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BACHELOR FINAL PROJECT “Economic-efficient construction: choice of building materials according to climate impacts from different countries”

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Valencia 2013

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1 Introduction

The point of this project, is to study thermal behaviour of different building materials in different environments. Environments was chosen by according to the two countries: Estonia and Spain. These two countries are very different in terms of their climate and this is the reason for making studies about different building materials in these countries. To simplify the process of the project, four different models with different combination of materials were used for the study. Two models from each country. Model 1 and 2 belongs to Estonia and 3 and 4 to Spain. Models were divided into two groups: with masonry-structure envelopes (Model 1 and 3) and with frame-structure envelopes (Model 2 and 4).

In the first phase of the project includes calculations were made in manual according calculation methods in each country. Calculations were based on the thermal conductivity and the risk of condensation in the model structures.

Second phase based on calculations with program called “Calener_VYP”. All calculations are made by Spain environmental data and first two models are analysed by under this and compare with models for Spain. Program analyses models energy consumption for heating and cooling comparing its own model.

2 Overview of thermal calculations in general for both countries

2.1 historical overview of the first thermal calculations

In Estonia, first calculations for the thermal activity were made in 1930 in construction regulations for Tallinn[1] and Nõmme[2]. In 1930. Tallinn building regulations required thermal conductivity of residential exterior wall to be $\leq 1{,}0$ kcal/($m^2 \cdot h \cdot K$) which is 1,17 W/($m^2 \cdot K$) and in Nõmme city $\leq 0{,}9$ kcal/($m^2 \cdot h \cdot C$) which is 1,05 W/($m^2 \cdot K$), based on thermal calculations. [1]

In 1937. - 1939. from Commission of engineer's of the investigation of outer walls, the investigation conducted by the according to the survey, heat conductivity of wooden walls were in that time in the range of 0,54…0,92 W/($m^2 \cdot K$), look **Image 1**. Comparison with the thermal conductivity of the walls should be aware that “upright-plank-wall” and frame-wall are with significantly smaller airtightness, which increases the cost of space heating.

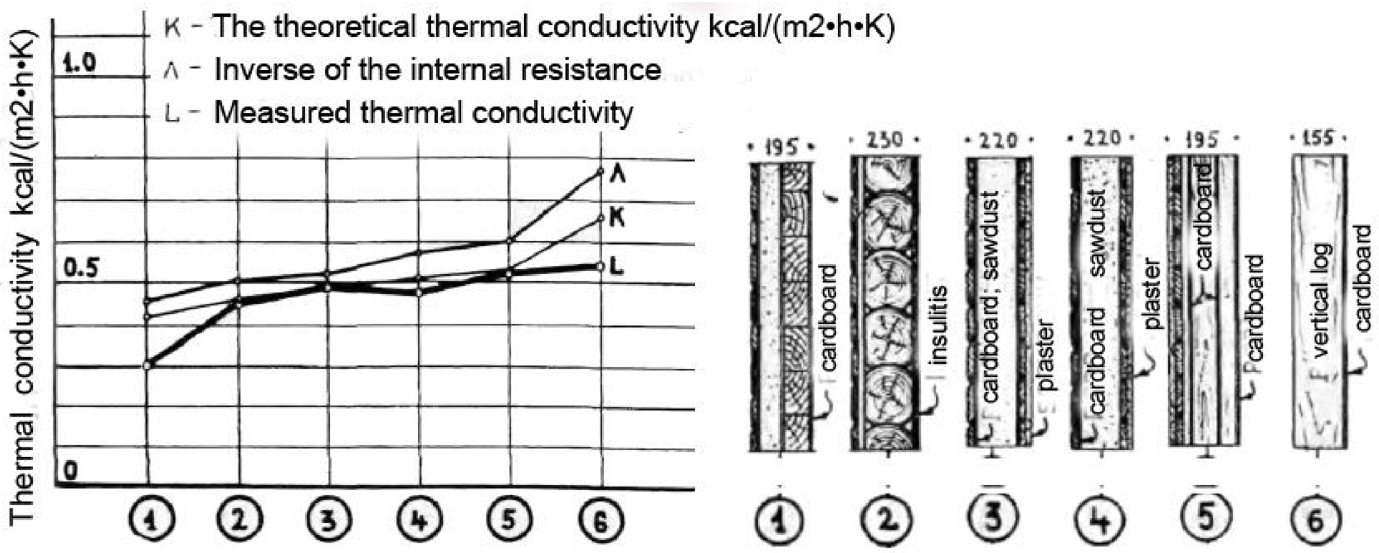


Image 1. measured thermal conductivities of wooden walls.

Requirements for thermal resistance of walls in 1937 in Nõmme city construction regulations:

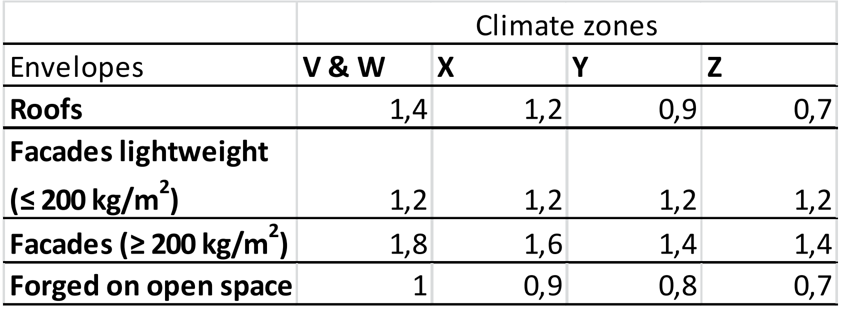
In the project must be showed, is residential built only for either summer or permanent use.

In summer residence it's not allowed to have stoves or other sources of heat in a residential apartment except cookers and it's heat-wall building structures shall be deemed sufficient if they meet the strength requirements of construction static rules.

Permanent residential needs to ensure of its external walls and ceiling thickness, design, and construction supplies in the material selection, that there is not going to be condensation of moisture in the residential.

In order to achieve this, dwellings limiting the external walls and ceilings can't let out the heat more than 0.9 kg cal. per square meter of surface area per hour, if the temperature difference between the interior and exterior is 1^oC by the means of the thermal technical calculations. [2]

In Spain, one of the first regulation what was used for thermal calculations were "RD 2429 1979 CT-79 condiciones termicas edificios" in year 1979. Area of Spain were divided into 5 climate zones (same in present) and every zone had its own requirements for thermal resistance of envelopes, look **Image 2**. [3]



	Climate zones			
Envelopes	**V & W**	**X**	**Y**	**Z**
Roofs	1,4	1,2	0,9	0,7
Facades lightweight (≤ 200 kg/m^2)	1,2	1,2	1,2	1,2
Facades (≥ 200 kg/m^2)	1,8	1,6	1,4	1,4
Forged on open space	1	0,9	0,8	0,7

Image 2. requirements for thermal conductivity W/(m^2·K) in Spain in 1979 for every climate zone.

2.2 Overview of the thermal calculations regulations and methods

2.2.1 Overview of regulations

Thermal behavior calculations have been made following the two regulations, which are: "EVS 908 -1:2010 HOONE PIIRDETARINDI SOOJUSJUHTIVUSE ARVUTUS (THERMAL CALCULATIONS FOR THE BUILDING ENVELOPE)" for Estonia and “Documento Basico HE: Ahorro de energia” for Spain. Both regulations are made to meet the requirements of minimum energy-efficient requirements.

Main minimum energy-efficient requirements for Estonia:

- Value of energy-efficient of buildings under construction shall not exceed the following limits:
    - Small houses (including semi-detached houses and townhouses), 180 kWh per square meter per year.
    - Apartment blocks of 150 kWh per square meter per year.
    - Office and administration buildings 220 kWh per square meter per year.
- General requirements for the external walls of the buildings:
    - To achieve thermal comfort in the rooms, value of the thermal conductivity can’t normally exceed 0,5 watts per square meter and degree [W/(m^2K)]. Windows with the higher value of the heat conductivity must ensure thermal comfort with heating solutions. To prevent mold, condensation and excessive heat losses, normally joints with higher heat conductivity will be insulated in the outside with adequate insulation.
    - Insulation must be selected on the basis that the building would be a good level of energy-efficiency. Generally, total special heat loss of the residential envelope is limited in heated surface area till value of 1,0 W/(m^2K). Selection of the insulation of a small buildings can be built on the following basic data: external wall thermal conductivity 0,2–0,25 W(m^2K), roofs and floors, thermal conductivity 0,15–0,2, windows and doors, thermal conductivity 0,7-1,4 W(m^2K), the final selections depend on the compactness of the building and the heating and ventilation solutions. Other buildings optimal insulation depends significantly on the free heat.
    - The average value of air leakage in envelope normally don’t exceed one cubic meters per hour per square meter of envelope [m^3/(hm^2)]. To avoid risks of moisture convection, building structure critical joints (eg, wall and roof connections, roof ceilings steam or air barrier joints, bushings) must be almost completely air resistant. [7]

Main minimum energy-efficient requirements for Spain:

To avoid decompensation between the thermal quality in different areas, each of the enclosures and interior partitions of the thermal envelope will have a transmittance not exceeding the values shown in Table 1.1 depending on the climate zone where building locates.

Enclosures and interior partitions	AREAS A	AREAS B	AREAS C	AREAS D	AREAS F
Facade walls, interior partitions contact habitable rooms, first meter perimeter resting on the ground floor and first metro walls in contact with the ground	1,22	1,07	0,95	0,86	0,74
Floors	0,69	0,68	0,65	0,64	0,62
Roofs	0,65	0,59	0,53	0,49	0,46
Windows and frames	5,70	5,70	4,40	3,50	3,10
Dividing walls	1,22	1,07	1,00	1,00	1,00

Table 1. Requirements for the U value (W/m2K) in Spain, Valencia.

In residential buildings, interior partitions that limit use with system units heating provided in the project, with the areas of the building unheated, will each transmittance not exceeding 1.2 W/m2K. [8]

2.2.2 Calculations method overview: EVS 908 -1:2010

Thermal resistance of the layer of the materials is calculated using the formula:

$$R = \frac{d}{\lambda}\left(\frac{m^2K}{W}\right),$$

where d- material layer thickness (m);

λ- thermal conductivity of materials (W/mK).

Thermal resistance of the inner and exterior surface of the building envelope					
Thermal resistance of the inner surface $R_{si} = \frac{m^2K}{W}$			Thermal resistance of the exterior surface $R_{se} = \frac{m^2K}{W}$		
Heat flow direction					
Hor.	Up	Down	Hor.	Up	Down
0,13	0,10	0,17	0,04	0,04	0,04

Table 2. Thermal resistance of the inner and exterior surface

Thermal conductivity is calculated using the formula:

$$U = \frac{1}{R_t}\, W/(m^2K)$$

where R_t –the total thermal resistance of the envelope.

Facade internal surface temperature is determined by applying the formula:

$$T_s = t_s - (t_s - t_v)\frac{R_{si}}{R_t}\,(°\text{C})$$

Similarly, we can find the temperature at any wall point x:

$$T_x = t_s - (t_s - t_v)\frac{R_{si} + R_x}{R_t}\,(°\text{C})$$

where T_s – temperature in internal surface

t_s – the internal temperature of the room

t_v – external temperature

R_x – thermal resistance of each successive layer.

