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Inverted flat roofs in North, Finland and Russia

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Abstract

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Abstract

The thesis work studied the main principle of an inverted (turned) flat roof, review and analyzation the existing types of inverted roof, the collection of information on the use in the Northern countries, in Finland and in Russia. The background of the study was that technology of the investigated roof requires more advanced engineering solutions and improvement for the climatic conditions of St. Petersburg, Finland and the Northern countries in general. The aim was to make an analyzation of existing solutions of inverted flat roof construction and to make a possible improvement of inverted flat roof for unfavorable climatic conditions.

New model of roof supports made of aluminium and stainless steel was developed for inverted roofs on supports. Found multifunctional insulation materials for inverted roofs are a good replacement for traditional insulation materials, as proven by thermal calculation. It is possible to conclude that the construction and use of the inverted flat roofs also possible in such countries with a harsh climate. Methods of system analysis, expert analysis and mathematical modelling, patent search, 3D-modelling, thermal calculation and analysis were used in the thesis work.

Keywords

Inverted roof, Flat roof, Inverted flat roof, Turned roof, Roof

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1 Introduction

The client of the thesis is Russian construction company Novyj Dom Invest, specializing in concrete construction in the role of the General Contractor. Due to the expansion of the company and new projects in St. Petersburg, the company plans to carry out roofing (roof works) independently.

Today, the use of inverted flat roofs is very common in the construction of modern buildings: combining a public, office building and a parking lot, combining a residential building and recreation space, etc. This happens, among other things, due to the use of an inverted (turned) flat roof. This roof technology is common in the South of Russia, in countries with a warm climate. However, the technology of the investigated roof requires advanced engineering solutions and improvement for the climatic conditions of St. Petersburg, Finland and the Northern countries in general. In such climatic conditions, the roof is exposed to snow, frost, rain, etc.

In its work as General Contractor in the construction projects, Novyj Dom Invest has already faced problems during the construction of flat roofs from its partners and subcontractors when accepting the work performed: insufficient thermal insulation of roof, leaks, destruction of layers during work, exposure to moisture and cold.

The company was interested in theoretical research and analysis that would help develop the possible improvement of inverted roof technology in such harsh climatic conditions.

For the purpose of theoretical research and analysis, review of existing examples of inverted roof using in North, Finland, Russia was carried out. Types of inverted flat roofs, engineering solutions are analysed.

In addition to theoretical research and analysis, it was necessary to offer engineering solutions that could possibly improve the technology and construction of the investigated roof in such unfavourable climatic conditions.

The methods of system analysis, expert analysis and mathematical modelling, patent search, 3D-modelling, thermal calculation and analysis were used in the thesis.

2 Inverted roof technology

The design of inverted (turned) flat roofs is reverse of a conventional (traditional) flat roof structure: the waterproofing layer is located under a layer of thermal insulation made of extruded polystyrene (XPS) insulation boards, which protects it from mechanical and temperature influences.

The finishing layer of the roof can be used with a functional purpose in the form of a covering of green vegetation, a sports field and a recreation area made of paving slabs, a rooftop parking, an open terrace, etc. This layer has a function of exploited finishing one.

Thermal insulation layer is especially important in the case of inverted roofs — it protects waterproofing from temperature influences, action of freeze, UV exposure (Building Research Establishment).

Some of the features of this roof technology have been studied early. Some of the studies agree on one thing, for example, in addition to main function of thermal insulation of XPS, XPS boards also protect waterproofing layers from expansion and contraction due to high and low temperatures (Kalibatas & Kovaitis 2017, 651; Francke & Geryło 2018, 1). Furthermore, XPS layer protect waterproofing layers from the mechanical loads imposed by traffic or people on a roof (Noreng & Jelle 2008, 3).

As with any type of flat roof, special attention is paid to thermal insulation, water- and vapour barriers, and their properties and connection with each other. Misar and Novotný (2017, 6) in their research touched on and sorted out the problem of heat loss of inverted roof's structures with experiment. As a result of research, they made a conclusion about the importance of the waterproofing materials in inverted flat roofs. Besides, gluing seams or sealing XPS boards with compressed tape does not lower the relative humidity inside the roof’s structure. (Misar and Novotný 2017, 6.)

