUCTIE VAN HET VERLIESOPPERVLAK	0.05 W/m.K
7. ALLE LINEAIRE BOUWKNOPEN DIE NIET ONDER 1 T.E.M 6 VALLEN	0.00 W/m.K

(1) met uitzondering van funderingsaanzetten.

(2) Voor een buitenhoek moet de hoek α – gemeten tussen de twee buitenoppervlakken van de scheidingsconstructies van het verliesoppervlak – voldoen aan: 180° < α < 360°.

(3) Voor een binnenhoek moet de hoek α – gemeten tussen de twee buitenoppervlakken van de scheidingsconstructies van het verliesoppervlak – voldoen aan: 0° < α < 180°.

Het uitrekenen van dergelijke psi-waardes is echter een complexe opgave. Daarom hebben de Steenbakkerijen van Ploegsteert voor de meeste bouwknopen, waar de *Lambdabloc* kan worden toegepast, een psi-waarde berekend. Deze kan door elke architect en EPB-verslaggever gebruikt worden. De berekening van deze psi-waardes is gebeurd met het gevalideerde programma, TRISCO. (link website)

Wanneer men een 'psi-waarde' (ψ_e) gebruikt in een EPB-verslag is het van belang dat de bouwknoop exact zo wordt uitgevoerd als opgegeven in het bouwknoopdetail waarop de berekening van deze 'psi-waarde' is gebaseerd.

3 Hoe de psi-waarde tabel van een bouwknoop gebruiken?

Uitgaand van enkele gegevens uit de detailtekening van een bouwknoop en de keuze van de isolatiematerialen kan men de psi-waarde (ψ_e) vinden.

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Nemen we volgende bouwknoop als voorbeeld: (tekening funderingsaanzet)

Volgende gegevens zijn hierbij van belang:

1. Spouwisolatie: dikte *(12cm)* en lambda-waarde *(0.034 W/mK)* van de isolatie.
2. Vloerisolatie: dikte *(8cm)* en lambda-waarde *(0.023W/mK)* van de isolatie.

Vervolgens vinden we in de tabel de volgende psi-waarde: -0.306 W/mK

dikte	muur opbouw	vloer opbouw	dikte
9 cm	gevelsteen	vloerafwerking, tegels	1 cm
3 cm	matig verluchte luchtspouw	dekvloer, gewapend	9 cm
zie matrix	isolatie	vloerisolatie	zie matrix
14 cm	thermoblokken van ploegsteert	dekvloer, ongewapend	8 cm
1 cm	bepeistering	vloerplaat in beton	15 cm