Through the wall, flowing vapor meets on the way with material resistance which is similar to the heat resistance:

$$R_a = \frac{d}{\delta_i}\,\left(\frac{m^2h\ Pa}{kg}\right)$$

where R_a – vapor resistance of the material

d – material layer thickness (m)

δ_i – vapor permeability of the material (kg/mh Pa).

Multi-layer barrier vapor resistance is calculated:

$$R_a = R_{a1} + R_{a2} + \cdots + R_{an}\,\left(\frac{m^2h\ Pa}{kg}\right)$$

where R_{a1}, R_{a2},..., R_{an} vapor resistance of the individual layers.

General vapor resistance of the barrier is given by:

$$R_{aü} = R_{as} + R_a + R_{av}\ (m^2h\ Pa/kg)$$

where R_{as} – vapor resistance of the facade internal surface (in calculations will be 1,5)

R_{av} – vapor resistance of the facade external surface (in calculations will be 0,75).

Vapor partial pressure in the point x:

$$e_x = e_s - (e_s - e_v)\frac{R_{ax}}{R_{aü}}$$

where e_s – vapor partial pressure in the indoor air (Pa)

e_v – vapor partial pressure in the outdoor air (Pa)

$R_{a\text{-}x}$ – vapor resistance between the facade internal surface and the point x (m^2h Pa/g)

$R_{aü}$ – general vapor resistance of the barrier (m^2h Pa/g). [9]

2.2.3 Calculations method overview: Documento Basico HE: Ahorro de energia

Calculating conditions for condensation:

1) external conditions:
   - calculating the saturation pressure Psat provincial capital in [Pa], from its outdoor temperature for the month of calculation in [° C]
   - calculation of the vapor pressure in capital of provincial P_e [Pa], by the expression:

     $P_e = \varphi_e \cdot P_{sat}(\theta_e)$

     where φ_e - outdoor relative humidity for the provincial capital and the month of calculation.
   - calculating the saturation pressure of the locality Psat [Pa], where θ is outside temperature for the locality and the month of calculation [º C].
   - calculation of the relative humidity to that location and month, by:

     $\phi_{e,loc} = P_e / P_{sat,loc}(\theta_{e,loc})$
2) Monthly climatic data in Valencia:
   - $T_{med(January)}$= 10,4 º C
   - $HR_{med(January)}$= 63%
3) Condiciones interiores:
   - It will take an internal ambient temperature of 20 ° C for January.
   - Class 3 or lower relative humidity: 55%

Controlling the condensation:

1) surface condensation:
   - Temperature factor of the inner surface of an enclosure: the temperature factor of the inner surface f_{Rsi}, for each enclosure, internal partition or thermal bridges built into the enclosures, is calculated from thermal transmittance by the following equation:

     $f_{Rsi} = 1 - U * 0{,}25$

     where U- the thermal transmittance of the enclosure, interior partition, or integrated into the thermal envelope.

- Minimum temperature factor of the inner surface: the temperature factor of acceptable minimum of the inner surface f_{Rsi}, min of a thermal bridge, enclosure or interior partition may be calculated from the following expression:

  $$f_{Rsi,min} = \frac{\theta_{si,min} - \theta_e}{20 - \theta_e}$$

  where θ_e- outdoor temperature of the town in January [ºC]

  $\theta_{si,min}$- the minimum acceptable internal surface temperature obtained from the following expression [° C]:

  $$\theta_{si,min} = \frac{237{,}3 \log_e\left(\frac{Psat}{610{,}5}\right)}{17{,}269 - \log_e\left(\frac{Psat}{610{,}5}\right)}$$

  where Psat- the maximum acceptable saturation pressure at the surface obtained from the following expression [Pa]:

  $$Psat = \frac{P_i}{0{,}8}$$

  where P_i- steam pressure which is obtained indoor with the following expression [Pa]:

  $$P_i = \theta_i * 2337$$

  where θ_i- is the indoor relative humidity.

2) Interstitial condensation

- The procedure for calculating the temperature distribution follows: calculation of the outer surface temperature θ_{se}:

  $$\theta_{se} = \theta_e + \frac{R_{se}}{R_T} * (\theta_i - \theta_e)$$

  where θ_e- outside temperature of the local area (Valencia) [ºC]

  θ_i- indoor temperature

  R_T- the total thermal resistance [m2 K / W]

  R_{se}- surface thermal resistance corresponding to the outside air [m2 K / W].

- Calculating the temperature in each of the layers composing the construction element according to the following expressions:

  $$\theta_1 = \theta_{se} + \frac{R_1}{R_T} * (\theta_i - \theta_e)$$

  $$\theta_2 = \theta_1 + \frac{R_2}{R_T} * (\theta_i - \theta_e)$$

  $$\dots$$

  $$\theta_n = \theta_{n-1} + \frac{R_n}{R_T} * (\theta_i - \theta_e)$$

  where θ_e- outdoor temperature

  θ_1 ... θ_{n-1}- the temperature in each layer [° C].

  R_1 ... R_n- thermal resistances of each layer [m2 K / W].

- calculating the inner surface temperature θ_{si}:

  $$\theta_{si} = \theta_n + \frac{R_{si}}{R_T} * (\theta_i - \theta_e)$$

  where θ_n- the temperature in the layer n [° C]

  R_{si}- surface thermal resistance corresponding to the indoor air [m2 K / W].

- Vapor pressure distribution: the vapor pressure distribution throughout the enclosure shall be calculated using the following expressions:

  $$P_1 = P_e + \frac{S_{d1}}{\sum S_{dn}} * (P_i - P_e)$$

  $$P_2 = P_1 + \frac{S_{d2}}{\sum S_{dn}} * (P_i - P_e)$$

  $$\dots$$

  $$P_n = P_{n-1} + \frac{S_{d(n-1)}}{\sum S_{dn}} * (P_i - P_e)$$

  where P_i- the vapor pressure of the inside air [Pa]

  P_e- the vapor pressure of the outdoor air [Pa]

  P_1 ... P_{n-1}- the vapor pressure in each layer n [Pa]

  S_{d1} ... $S_{d(n-1)}$- air equivalent thickness of each layer against the diffusion of vapor water calculated by the following expression [m]:

  $$S_{dn} = e_n * \mu_n$$

  where μ_n- is a factor of resistance to water vapor diffusion of each layer

  e_n- is the n layer thickness [m].

- For analytical calculation of Pi and Ps, as a function of temperature and relative humidity, the following expression is used:
  $P_i = \phi_i * P_{sat}(\theta_i)$
  $P_e = \phi_e * P_{sat}(\theta_e)$
  where ϕ_i- the relative humidity of the indoor environment
  ϕ_e- the relative humidity of the outdoor environment. [8]

2.2.4 Comparison of two methods

Basically these two methods are with the same system. Differences are in the shapes of the formulas and signs and maximum vapor partial pressure are found differently. In the method of Estonia maximum vapor partial pressure is found by means of table of the ratio between temperature and vapor pressure. In Spain it is calculated manual by specific formula.

3 Thermal calculations: model walls

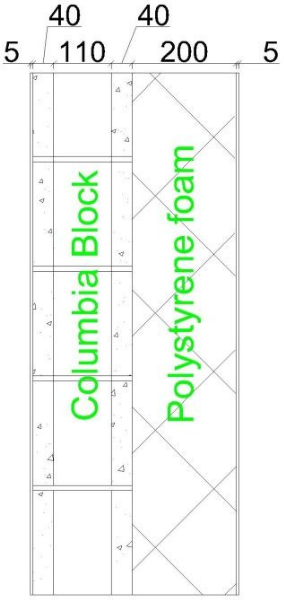
3.1 Structure and materials of the models walls

The choice of building materials for the model wall constructions was based on the building tradition in each country, climate, material cost and good indicators of the thermal conductivity.

Model 1, masonry-structure:
Wall 1

Wall components	thickness (m)
cement plaster	0,005
Columbia block *	0,19
polystyrene foam	0,2
cement plaster	0,005
Total	0,4

Columbia block *- concrete hollow blokk
Table 3. Model 1 wall structure and choice of materials. [4]



Roof 1

Roof components	**thickness (m)**
2xSBS	0,006
Rockwool slab (strengthened)	0,02
Rockwool slab with ventilation slots	0,08
Rockwool slab	0,18
rockwool slab	0,18
Vapor barrier	0,001
reinforced concrete panel	0,25
cement plaster	0,005
Total	

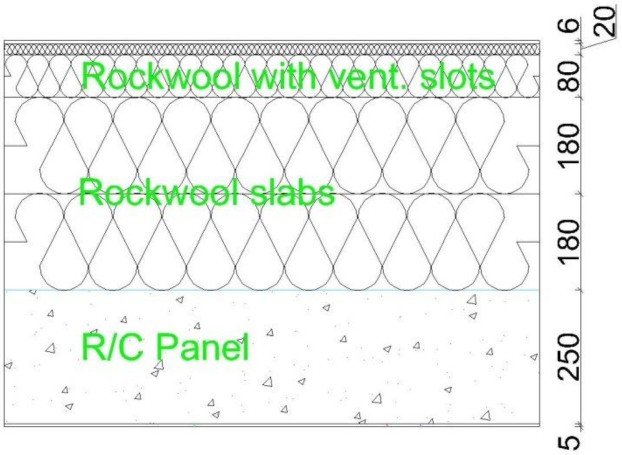


Table 4. Model 1 roof structure and choice of materials. [4]

Floor 1

Floor components	**thickness (m)**
ceramic tile	0,005
blinding	0,01
reinforce concrete	0,1
expanded polystyrene EPS	0,15
sand	0,4
untouched soil	-
Total	

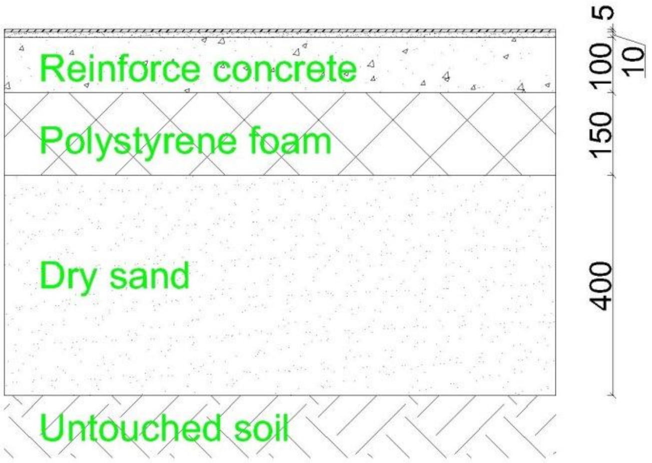
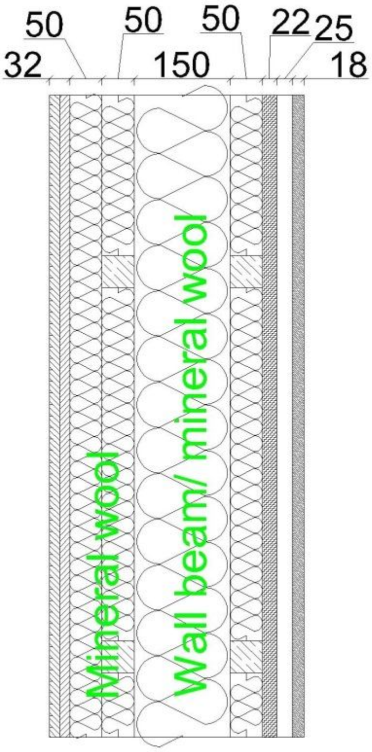