There are many engineering solutions for inverted roofing. Always, the structure of inverted roofs includes following layers (Figure 1):

1. An exploitable finish layer: paving tiles, concrete slabs, composite decking boards (in some cases, in the combination with gravel ballast), vegetation (green roof) etc.

2. An additional waterproofing layer, as known as water flow reducing layer (WFRL).

3. A thermal insulation of XPS-boards.

4. A drainage layer: gravel.

5. A waterproofing layer: liquid waterproofing membrane, bitumen rubber liquid membrane or waterproofing membrane.

6. A cement and sand screed, as known as screed to falls (it could be combined with reinforcement inside).

7. A structural concrete slab (hollow core slabs or cast-in-situ).

8. An internal finish layer.

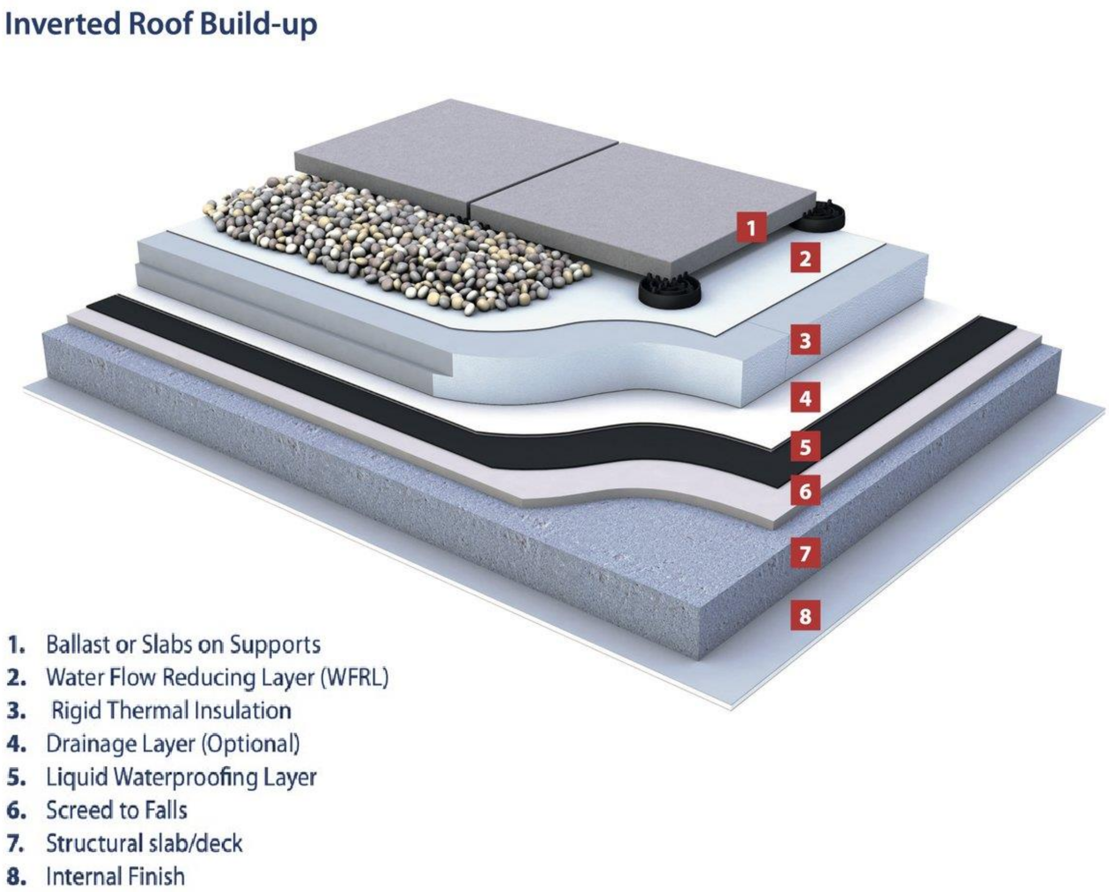

Figure 1. Example of inverted flat roof structure (adapted from LRWA)

The composition of the roof structure may differ slightly; it depends on its functional purpose and the finish layer, but the sequence of the layers is the same. In some cases, for example, in the case of green roof the roof can be supplemented with additional filtration layers, substrate and water vapour barrier layers (Cascone 2019, 5).