LAMBDA-BLOK van PLOEGSTEERT
van 14 cm breed

LAMBDA-BLOK 25cm hoog

Ψe lim=0,05 W/mK Waarde bij ontstentenis 0,20 W/mK			VLOERISOLATIE																			
			60					80					100					120				
			0,023	0,030	0,033	0,034	0,059	0,023	0,030	0,033	0,034	0,059	0,023	0,030	0,033	0,034	0,059	0,023	0,030	0,033	0,03
SPOUWISOLATIE	80	0,023	-0,298	-0,427	-0,472	-0,485	-0,747	-0,295	-0,420	-0,464	-0,477	-0,748	-0,306	-0,421	-0,466	-0,483	-0,750	-0,305	-0,416	-0,460	-0,47
		0,029	-0,313	-0,442	-0,487	-0,500	-0,762	-0,311	-0,435	-0,479	-0,493	-0,764	-0,322	-0,437	-0,482	-0,499	-0,766	-0,322	-0,433	-0,477	-0,49
		0,030	-0,316	-0,444	-0,489	-0,502	-0,764	-0,313	-0,437	-0,482	-0,495	-0,766	-0,324	-0,440	-0,484	-0,502	-0,768	-0,324	-0,435	-0,480	-0,49
		0,032	-0,320	-0,449	-0,493	-0,507	-0,769	-0,318	-0,442	-0,487	-0,500	-0,771	-0,329	-0,445	-0,489	-0,507	-0,773	-0,329	-0,440	-0,485	-0,49
		0,033	-0,323	-0,451	-0,496	-0,509	-0,771	-0,320	-0,444	-0,489	-0,502	-0,773	-0,332	-0,447	-0,492	-0,509	-0,776	-0,332	-0,443	-0,487	-0,50
		0,034	-0,325	-0,454	-0,498	-0,511	-0,773	-0,322	-0,447	-0,491	-0,504	-0,775	-0,334	-0,450	-0,494	-0,512	-0,778	-0,334	-0,445	-0,490	-0,50
		0,036	-0,329	-0,458	-0,502	-0,516	-0,778	-0,327	-0,451	-0,496	-0,509	-0,780	-0,339	-0,454	-0,499	-0,516	-0,783	-0,339	-0,450	-0,494	-0,50
	100	0,023	-0,293	-0,422	-0,467	-0,480	-0,744	-0,288	-0,413	-0,458	-0,471	-0,743	-0,297	-0,413	-0,458	-0,476	-0,743	-0,295	-0,407	-0,452	-0,46
		0,029	-0,306	-0,435	-0,480	-0,493	-0,756	-0,302	-0,426	-0,471	-0,484	-0,756	-0,311	-0,427	-0,472	-0,490	-0,757	-0,310	-0,421	-0,466	-0,47
		0,030	-0,308	-0,437	-0,482	-0,495	-0,759	-0,304	-0,429	-0,473	-0,487	-0,759	-0,313	-0,429	-0,474	-0,492	-0,759	-0,312	-0,424	-0,468	-0,48
		0,032	-0,312	-0,441	-0,486	-0,499	-0,763	-0,308	-0,433	-0,477	-0,491	-0,763	-0,318	-0,434	-0,478	-0,496	-0,764	-0,317	-0,428	-0,473	-0,48
		0,033	-0,314	-0,443	-0,488	-0,501	-0,765	-0,310	-0,435	-0,479	-0,493	-0,765	-0,320	-0,436	-0,480	-0,498	-0,766	-0,319	-0,430	-0,475	-0,48
		0,034	-0,316	-0,445	-0,490	-0,503	-0,766	-0,312	-0,437	-0,481	-0,495	-0,767	-0,322	-0,438	-0,483	-0,500	-0,768	-0,321	-0,432	-0,477	-0,49
		0,036	-0,320	-0,449	-0,494	-0,507	-0,770	-0,316	-0,441	-0,485	-0,499	-0,771	-0,326	-0,442	-0,487	-0,505	-0,772	-0,325	-0,437	-0,481	-0,49
	120	0,023	-0,291	-0,421	-0,466	-0,479	-0,744	-0,285	-0,410	-0,455	-0,468	-0,742	-0,293	-0,409	-0,454	-0,472	-0,741	-0,290	-0,402	-0,447	-0,46
		0,029	-0,303	-0,433	-0,477	-0,491	-0,755	-0,297	-0,422	[illegible]	[illegible]	[illegible]	-0,305	-0,421	-0,466	-0,484	-0,753	-0,303	-0,415	-0,459	-0,47
		0,030	-0,304	-0,434	-0,479	-0,493	-0,757	-0,298	[illegible]	[illegible]	[illegible]	[illegible]	-0,307	-0,423	-0,468	-0,486	-0,755	-0,305	-0,417	-0,462	-0,47
		0,032	-0,308	-0,438	-0,483	-0,496	-0,761	-0,302	-0,428	[illegible]	[illegible]	[illegible]	-0,311	-0,427	-0,472	-0,490	-0,759	-0,309	-0,421	-0,465	-0,47
		0,033	-0,310	-0,440	-0,485	-0,498	-0,762	-0,304	-0,429	-0,474	-0,488	-0,761	-0,313	-0,429	-0,474	-0,492	-0,761	-0,311	-0,423	-0,467	-0,48
		0,034	-0,312	-0,441	-0,486	-0,500	-0,764	-0,306	-0,431	-0,476	-0,489	-0,763	-0,315	-0,431	-0,476	-0,494	-0,763	-0,313	-0,425	-0,469	-0,48
		0,036	-0,315	-0,445	-0,490	-0,503	-0,767	-0,309	-0,435	-0,480	-0,493	-0,766	-0,318	-0,435	-0,480	-0,497	-0,766	-0,316	-0,428	-0,473	-0,48
		0,023	-0,292	-0,422	-0,467	-0,481	-0,746	-0,284	-0,410	-0,455	-0,468	-0,743	-0,291	-0,408	-0,453	-0,471	-0,741	-0,287	-0,400	-0,445	-0,45
		0,029	-0,302	-0,432	-0,477	-0,491	-0,756	-0,294	-0,420	-0,465	-0,479	-0,753	-0,301	-0,418	-0,463	-0,481	-0,751	-0,298	-0,411	-0,456	-0,46

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