Table 5. Model 1 floor structure and choice of materials. [4]

Model 2, frame-structure:
Wall 2



Wall components	**thickness (m)**
gypsum wallboards	0,026
wall purlins (V)	0,05
wall purlins (H)	0,05
wall beam	0,15
glass wool	0,3
Paper*	m/λ=
wall purlins (H)	0,05
wind barrier slab*	0,02
wall purlins (V)	0,02
air space	0,02
timber cladding	0,018
Total	0,384

wind barrier slab*- compressed and dense rockwool slab
Table 6. Model 2 wall structure and choice of materials. [4]

Roof 2

Roof components	**thickness (m)**
roof tile	0,025
roof purlins (H)	0,05
roof purlins (V)	0,02
wind barrier material*	0,001
roof rafter	0,2
glass wool	0,185
Vapor barrier	0,001
wall purlins (H)	0,05
glass wool	0,05
gypsum wallboards	0,026
Total	0,371

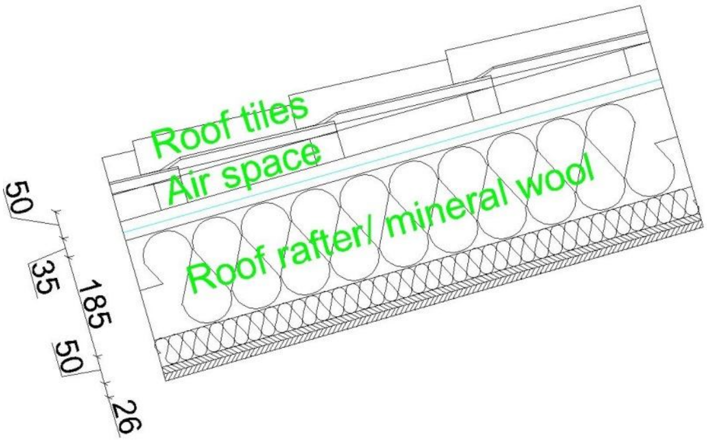
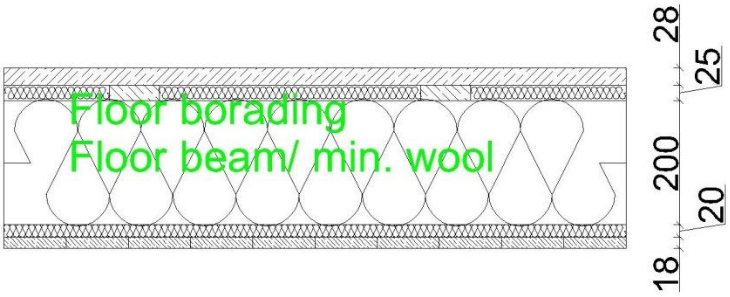


Table 7. Model 2 roof structure and choice of materials. [4]

Floor 2

Wall components	**thickness (m)**
timber boarding	0,028
floor purlin	0,025
glass wool	0,025
floor beam	0,22
glass wool	0,2
wind barrier	0,02
floor ground boarding*	0,018
Total	0,311

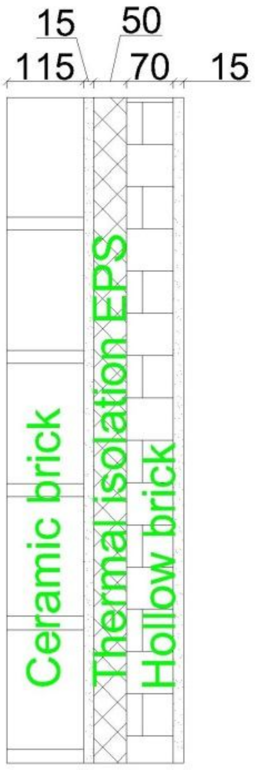
Table 8. Model 2 floor structure and choice of materials. [4]



Model 3 (for the floor is used „Floor 1“), masonry-structure:
Wall 3

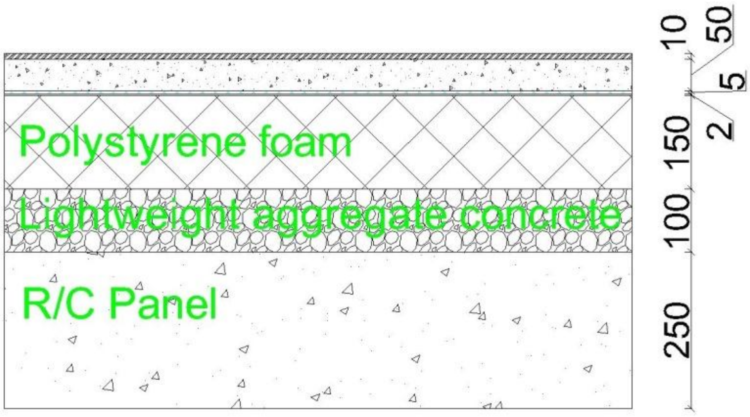
Wall components	**thickness (m)**
ceramic brick	0,115
plaster mortar*	0,015
thermal insulation*	0,05
hollow brick	0,07
lining (plaster mortar)	0,015
Total	0,265

Table 9. Model 3 wall structure and choice of materials. [6]



Roof 3

Roof components	**thickness (m)**
ceramic tile	0,01
blinding*	0,05
polyethylene foam	0,005
PVC roof coating	0,002
expanded polystyrene EPS	0,15
Lightweight aggregate concrete*	0,1
reinforced concrete panel	0,25
Total	0,567



blinding- concrete with ρ=2000 kg/m3

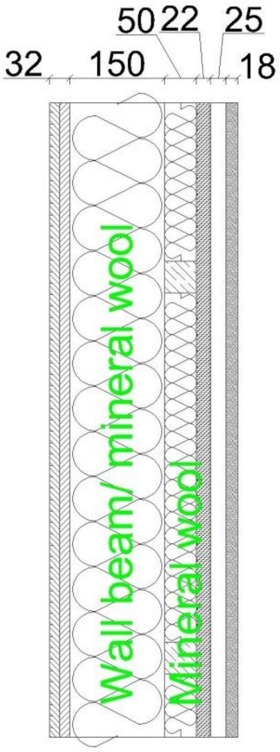
Lightweight aggregate concrete*- Concrete for the slope formation

Table 10. Model 3 roof structure and choice of materials. [6]

Model 4 (for the floor is used „Floor 2“), frame-structure:
Wall 4

Wall components	**thickness (m)**
timber cladding	0,018
air space	0,02
wall purlins (V)	0,05
wind barrier slab*	0,02
wall purlins (H)	0,05
glass wool	0,05
paper*	
glass wool	0,15
wall beam	0,15
gypsum wallboards	0,026
Total	0,304

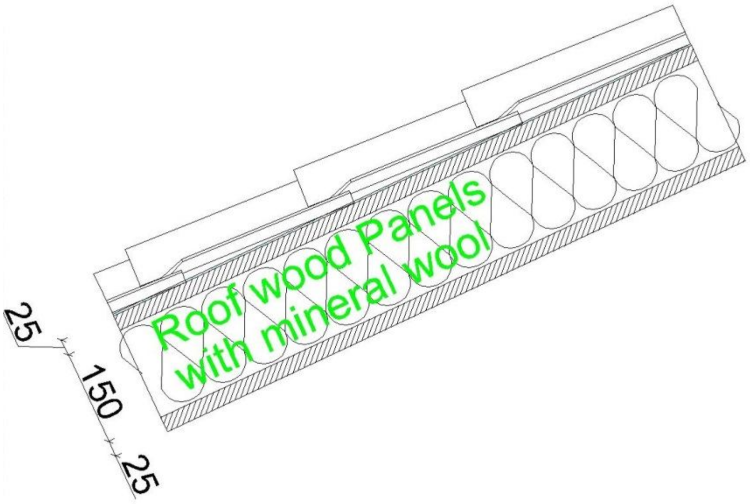
Table 11. Model 4 wall structure and choice of materials. [6]



Roof 4

Roof components	**thickness (m)**
concrete roof tile	0,03
PVC roof coating	0,002
solid wood panels (SWP)	0,025
mineral wool (MW)	0,15
solid wood panels (SWP)	0,025
Total	0,232

Table 12. Model 4 roof structure and choice of materials. [6]



3.2 Thermal manual calculations:

3.2.1 Model 1

Wall:

Initial data: indoor and outdoor temp.: T_i= 22° C and T_i= -23°; thermal resistance of the inner and exterior surface: R_i=0,13 and R_o=0,04. Calculations results of the first model wall shows, that requirements for the U value are compliant with the regulations in Estonia (EVS 908 -1:2010). U=0,2<0,25 W(m^{2}K) and total thermal resistance of the wall is R_T=4,89 (m^{2}k/W) (Table 13.). Vapour partial pressure does not exceed maximum vapour pressure in any layer, which means, that there is no risk for the condensation. (Image 3.). [5]

wall components	thickness (m)	thermal-conductance (λ)	S_n (W/m^{2}K)	R0=	U=	Vapor conductance (m h Pa)
cement plaster	0,005	0,81	9,76	0,006	0,205	0,12
Columbia block *	0,19	1,19	10,9	0,160		0,11
polystyrene foam	0,2	0,044	0,49	4,545		0,05
cement plaster	0,005	0,81	9,76	0,006		0,12
Total	0,4			4,887		

Temp. In every layer		Vapor tightness		Vapor partial pressure (Pa)		Max. vapor partial pressure (Pa)	
T_{is}=	20,8031	R_{a1}=	0,041667	id $e_{s\ t22/p45\%}$=	1185,4	E_1=	2457,344
T1=	20,7462	R_{a2}=	1,727273	e_{a1}=	1177,2	E_2=	2448,908
T2=	19,2762	R_{a3}=	4	e_{a2}=	839,83	E_3=	2236,126
T3=	-22,575	R_{a4}=	0,041667	e_{a3}=	58,538	E_4=	82,7568
T_{IO}=	-22,632	R_a=	5,810606	od $e_{s\ t-23/p80\%}$=	50,4	E_5=	82,2912

Table 13. Model 1external wall calculations results.