At the beginning of roof's construction, the installation of the main loadbearing layer of the roof is carried out – a cast-in-situ reinforced concrete roof slab or hollow core slabs as the base. It is worthwhile to provide for the removal of cement laitance from the concrete screed with a grinder. Before installing the next layers of the roof, it is necessary to prepare the base – cleaning the surface from debris and dust using a compressor or brushes.

The next phase – to lay cement-sand screed (as known as screed to falls) layer. A prerequisite is the general slope, which creates a natural drainage of moisture from the surface. This slope will ensure proper water flow from the roof. (Novozhilov.)

On the layer of cement-sand screed, a layer of waterproofing is applied, for example, from bitumen mastic for waterproofing the underlying layers of the roof. It is also possible to use liquid waterproofing layer or membrane.

Additional there is the option of vapour barrier material in the form of a membrane. It could be located over waterproofing layer. It provides protection against condensation and excess moisture. In addition, this type of material allows to work with a roof of any complexity and geometry.

The drainage layer is responsible for eliminating stagnant water in the upper layers of the roof and in the lower parts of the upper exploited layer. Crushed stone or gravel (from 20 mm and more) and geotextile drainage cover are used as drainage layer (Dow - Building Solutions: Insulating Inverted Flat Roofs with STYROFOAM, 17).

On the inverted surfaces of the roof, it is also provided for the placement of drainage systems, which are also installed in the waterproofing and thermal insulation layer (Figure 2).

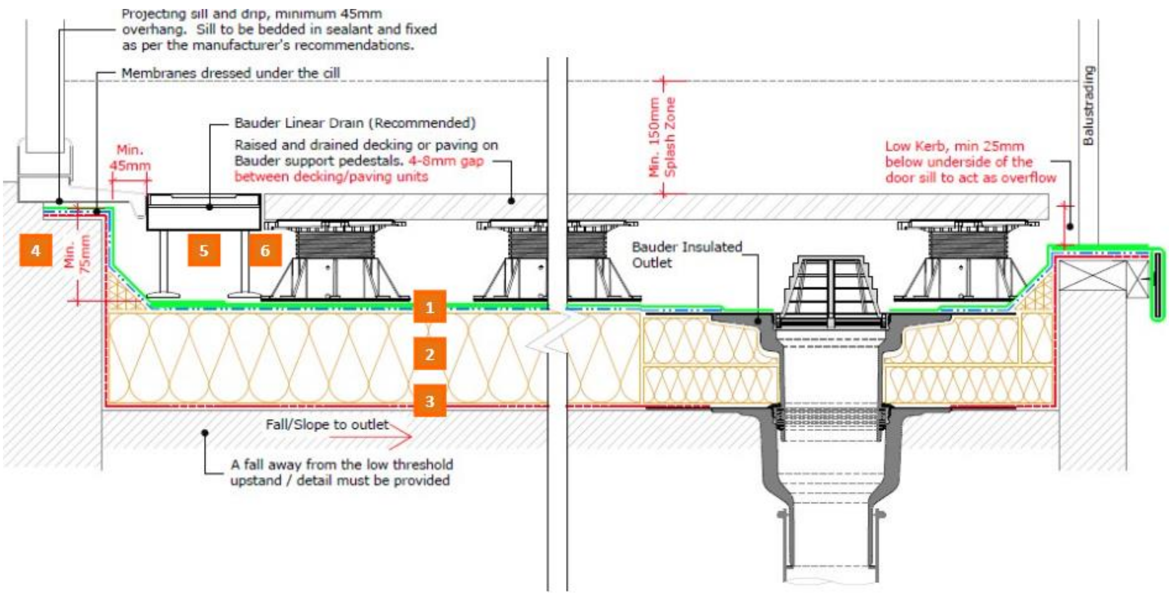

Figure 2. Example of drain system in inverted flat roof with paving (adopted from BAUDER 2018)

In the most of cases of inverted roofing, drainage is provided internally (BAUDER 2018).

Water on the surface of the roof penetrates through the ballast or drain between the XPS-boards until it reaches the layer of membrane. As the next step, it drains through roof drainage in the form of outlets. (Building Research Establishment.)

Thermal insulation in the form of plates of extruded polystyrene foam (XPS boards), located in two layers on the main waterproofing system and vapour barrier layer (Figure 3). Such XPS boards have a closed cellular structure, high strength, heat-insulating properties, heat-, frost-, bio-, chemical and water resistance, slight shrinkage and water absorption, low density (TechnoNICOL). Two layers of XPS stacked with staggered seams. In some cases, it could be more than two layers of XPS.

Figure 3. Two layers of XPS board for flat roof (M-Strana 2018)

Then it is important to install additional waterproofing layer or water flow reducing layer (WFRL) over thermal insulation (Polyfoam XPS 2019). There is option to use geotextile instead of WFRL.

At the final stage of roof construction, the installation of roof supports and a finishing layer, for example, from paving slabs, is carried out (Figure 4).

Figure 4. Installation of roof supports and paving slabs (Polyfoam XPS 2019)

The roof on supports is designed for the convenience of repairing waterproofing: removing the slabs, access to the roof insulation will be convenient for repairing. An exploitable finish layer also could be made from concrete slabs, composite decking boards, green modulus, and in some cases, in the combination with gravel ballast in the space between support elements. (STM-Stroy.)

As mentioned above, the composition of inverted flat roof structure may differ slightly: it depends on its functional purpose and the finish layer.

These differences and other existing engineering solutions will be detailed in Chapter 4.1.

3 Inverted roof use cases overview

3.1 Examples of use in Norway

Multi-storey building with garden green roof in Oslo

Inverted flat roofs, especially green roofs are very popular in Norway. The multi-storey building with impressive green roof located in a modern district of Bjørvika, in Oslo (Figure 5).

Figure 5. Multi-storey building with garden green roof in Oslo, Norway (LECA)

The building has a multi-level roof with green spaces, pedestrian areas and walkways.

This green roof is used for drainage, storm water storage and retention. In this way, the water binds to the green roof, so that the rainwater system is not overloaded. This in turn prevents damage and flooding at ground level.

Expanded clay from Leca (Leca-kevytsora) is also used as drainage. The thickness of this layer is 12–20 mm and 4–12 mm. (LECA.)

Two seasons hotel in Stavanger

The 6-floor hotel is located on top of a 5-floor existing parking garage. The building is located along a busy street in the Stavanger city center (Figure 6). Architectural design by JDS Architects. (JDS Architects 2020.)

Figure 6. Two Seasons hotel in Stavanger, Norway (JDS Architects)

The building area is 8500 m^2 with green spaces all over the roof, and the roof level mark changes smoothly from 16.5 meters to 20.0 meters (JDS Architects).

3.2 Examples of use in Sweden

Urban Escape in Stockholm

Urban Escape is a multi-storey relatively new building built in the spring of 2019 in Stockholm. It consists of 5 buildings and combines offices, hotels, trade, restaurants, meeting places and services in one area (Figure 7).

Figure 7. Urban Escape Stockholm, Sweden (ArkDes Vänner 2017)

Main contractor are AMF and Skanska, Ahrbom & Partners and Studio Stockholm made architectural design. The rooftop consists of approximately 3500 m^2 of outdoor space. (Sleeper Magazine 2016, 140–141.)

An exploitable finish layer of the roof is presented in the form of:

- Decking, where the open terraces of restaurants and cafes is located.
- Green spaces and vegetation for recreation area.
- Paving slabs (tiles) for the movement of pedestrians.

The Winery Hotel in Solna (Stockholm)

The Winery Hotel is 6-floors building: in that case, there are rooftop terrace with swimming pool (Figure 8).

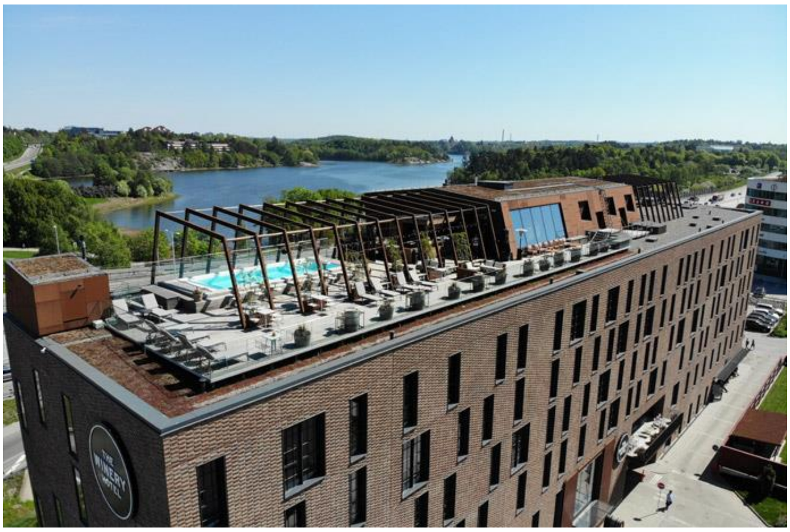

Figure 8.The Winery Hotel in Stockholm, Sweden (Fabege AB)