Roof:

Initial data: indoor and outdoor temp.: T_i= 22° C and T_i= -23°; thermal resistance of the inner and exterior surface: R_i=0,10 and R_o=0,04. Calculations results of the first model Roof shows, that requirements for the U value are compliant with the regulations in Estonia (EVS 908 -1:2010). U=0,08<0,15 W(m^{2}K) and total thermal resistance of the wall is R_T=12,93 (m^{2}k/W) (Table 14.). Vapor partial pressure exceed maximum vapour pressure line under roof covering layer, but it does not show the risk of condensation, because the upper slab of mineral wool is with ventilation slots. Only possible risk can be in the cero point, which is center of mineral wool slabs. If ventilation is not good enough, wool can absorb and keep moisture and and it will significantly affects wool thermal insulation properties (Image 7.). [5]

Roof components	thickness (m)	thermal-conductance (λ)	S_n (W/m^{2}K)	R0=	U=	Vapor conductance (m h Pa)
2xSBS	0,006	0,18	3,53	0,03	0,08	0,008
Rockwool slab (strengthened)	0,02	0,038	1,11	0,53		0,5
Rockwool slab with ventilation slots	0,08	0,036	0,5	2,22		0,5
Rockwool slab	0,18	0,036	0,5	5,00		0,5
rockwool slab	0,18	0,036	0,5	5,00		0,5
Vapor barrier	0,001			0,02		0,002
reinforced concrete panel	0,25	2,04	18,95	0,12		0,03
cement plaster	0,005	0,81	9,76	0,01		0,09
Total				12,93		

Temp. In every layer		Vapor tightness		Vapor partial pressure (Pa)		Max. vapor partial pressure (Pa)	
T_{IO}=	-22,79	R_8=	0,75	od $e_{s\ t-23/p80\%}$=	50,40	E_9=	81,0496
T7=	-22,68	R_7=	0,04	e_{a7}=	131,02	E_8=	81,9032
T6=	-20,87	R_6=	0,16	e_{a6}=	135,32	E_7=	95,9488
T5=	-13,22	R_5=	0,36	e_{a5}=	152,51	E_6=	194,794
T4=	4,00	R_4=	0,36	e_{a4}=	191,21	E_5=	813,3
T3=		R_3=	0,50	e_{a3}=	229,90	E_4=	
T2=	21,21	R_2=	8,33	e_{a2}=	283,65	E_3=	2519,533
T1=	21,63	R_1=	0,06	e_{a1}=	1179,38	E_2=	2585,599
T_{is}=	21,66	R_a=	10,56	id $e_{s\ t22/p45\%}$=	1185,35	E_1=	2590,318

Table 14. Model 1external roof calculations results.

Floor:

Initial data: indoor and outdoor temp.: T_i= 22° C and T_i= -23°; thermal resistance of the inner and exterior surface: R_i=0,17 and R_o=0,04. Calculations results of the first model floor shows, that requirements for the U value is compliant with the regulations in Estonia (EVS 908 -1:2010). U= <0,25 W(m^{2}K) and total thermal resistance of the wall is R_T=5,21 (m^{2}k/W) (Table 15.). Calculations for U value was made with Spanish method and in case, where floor is united with soil. In this case, there are no risk for condensation, when there are enough dry sand. Problem can be with thermal bridges, in case, if foundation is not isolated with the required insulation. [8]

FLoor components	thickness (m)	thermal-conductance (λ)	**R=**	**U*=**
ceramic tile	0,005	2,5	0,00	U<0,27
blinding	0,01	1,86	0,01	
reinforce concrete	0,1	2,04	0,05	
expanded polystyrene EPS	0,15	0,033	4,55	
sand	0,4	1	0,40	
untouched soil	-			
Total			5,21	

Table 15. Model 1floor calculations results.

U*- U value is taken from table and it depends on total thermal resistance R and value of B’. B’ is coming from formula:

$$B' = \frac{A}{\frac{1}{2} * P}$$

where A is total floor area

and P is perimeter length of the floor.

3.2.2 Model 2

Wall:

Initial data: indoor and outdoor temp.: T_i= 22° C and T_i= -23°; thermal resistance of the inner and exterior surface: R_i=0,13 and R_o=0,04. Calculations results of the second model wall shows, that requirements for the U value is compliant with the regulations in Estonia and even better solution than first model wall(EVS 908 -1:2010). U=0,105<0,25 W(m^2K) and total thermal resistance of the wall is R_T=9,52 (m^2k/W) (Table 16.). Vapour partial pressure exceed maximum vapour pressure in two layers, which means, that there is a little risk for the condensation, but it’s not progressive, because condensation area is small and locates behind the wind barrier (Image 4.). [5]

wall components	thickness (m)	thermal-conductance (λ)	S_n (W/m^{2}K)	R0=	R'0*=	U=	conductance (m h Pa)
gypsum wallboards	0,026	0,21	3,66	0,12381	0,12381	0,105	0,12
wall purlins (V)	0,05	0,18	4,54		0,277778	U'*=	0,06
wall purlins (H)	0,05	0,18	4,54		0,277778	0,413	0,06
wall beam	0,15	0,18	4,54		0,833333		0,06
glass wool	0,3	0,033	0,5	9,090909			0,5
Paper*	m/λ=	0,02		0,02	0,02		0,01
wall purlins (H)	0,05	0,18	4,54		0,277778		0,06
wind barrier slab*	0,02	0,07	1,11	0,285714	0,285714		0,49
wall purlins (V)	0,02	0,18	4,54		0,111111		0,06
air space	0,02						
timber cladding	0,018	0,18	4,54		0,1		0,06
Total	0,384		32,51	9,520433	2,418413		1,48

Temp. In every layer		Vapor tightness		Vapor partial pressure (Pa)		Max. vapor partial pressure (Pa)	
T_{is}=	21,4	R_{a1}=	0,216667	id $e_{s\ t22/p45\%}$=	1185,4	E_1=	2549,42
T1=	20,8	R_{a2}=	0,1	e_{a1}=	898,6	E_2=	2459,86
T2=	13,6	R_{a3}=	0,1	e_{a2}=	766,2	E_3=	1577,227
T3=	6,5	R_{a4}=	0,3	e_{a3}=	633,9	E_4=	984,55
T1=	-15,0	R_{a5}=	0,1	e_{a4}=	236,8	E_5=	175,504
T2=	-22,2	R_{a6}=	0,040816	e_{a5}=	104,4	E_6=	91,9136
T_{IO}=	-23,5			od $e_{s\ t-23/p80\%}$=	50,4	E_7=	81,5928
		R_a=	0,857483			E_8=	

Table 16. Model 2 external wall calculations results.

Roof:

Initial data: indoor and outdoor temp.: T_i= 22° C and T_i= -23°; thermal resistance of the inner and exterior surface: R_i=0,10 and R_o=0,04. Calculations results of the first model Roof shows, that requirements for the U value are compliant with the regulations in Estonia (EVS 908 -1:2010). U=0,14<0,15 W(m^{2}K) and total thermal resistance of the wall is R_T=7,29 (m^{2}k/W) (Table 17.). Vapor partial pressure exceed maximum vapour pressure line behind one layer, which is vapour barrier. It may be risk for condensation in vapour barrier surface, if moisture throughput is not fast enough. Under the vapour barrier is little airspace, but without ventilation and after that becomes mineral wool layer. In case of condensation, it can significantly affect the wool thermal insulation properties (Image 8.). [5]

wall components	thickness (m)	thermal-conductance (λ)	S_n (W/m^{2}K)	R0=	U=	Vapor conductance (m h Pa)
roof tile	0,025	1,86	17,88		0,137	0,03
roof purlins (H)	0,05	0,18	4,54			0,06
roof purlins (V)	0,02	0,18	4,54			0,06
wind barrier material*	0,001			0,02		0,008
roof rafter	0,2	0,18	4,54			0,06
glass wool	0,185	0,033	0,5	5,61		0,5
Vapor barrier	0,001			0,02		0,08
wall purlins (H)	0,05	0,18	4,54			0,06
glass wool	0,05	0,033	3,66	1,52		0,5
gypsum wallboards	0,026	0,21		0,12		0,12
Total				7,285		1,478

Temp. In every layer		Vapor tightness		Vapor partial pressure (Pa)		Max. vapor partial pressure (Pa)	
T_{IO}=	-23,4942	R_{a1}=	0,216667	od $e_{s\ t-23/p80\%}$=	50,40	E_1=	2549,42
T2=	-23,3706	R_{a2}=	0,1	e_{a3}=	222,54	E_2=	2459,86
T1=	11,25834	R_{a3}=	0,0125	e_{a4}=	732,06	E_3=	1577,227
T2=	20,61752	R_{a4}=	0,37	e_{a5}=	749,27	E_4=	984,55
T_{is}=	21,38229	R_{a5}=	0,125	e_{a6}=	886,98	E_5=	91,9136
				id $e_{s\ t22/p45\%}$=	1185,35	E_6=	81,5928

Table 17. Model 2 external roof calculations results.

Floor:

Initial data: indoor and outdoor temp.: T_i= 22° C and T_i= -23°; thermal resistance of the inner and exterior surface: R_i=0,17 and R_o=0,04. Calculations results of the first model floor shows, that requirements for the U value is compliant with the regulations in Estonia (EVS 908 -1:2010). U= <0,27 W(m^{2}K) and total thermal resistance of the wall is R_T=7,84 (m^{2}k/W) (Table 18.). Calculations for U value was made with Spanish method and in case, where floor is not united with soil and between soil and floor, there is ventilation space. In this case, there are no risk for condensation, when there is required ventilation. [8]

Floor components	thickness (m)	thermal-conductance (λ)	R=	U=
timber boarding	0,028	0,18	0,16	U<0,27
floor purlin	0,025	0,18	0,14	
glass wool	0,025	0,033	0,76	
floor beam	0,22	0,18	1,22	
glass wool	0,2	0,033	6,06	
wind barrier	0,02	0,036	0,56	
floor ground boarding*	0,018	0,18	0,10	
Total			7,84	

Table 18. Model 2 floor calculations results.

3.2.3 Model 3

Wall:

Initial data: indoor and outdoor temp.: θi= 20°C and θe= 10,4°C; thermal resistance of the inner and exterior surface: R_i=0,10 and R_o=0,04.

Calculations results of the first model wall shows, that requirements for the U value are compliant with the regulations in Spain (Documento Basico HE: Ahorro de energia). U=0,44<0,86 W(m^{2}K) and total thermal resistance of the wall is R_T=2,26 $\left(\frac{m^2K}{W}\right)$ (Table 19.). Vapour partial pressure does not exceed maximum vapour pressure in any layer, which means, that there is no risk for the condensation. (Image 5.). [8]

Wall components	μ	thickness (m)	thermal-conductance (λ)	R (m^{2}K/W)	U=
ceramic brick	10	0,115	0,35	0,18	0,44
plaster mortar*	10	0,015	1,3	0,01	
thermal insulation*	100	0,05	0,029	1,72	
hollow brick	10	0,07	0,4375	0,16	
lining (plaster mortar)	10	0,015	1,3	0,01	
Total	140	0,265		2,26	

plaster mortar*- high resistance to the filtration consists of a plaster mortar

thermal insulation*- Poliestireno Expandido (EPS)

Table 19. Model 3 external wall calculations results.

Condensation risk has been calculated by Spanish regulation (Documento Basico HE: Ahorro de energia) and its includes:

- Temperature factor on inner surface:
  f_{Rsi}=0,889
- Minimum temperature factor on inner surface:
  $f_{Rsi,min}$=-0,467

Roof:

Initial data: indoor and outdoor temp.: θi= 20°C and θe= 10,4°C; thermal resistance of the inner and exterior surface: R_i=0,17 and R_o=0,04.