The hotel built in February 2016 in Solna (Stockholm) by Veidekke’s Swedish subsidiary Arcona and by the architectural project Archus Arosia Arkitekter AB. The rooftop terrace is one of the largest open space terrace in Stockholm. (Fabege AB.)

The open terrace is located at the level of 15.5 meters (Figure 9).

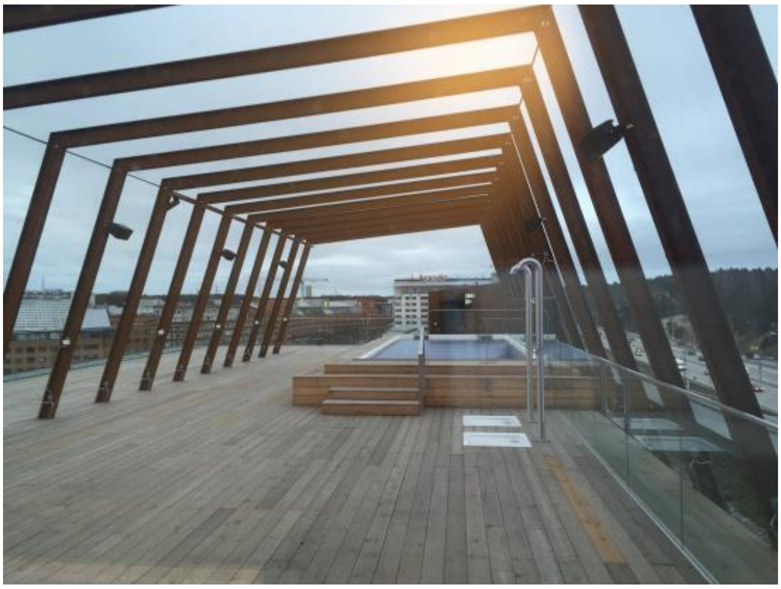

Figure 9. Open terrace on the rooftop with swimming pool (Tripadvisor)

An exploitable finish layer of the roof is presented in the form of timber boards and decking for recreation area, where bar and swimming pool are located.

3.3 Examples of use in Finland

Green roof in the REDI shopping centre in Helsinki

In Helsinki's Kalasatama, a green roof almost the size of Esplanadi Park has been built on top of SRV's shopping centre REDI and Itäväylä (Figure 10).

Figure 10. Open park area with green roof in Helsinki, Finland (Leca Finland)

Designed by Maisema-Arkkitehtitoimisto Maanlumo Oy. The general contractor was SRV Rakennus Oy. Contractor, performing roofing work was Terrawise Oy.

A total area of open park is about 13.000 m². The park area with green roof is located above street level at an altitude of +22.5 to +24.5 meters. The open park has gentle hills, at most 1.2 m high, with the lightest layer being the thickest.

In the construction of the park deck, gravel from Leca (Leca-Murska and Leca-sora) was utilized as a lightweight soil and to improve the moisture conditions of the plants. The crushed Leca gravel binds moisture and allows water to capillary rise throughout the deck from the lowest storm-water collection cell for plant use.

The thickness of the gravel layer varies between 50 and 350 mm, weight is about 600 kg / m³. (Leca Finland.)

Green roof of Tampere University of Technology campus in Tampere

The inverted flat roof of the Tampere University of Technology new campus is a green roof combined with a sidewalk walkway from paving slabs (Figure 11). The vegetation (grass, bushes) has a large roof area.

Figure 11. Green roof with paving slabs of Tampere University of Technology in Tampere, Finland (BINUS University 2019)

The green roof has proven to have many positive environmental aspects, from absorption CO_2 to reducing the amount of dust. This type of roof is only the part of other sustainable construction solutions, such as solar panels in the campus building. (BINUS University 2019.)

3.4 Examples of use in Russia

Inverted flat roof of the residential multi-storey building in St. Petersburg

An example of the use of an exploited inversion roof in a multi-storey residential building is also a residential multi-storey building at the address: 43, Prospekt Prosvescheniya, London Park RC, St. Petersburg (Figure 12). The roof is located at the level of the third floor and represents green spaces, a recreation area, and playgrounds, and sidewalk paths for residents. This roof planning solution creates a courtyard (roof-yard) for the residents.

Figure 12. The flat roof of a residential multi-storey building in St. Petersburg, Russia (Novostroy 2018)

This solution is an example of creating a safe space intended only for the residents of the house. The roof structure includes thermal insulation from extruded polystyrene foam plates in four layers from Penoplex. (Premium Balkon.)

Green roof of “The Royal Beach” restaurant in St. Petersburg

This example is not about flat roof, but in that case there also the same inverted structure of the roof. Two-storey leisure and entertainment complex with a banquet hall and a panoramic restaurant “The Royal Beach” on the shores of the Gulf of Finland in St. Petersburg (Figure 13). It was built in 2015 according to the project of the architectural studio Astragal Design, and where the design engineer of the project was Sadikov P.V. The height of the building is 9 m. The structural scheme of the building uses metal structures. The project provides for the reconstruction of a green area on the northern border of the site along the South road, repair of bank protection structures. The roof structure includes XPS boards as thermal insulation from Penoplex Company. (Archi.)

Figure 13. Green roof of “The Royal Beach” restaurant in St. Petersburg, Russia (Archi)

As it possible to see, many use cases are with pavement slabs for walking space, green roofs with vegetation.

4 Expert analysis of inverted flat roofs with mathematical modelling

4.1 Existing engineering solutions of inverted flat roof construction and systematization

There are many different engineering solutions for inverted roof construction. It is necessary to systemize them. It is the first step of following expert analysis of roofs.

Existing solutions of the inverted flat roof construction are possible to divide according to the structural peculiarity into three main groups:

- Group 1. Inverted flat roof on supports (subgroups: unregulated and adjustable).
- Group 2. Inverted flat roof without supports.
- Group 3. Inverted rooftop parking.

Next, each group and their construction options (solutions) are considered.

4.1.1 Group 1: inverted flat roof on supports

As a rule, inverted flat roofs on supports are built if pipes are used to heat the roof surface during the cold season. It is easy to place them between the roof supports.

Another advantage roof on supports is the convenience for repairing other layers. It is enough to remove the finishing layer and part of the supports to find the place of leakage or damage to the lower layers: XPS, WFRL or waterproofing (STM-Stroy).

This group can be divided into 2 subgroups: with unregulated and with adjustable heights paving supports. The main difference is in the ability to adjust the supports and the slope of the roof surface.

The roof composition with unregulated and with adjustable heights paving supports is as follows:

1. A reinforced concrete slab as a base.
2. A slope-forming layer.
3. A vapour barrier.
4. A thermal insulation (XPS).
5. A separation layer (glassware).
6. A waterproofing.

7. Geotextiles.
8. Supports (unregulated and adjustable heights paving supports).
9. An exploitable finish layer (paving tiles, concrete slabs, composite decking boards, green modular construction, ceramic slabs, rubber slabs).

Subgroup 1a. Unregulated supports

Unregulated plastic supports are plastic rings with protruding beacons for assembly (Figure 14). The diameter of the non-adjustable supports is usually 140 mm. Thickness can vary: 15 mm, 20 mm, etc. (Kabel-house 2019.)

Figure 14. Unregulated supports (Kabel-house 2019)

Subgroup 1b. Adjustable (regulated) heights paving supports

Adjustable (regulated) supports are a structural system for erecting surfaces of a flat roof made of concrete, granite and ceramic slabs, wooden flooring, composite materials. As it was described before, the main advantage of this system is the ability to easily dismantle the floor in the event of an accident or during scheduled repairs (STM-Stroy; Roofinglines 2018). These supports help to reduce assembly time and avoid additional costs when laying flooring on a soft roof and sloped surfaces.