Calculations results of the first model wall shows, that requirements for the U value are compliant with the regulations in Spain (Documento Basico HE: Ahorro de energia). U=0,175<0,86 W(m^2K) and total thermal resistance of the wall is R_T=5,7 $\left(\frac{m^2K}{W}\right)$ (Table 20.). Vapour partial pressure does not exceed maximum vapour pressure in any layer, which means, that there is no risk for the condensation. (Image 9.). [8]

Roof components	μ	thickness (m)	thermal-conductance (λ)	R (m^2K/W)	U=	Temp. In every layer		S_D	Vapor pressure P (Pa)		Vapor pressure(θ)P_{sat} (Pa)	
ceramic tile	10000	0,01	1,3	0,008	0,175	θ_{Se}=	10,47	100	P_1=	938,6	$P_{sat(\theta e)}$=	1260,6
blinding*	70	0,05	1,65	0,030		θ_1=	10,48	3,5	P_2=	943,7	$P_{sat,1}$=	1267,3691
polyethylene foam	100	0,005	0,05	0,100		θ_2=	10,53	0,5	P_3=	944,4	$P_{sat,2}$=	1271,6897
PVC roof coating	100000	0,002	0,14	0,014		θ_3=	10,70	200	P_4=	1233,3	$P_{sat,3}$=	1286,0398
expanded polystyrene EPS	100	0,15	0,029	5,172		θ_4=	10,72	15	P_5=	1255,0	$P_{sat,4}$=	1288,1014
Lightweight aggregate concrete*	60	0,1	1,15	0,087		θ_5=	19,43	6	P_6=	1263,7	$P_{sat,5}$=	2255,5652
reinforced concrete panel	60	0,25	2,04	0,123		θ_6=	19,57	15			$P_{sat,6}$=	2276,1705
Total	110390	0,567		5,704		θ_{Si}=	19,78	340			$P_{sat(\theta i)}$=	2305,4893

blinding- concrete with ρ=2000 kg/m3
Lightweight aggregate concrete*- Concrete for the slope formation
plaster mortar*- high resistance to the filtration consists of a plaster mortar
thermal insulation*- Poliestireno Expandido (EPS)

Table 20. Model 3 external roof calculations results.

Floor: for this Model 3 is used Model 1 floor.

3.2.4 Model 4

Wall:

Initial data: indoor and outdoor temp.: θi= 20°C and θe= 10,4°C; thermal resistance of the inner and exterior surface: R_i=0,13 and R_o=0,04.

Calculations results of the first model wall shows, that requirements for the U value are compliant with the regulations in Spain (Documento Basico HE: Ahorro de energia). U=0,13<0,86 W(m^{2}K), which is almost seven times more than aloud and total thermal resistance of the wall is R_T=7,71 $\left(\frac{m^2K}{W}\right)$ (Table 21.). Vapour partial pressure does not exceed maximum vapour pressure in any layer, which means, that there is no risk for the condensation. (Image 6.). [8]

wall components	μ	thickness (m)	thermal-conductance (λ)	R (m^2K/W)	U=	Temp. In every layer		S_D	Vapor pressure P (Pa)		Vapor pressure(θ)P_{sat} (Pa)	
timber cladding	20	0,018	0,18		0,13	θ_{Se}=	10,45		P_e=	794,178	$P_{sat(\theta e)}$=	1264,8
air space	-	0,02				θ_1=	10,81		P_1=	824,78	$P_{sat,1}$=	1295,2
wall purlins (V)	20	0,05	0,18			θ_2=	13,03		P_2=	939,52	$P_{sat,2}$=	1500,0
wind barrier slab*	100	0,02	0,07	0,29		θ_3=	19,71	2	P_3=	1283,76	$P_{sat,3}$=	2294,6
wall purlins (H)	20	0,05	0,18			θ_{Si}=	19,81		P_4=	1285,35	$P_{sat(\theta i)}$=	2310,1
glass wool	150	0,05	0,028	1,79				7,5	P_i=	1285,35		
Paper*				0,02								
glass wool	150	0,15	0,028	5,36				22,5				
wall beam	20	0,15	0,18									
gypsum wallboards	4	0,026	0,3	0,09				0,10				
Total	484	0,304		7,71				32,10				

Table 21. Model 4 external wall calculations results.

Roof:

Initial data: indoor and outdoor temp.: θi= 20°C and θe= 10,4°C; thermal resistance of the inner and exterior surface: R_i=0,17 and R_o=0,04.

Calculations results of the first model wall shows, that requirements for the U value are compliant with the regulations in Spain (Documento Basico HE: Ahorro de energia). U=0,33<0,86 W(m^{2}K) and total thermal resistance of the wall is R_T=3,3 $\left(\frac{m^2K}{W}\right)$ (Table 22.). Vapour partial pressure does not exceed maximum vapour pressure in any layer, but there is point of tangency under the PVC roof coating. It can be risk for the condensation, because PVC is strong moisture barrier and vapour has no direction to move out and moisture gathers top of the wood slab. Accumulated moisture can damage the wood slabs and affect the mineral wool thermal insulation properties (Image 10.). [8]

Roof components	μ	thickness (m)	thermal-conductance (λ)	R (m^2K/W)	U=	Temp. In every layer		S_D	Vapor pressure P (Pa)		Vapor pressure(θ)P_{sat} (Pa)	
concrete roof tile	60	0,03	1,5	0,02	0,303	θ_{Se}=	10,52		P_1=	1274,19	$P_{sat(\theta e)}$=	1270,42
PVC roof coating	100000	0,002	0,14	0,01		θ_1=	10,56	200	P_2=	1279,59	$P_{sat,2}$=	1273,94
solid wood panels (SWP)	90	0,025	0,17	0,15		θ_2=	10,99	2,3	P_3=	1279,95	$P_{sat,3}$=	1310,72
mineral wool (MW)	1	0,15	0,0531	2,82		θ_3=	19,19	0,2	P_4=	1285,35	$P_{sat,4}$=	2222,98
solid wood panels (SWP)	90	0,025	0,17	0,15		θ_{Si}=	19,62	2,3			$P_{sat(\theta i)}$=	2282,85
Total	100241	0,232		3,30				205				

Table 22. Model 4 external roof calculations results.

Floor: for this Model 4 is used Model 2 floor.

3.2.5 Conclusion of the manual calculations:

Comparing all the models calculation results, it can be say: envelopes of masonry structures (Model 1 and Model 3) are more resistant for condensation in both environments than frame-structure envelopes (Model 2 and Model 4), but frame-structure are with better thermal insulation properties (Table 23). Environmental effects on the envelopes are also different between masonry structures and frame-structures. Impact of indoor and outdoor temperatures changes are more lower to masonry structures than frame-structures. Model 2 wall and roof, they both have a risk of condensation, when the temperature difference is big (Table 16 and 17). Model 4 has risk of condensation only in roof, but temperature difference is much smaller (Table 22). Masonry-structures envelopes has no remarkable risks of condensation, but problem can be with thermal bridges. Incorrect or inadequate joint solutions can significantly affect the envelope thermal insulation properties. In Spain, the affect is not so big than in Estonia because of temperature differences (Image 1 and 2), but still considerable.

	Model 1	Model 2	Model 3	Model 4
Wall	0,2	0,11	0,44	0,13
Roof	0,08	0,14	0,175	0,19
Floor	U<0,25*	U<0,25*	U<0,25*	U<0,25*

*stained areas- masonry structure
*Floor U values are taken from table E.3 and E.4 from “Documento Basico HE “.
Table 23. Models envelope manually calculated U values [$W/(m^2K)$].

3.3 Models thermal calculations with program “Calener_VYP”:

3.3.1 Model 1

U values of the envelope: wall- U=0,13; roof- U=0,07; floor- U=0,18.

Demand for the heating and cooling comparing with program solution is:

heating- 37,7 % and cooling- 81,2 %.

Relative proportion of cooling and heating:

heating- 84,6 % and cooling- 15,4 %.

3.3.2 Model 2

U values of the envelope: wall- U=0,10; roof- U=0,13; floor- U=0,14.

Demand for the heating and cooling comparing with program solution is:

heating- 38,9 % and cooling- 101,1 %.

Relative proportion of cooling and heating:

heating- 82,2 % and cooling- 18,0 %.

3.3.3 Model 3

U values of the envelope: wall- U=0,34; roof- U=0,17; floor- U=0,18.

Demand for the heating and cooling comparing with program solution is:

heating- 48,8 % and cooling- 77,7 %.

Relative proportion of cooling and heating:

heating- 88,1 % and cooling- 11,9 %.

3.3.4 Model 4

U values of the envelope: wall- U=0,14; roof- U=0,19; floor- U=0,14.

Demand for the heating and cooling comparing with program solution is:

heating- 42,8 % and cooling- 106,0 %.

Relative proportion of cooling and heating:

heating- 82,6 % and cooling- 17,4 %.

3.3.5 Conclusion of the models thermal calculations with program:

Relative proportion for heating and cooling is almost with the same percentage for all models. For heating it varies from 82 to 88,1 % and cooling from 11,9 to 18 %. It show's, that most of the energy consumption will go for heating and less than 20% for cooling.

Program compare these models with its own "adequate" model and gives results in percentages. Results show's each model proportion of the energy consumption for heating and cooling comparing its own model.

Results are again mostly with same percentage, but there are differences between masonry-structure and frame-structure envelopes in cooling. Masonry-structure envelope models consume 20% less energy for cooling than program "adequate" model, varies from 77,7 to 81,2%. Frame-structure envelope model consume almost the same amount as program model, varies from 101,1 to 106,0 %. Heating percentages are the same in both models.

Differences are also between Spain (models 3 and 4) and Estonia (model 1 and 2) envelope structures in heating. Both Spain models has reference demands over 40% varies from 42,8 to 48,8 %. Estonia models reference demands varies from 37,7 to 38,9 %.

	Model 1	Model 2	Model 3	Model 4
Wall	0,13	0,1	0,34	0,14
Roof	0,07	0,13	0,17	0,19
Floor	0,18	0,14	0,18	0,14

*stained areas- masonry structure

Table 24. Models envelope U values [W/(m^{2}K)] calculated with program.

	Model 1		Model 2		Model 3		Model 4	
	heating	cooling	heating	cooling	heating	cooling	heating	cooling
Reference demand* (%)	37,7	81,2	38,9	101,1	48,8	77,7	42,8	106
Relative proportion of cooling and heating (%)	84,6	15,4	82	18	88,1	11,9	82,6	17,4

*stained areas- masonry structure

*reference demand- demand for the heating and cooling comparing with program solution (%)

Table 25. Models envelope heating and cooling demands, calculated with program.

3.4 Comparison of manual and program “Calener_VYP” calculations

These two calculation methods has different fields of research, but the results can be considered much in common. The main idea of manual calculations by different regulations was to examine the thermal insulation properties and risk of condensation in models envelope structures. Program “Calener_VYP” gave the results of the energy consumption amount in percentage to ensure a comfortable living environment.

U values of models envelopes were found with both methods. Results were almost the same for the same envelopes. Some considerable differences were in Model 1 wall and Model 3 wall (Table 23 and 24). Model 3 wall U value difference was the biggest one 0,1 W/(m^{2}K), where manually calculated value were 0,44 W/(m^{2}K) and “Calener_VYP” program gave 0,34 W/(m^{2}K). This is due to the difference of material properties in the program directory and in materials, which were used in hand-made calculations. Model 1 wall U value difference was 0,07 W/(m^{2}K), where manually calculated value 0,2 W/(m^{2}K) and with program 0,13 W/(m^{2}K).