As it presented in Figure 15, adjustable heights paving supports usually consist of:

1. A base.
2. An adjustment ring.
3. A locking ring.

4. Extenders.

5. A head.

6. A slope corrector.

7. Spacer tabs.

8. A shim.

9. Cradle and spacer support system.

10. A key for adjusting the height of a support.

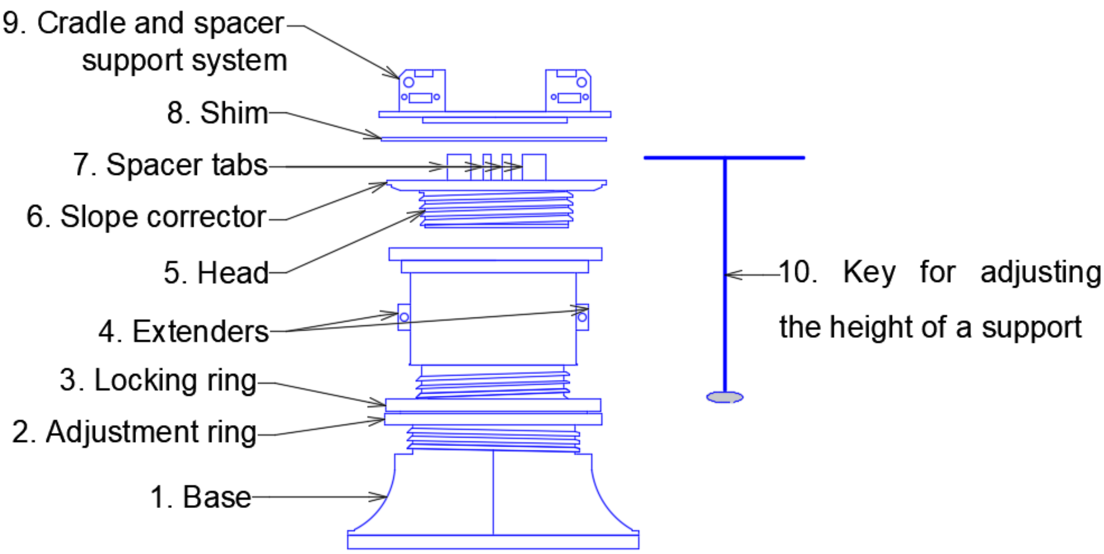

Figure 15. Adjustable heights paving supports (adopted from LLC StroySystems)

Coating of the finish layer

The outer cover of the roof terrace on the supports should have the following characteristics: bending strength, frost resistance, low water absorption, durability.

This roof can serve as a garden space from green spaces. An example is the roofing system GreenSkin (Figure 16).

Figure 16. Inverted roof system GreenSkin with green modular spaces (GreenSkin)

The main elements of the system in this case are adjustable supports of various heights with a slope compensator and modular structures in the form of trays (cells) for soil measuring 30x30 cm, 40x40 cm, etc. Using supports, a surface is created on which a carpet is formed from the Greenskin Box modules. The modules are filled with soil and are suitable for planting all types of lawns, sedums and other green spaces. (GreenSkin.)

For this type of roof, it is possible to use a composite decking boards as an exploitable finish layer.

It is also possible to use paving tiles, rubber slabs as a used layer on supports, and the option with the device of self-supporting ceramic granite on screw adjustable supports with a slope corrector (the fracture load of such plates is 1000 kg, the weight of 1 m^2 of the plate is about 40-50 kg). (TechnoNICOL.)

The arrangement of this roof in Russia, for example, is presented by solutions in the form of TN-Roof Terrace system from the TechniNICOL Company (Figure 17).

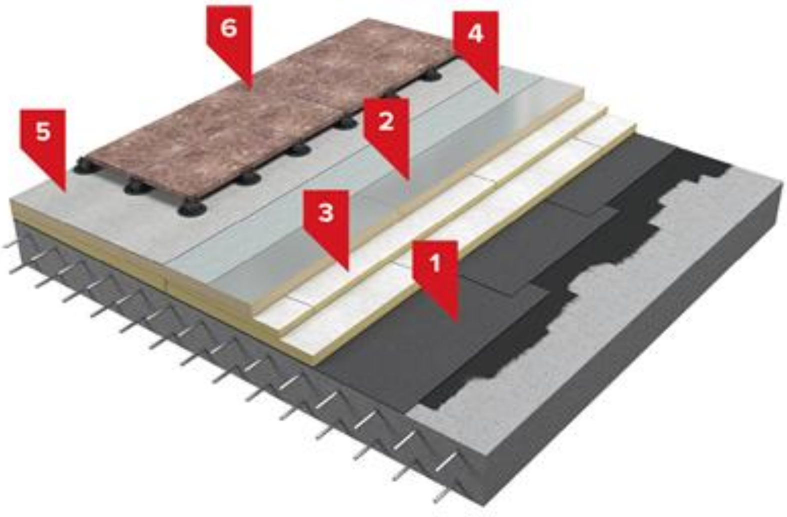

Figure 17. TN-Roof Terrace Pavement system from TechnoNICOL (TechnoNICOL)

This roof system has adjustable (regulated) plastic supports for slabs.