Manual calculations showed, that masonry structures are more resistant for condensation in both environments. “Calener_VYP” program results showed, that masonry structures envelope models consume 20% less energy for cooling than program “adequate” model (calculations are made for Spain environment). These results can be concluded: Model 1 and Model 2 masonry structures envelopes are with good construction-physics properties (resistant for condensation and with good thermal insulation properties) and an economically efficient as energy-efficient structure in both countries (Estonia and Spain).

Frame-structure envelopes are with the good thermal insulation properties, but it has bigger risk of condensation. Good thermal insulation depends on quality of construction, which is harder to achieve for frame-structure than masonry structures. Energy consumption percentage is the same for heating as masonry structures envelope models. For cooling the percentage is bit bigger, about 20% comparing with program “adequate” model (Table 25). Cooling consumes much more energy than heating and for Spain cooling is important to achieve indoor comfort.

For summary, it can be say that frame-structure envelopes is more suitable for the environment in Estonia, the energy is required only for heating and good ventilation solution can avoid risks of condensation.

4 Outlook into the future solutions to improve thermal insulation properties of building materials: phase change materials (PMCs)

Three lecturers from Norwegian University of Science and Technology has made research about phase change materials (PCMs). They said, that PCMs can be possible solution for reducing the energy consumption of buildings. By storing and releasing heat within a certain temperature range, it raises the building inertia and stabilizes indoor climate.

Phase change materials property is to storage the heat energy in a latent form, making bigger heat storage capacity per unit volume than ordinary building materials. When the the surrounding environmental temperature rises, the chemical bonds of the material will break up when the material will change from solid to liquid. The result of this process of phase change will absorb heat and it is known as an endothermic process. When the the surrounding environmental temperature drops again, the PCM will go back to the solid and release the absorbed heat. Interior temperature stabilises during this process, alleviates the peak hours of cooling loads and decreases heating loads. It does not affect the thermal resistance of the building envelope but affects surface temperatures.

One of the most important criteria for selecting PCMs is a proper phase change point or phase change temperature range. These materials should be simple and not expensive, have good crystallization properties, be thermally and chemically stable non-toxic and non-flammable.

Organic and most widely used phase change materials (PCMs) can be divided into two: paraffins and non-paraffins. The main phase change materials of paraffins are: polyglycols (E 400, E 600 and E 6000); dodecanol; tetradodocanol; biphenyl e.t.c.

The main non-paraffins are: erythitol; dimethyl-sulfoxide; acids (capric, capricinic, laurinic, meristic etc.) etc.

PCMs can use in any porous building material, but biggest effects currently gives gypsum wallboards, concrete and insulation materials.

Wallboards are very suitable for the application of PCMs because they are cheap and widely used in construction. Wallboards enhanced with PCMs will provide thermal storage around the complete building, enabling passive solar design and alleviates the peak hours of cooling loads.

Other possibility for using PCMs in building constructions is PCM enhanced concrete or the so-called thermocrete and PCM enhanced clay tiles. Thermocrete is a heat storage medium combining an appropriate PCM with a concrete matrix or open-cell cements to produce low cost storage materials with structural and thermostatic properties.

Phase change materials still needs to more testing and to develop, but the principle behind is promising. Potential energy savings have been reported in literature, but current properties of the available phase change materials do not yet seem optimal for wide-spread building applications. There are only few materials with a transition around comfort temperature, they are with relatively low heat of fusion. [10]

5 Summary

Following the model calculation results in this study, it can be stated that in both countries Estonia and Spain, most economically efficient as energy-efficient structure were masonry-structures envelope models (Model1 and 2). Combining energy consumption for heating and cooling, and thermal insulation properties. These external envelopes can be improved with developing building materials thermal insulation properties. In this research was focused on phase change materials as potential ability to modify the building envelopes more energy efficient.

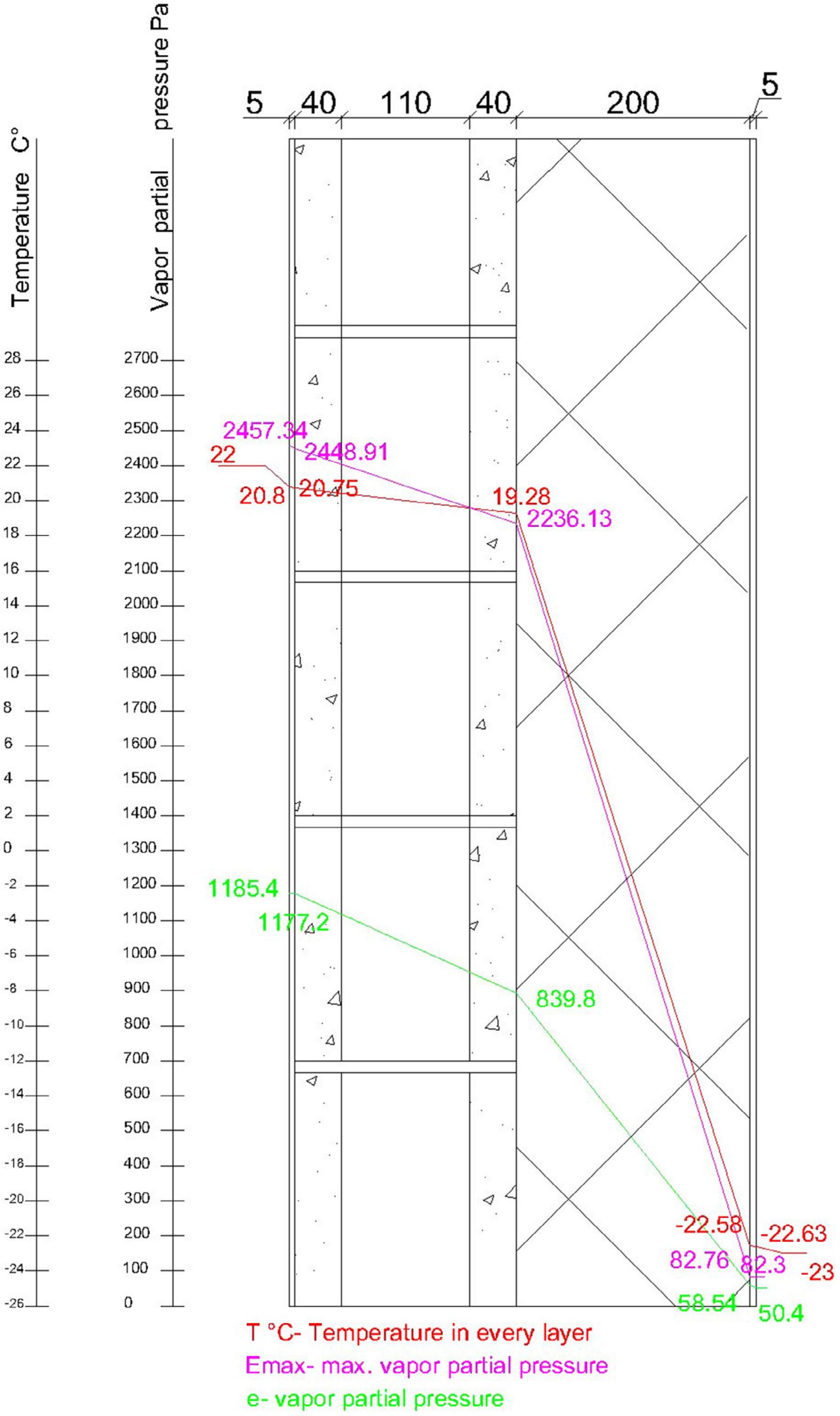


Image 3. Model 1 wall

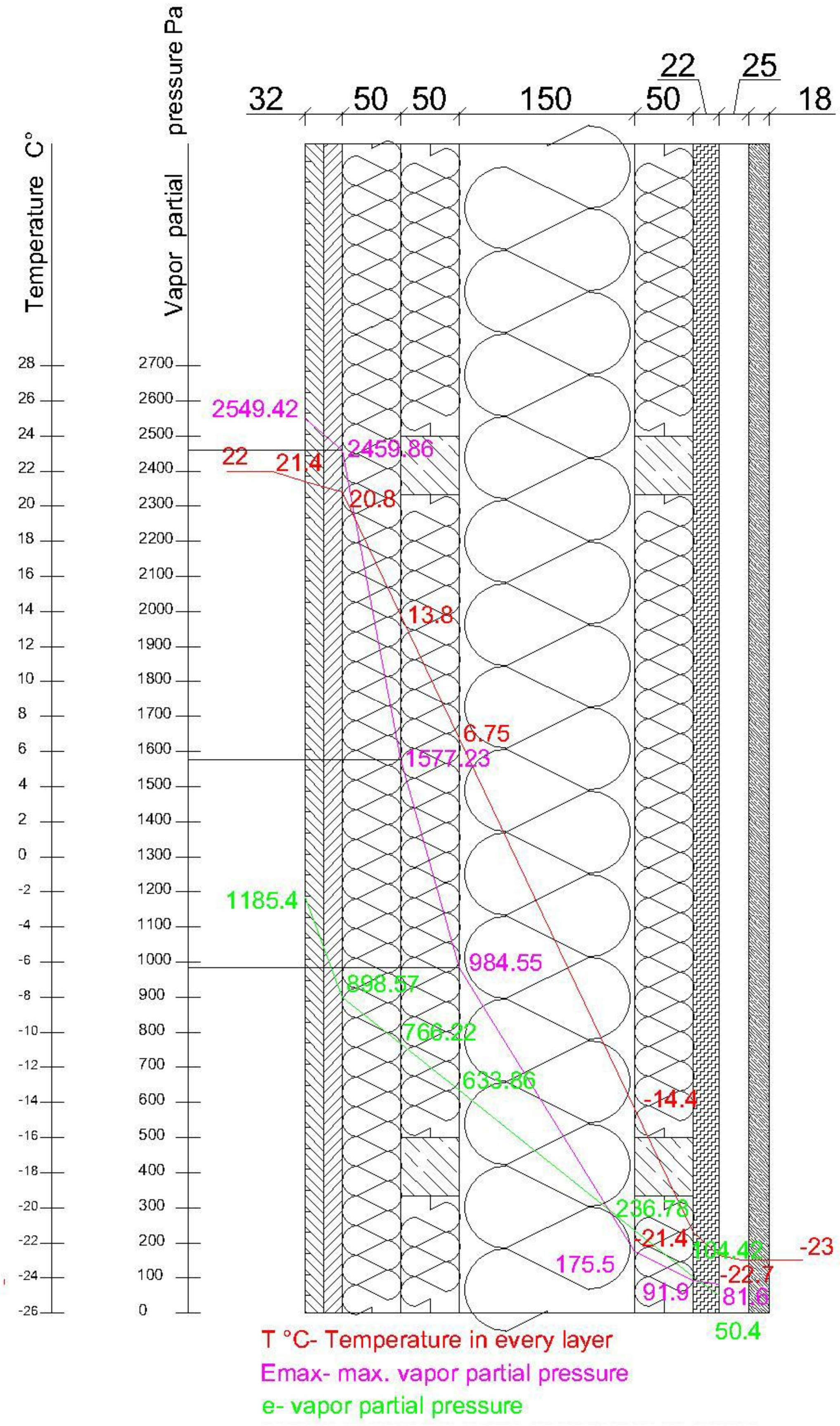


Image 4. Model 2 wall

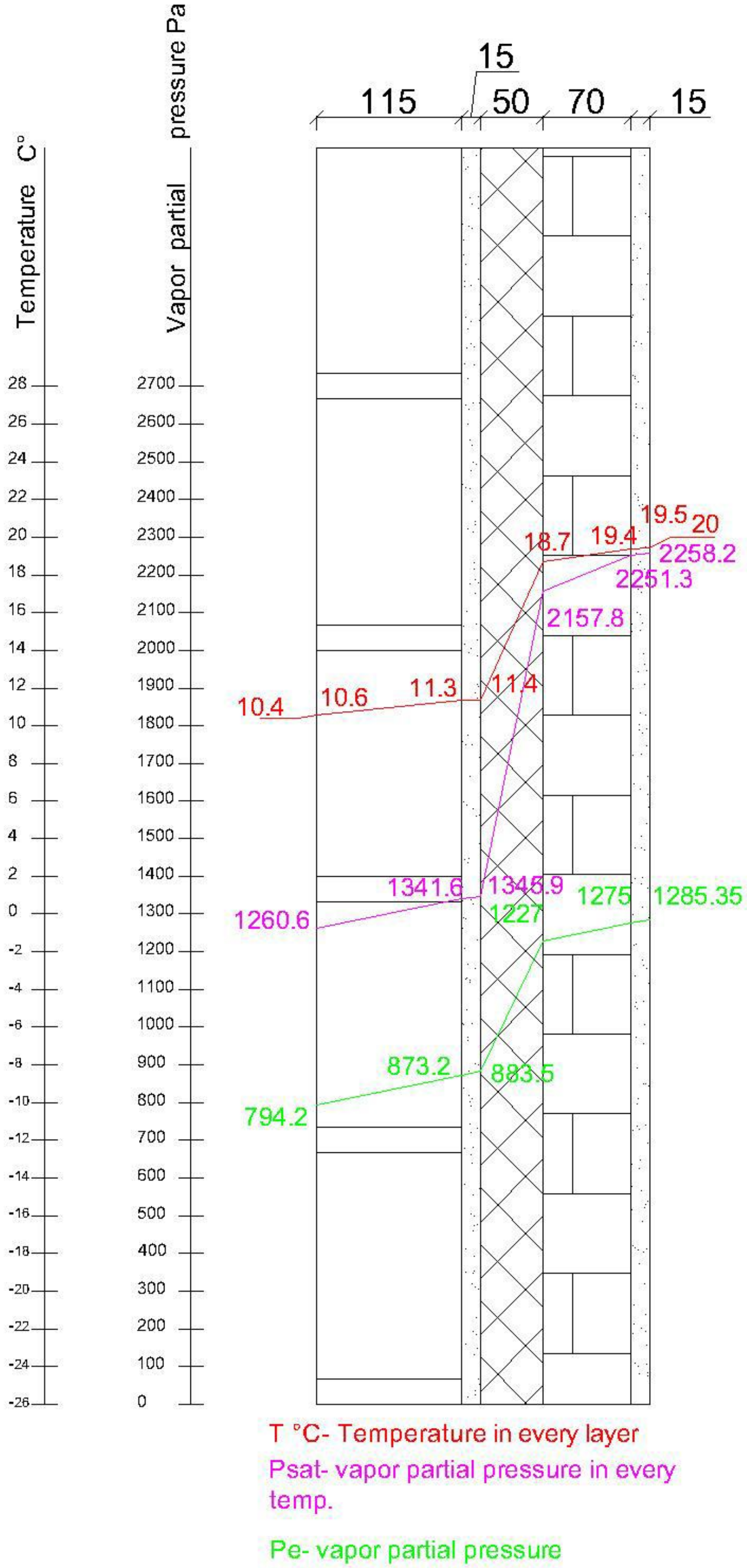


Image 5. Model 3 wall

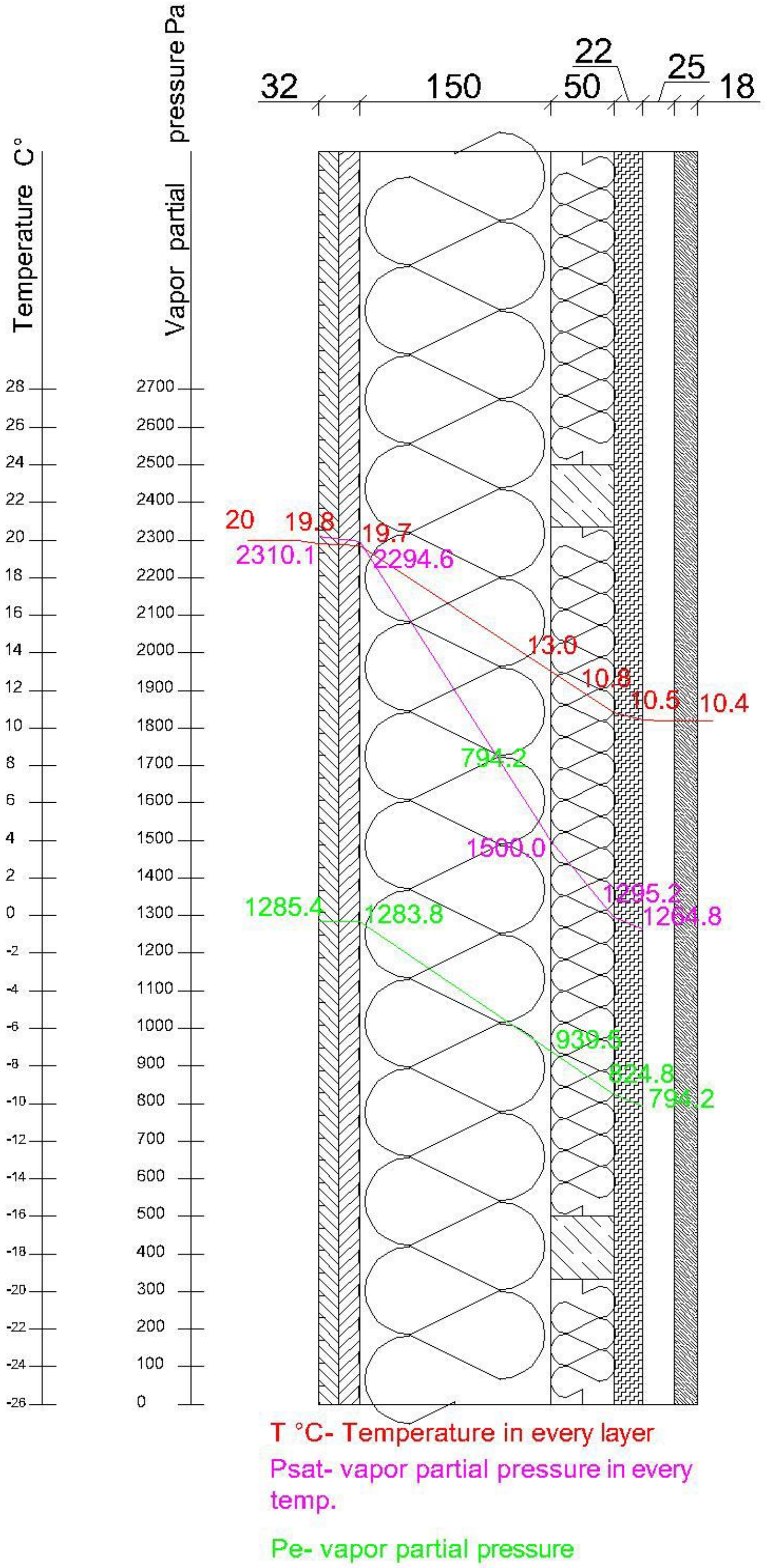


Image 6. Model 4 wall

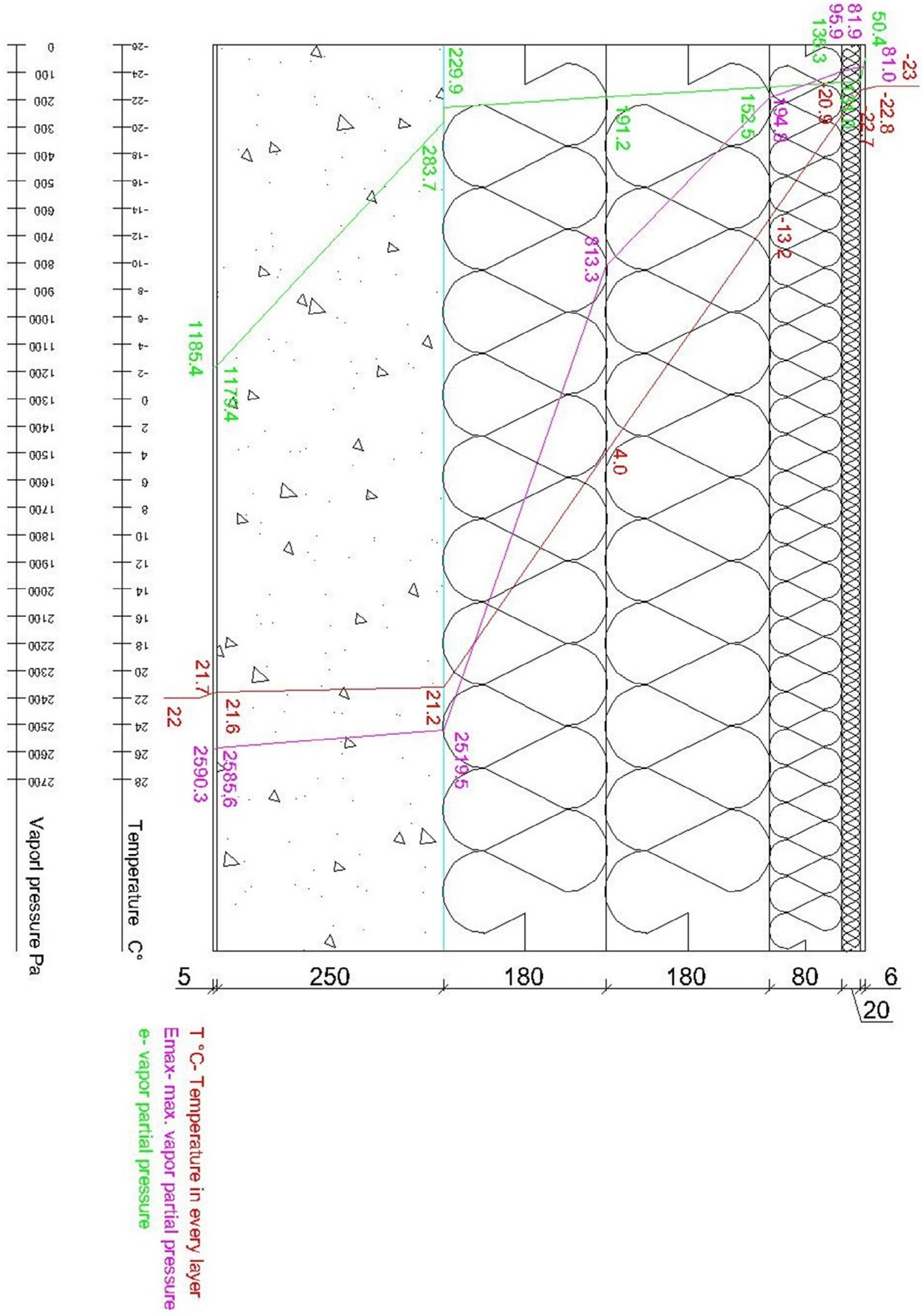


Image 7. Model 1 roof

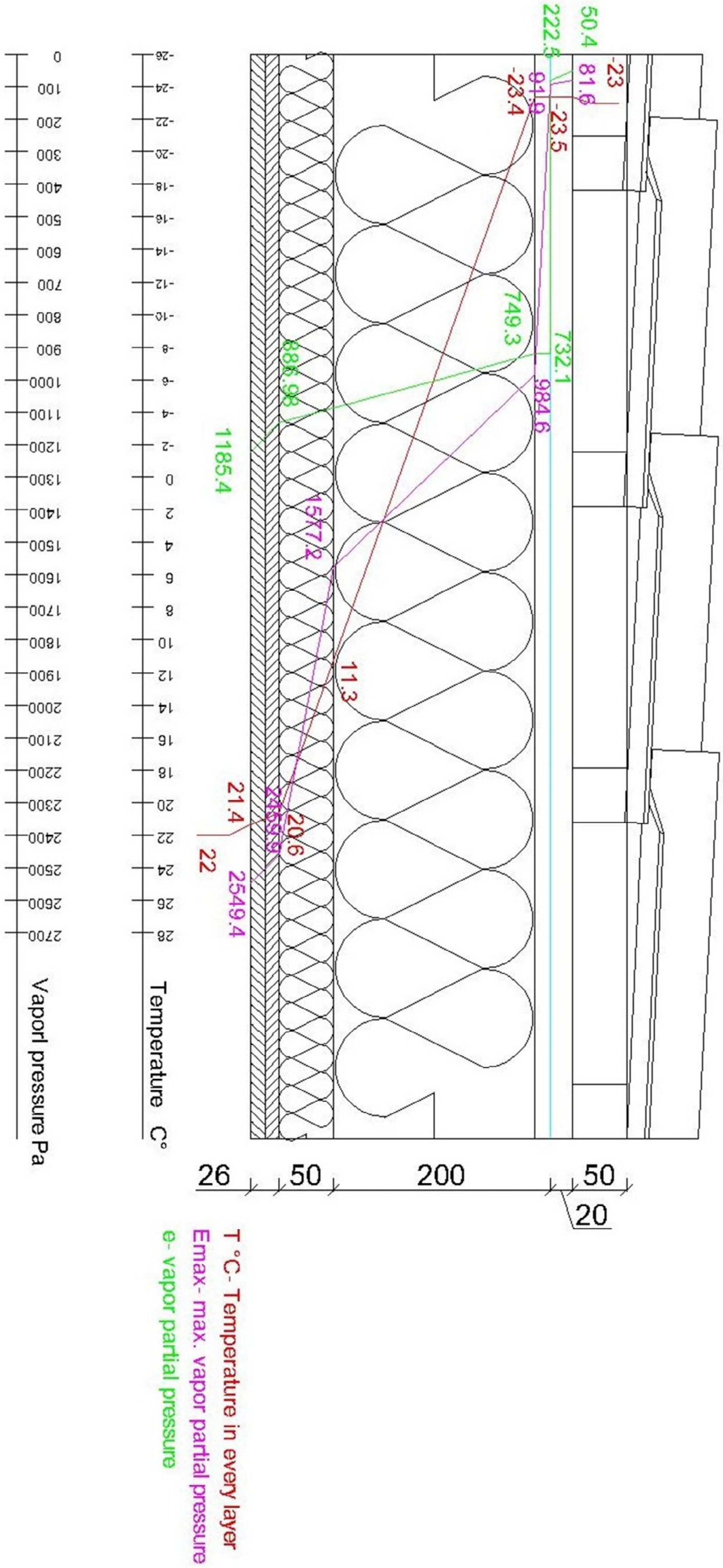


Image 8. Model 2 roof

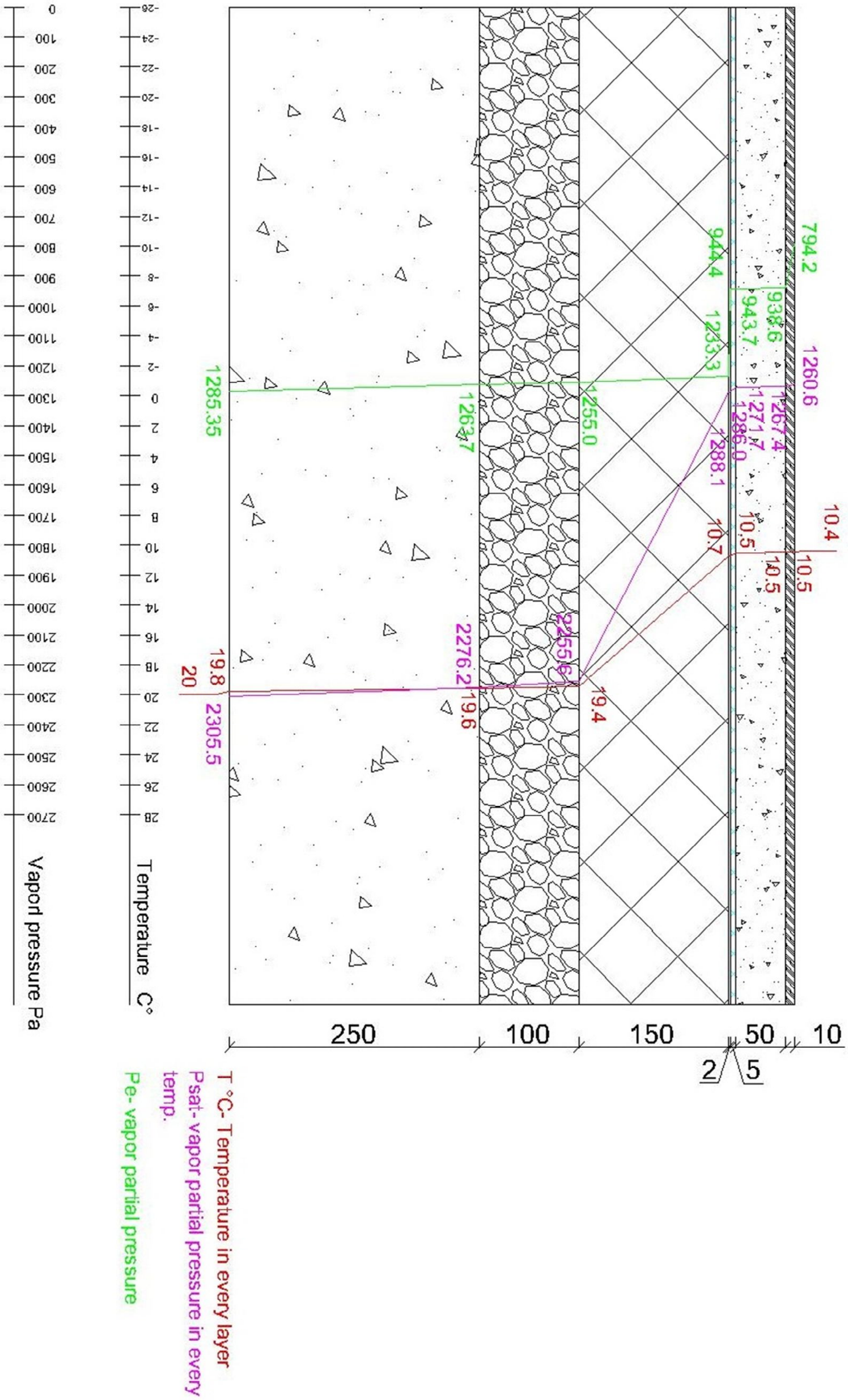


Image 9. Model 3 roof

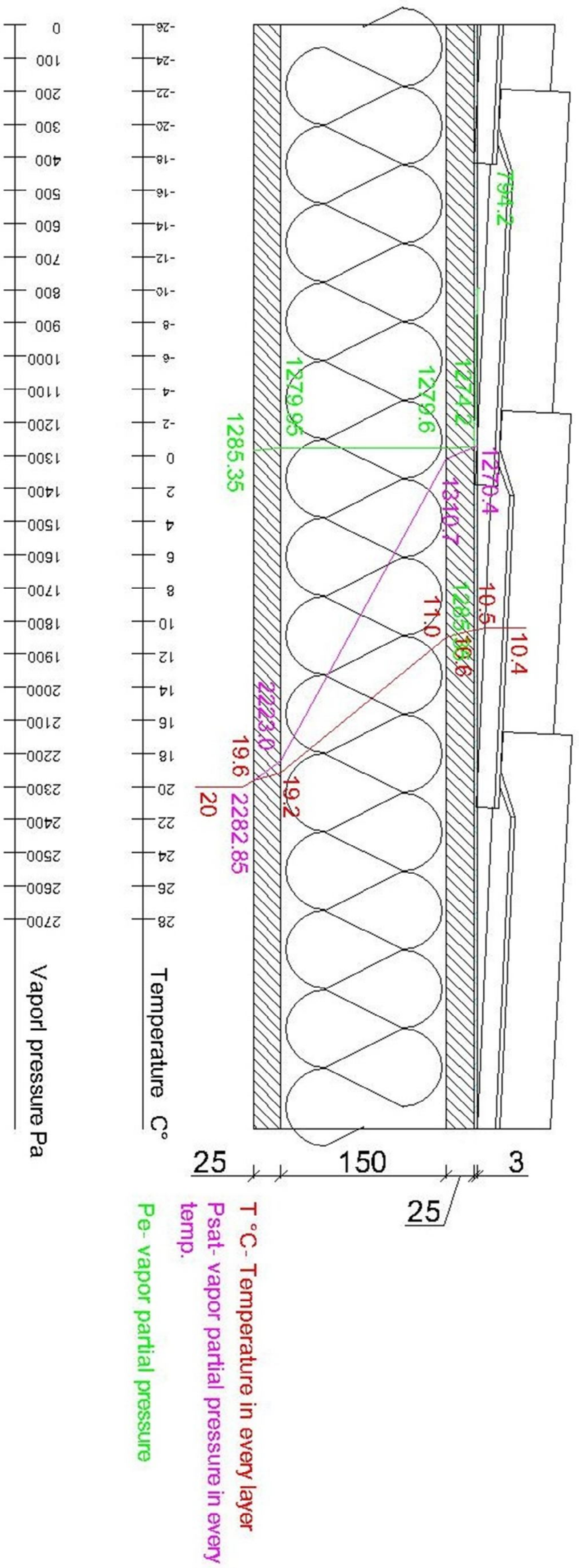


Image 10. Model 4 roof

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