4.1.2 Group 2: inverted flat roof without supports

Such a roof is able to withstand slightly higher loads. In addition, a roof without supports allows the use of vegetation and drainage.

The roof has the following inverted roof structure:

1. A reinforced concrete slab as a base.
2. A concrete bracing.
3. A waterproofing (membrane).
4. A drain membrane.
5. A thermal insulation (XPS).
6. A geotextile.
7. A cement and sand mixture (pillow).
8. An exploitable finish layer: paving tiles, paving stones, rubber slabs, green spaces and plants (for green roof — additional arrangement of layers, that described below).

The existing solutions for the construction of the inverted flat roof with landscaping in Russia are mainly represented by option of the TN-Roofing Green system from TechnoNICOL Group of Companies (Russia), the roofing system with landscaping from PENOPLEX LLC (Russia), Green Roof systems from Isopan (Italy). Thera are also Protan Inverted Roofing

Systems from Protan (UK), solutions from Finnfoam (Finland). (PENOPLEX; Protan AS; Finnfoam Oy.)

The existing solutions for the device of the operated safe inverted roof for pedestrian areas and recreation spaces are represented by the TN-Roofing Pavement systems from TechnoNICOL Group of Companies (Figure 18).

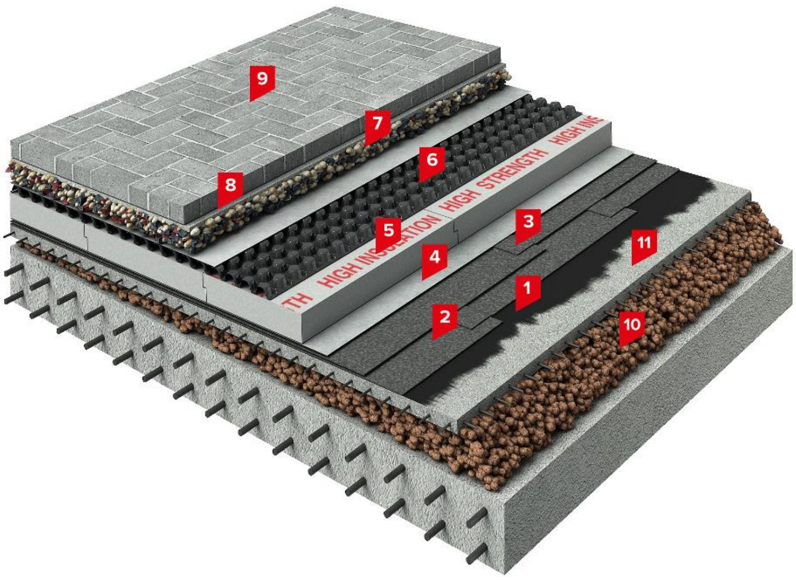

Figure 18. TN-Roof Pavement systems for pedestrian load with drainage layer (TechnoNICOL)

For a green roof, the main difficulty of organizing is in the possible effect of plant roots on waterproofing. As Cascone (2019, 5—9) described in the article, the structure of the green roof, in addition to the usual layers of the inverted roof, also includes:

- geotextiles as a separation layer
- profiled drain membrane
- geotextiles as a filter layer
- fertile soil with plants.

Coating of the finish layer

The cover of the upper operating layer of the safe inverted roof, as well as the inverted flat roof on the supports, is approximately identical: green spaces, lawns and beds are used to create green roofs, and paving tiles, paving bars, rubber slabs, etc. are used for the pedestrian zone and recreation spaces. For landscaping, plant varieties specially bred are usually used.

4.1.3 Group 3: inverted rooftop parking

The inverted rooftop parking combines the properties of inverted flat roof and rigid road clothing. This engineering solution of the inverted roof construction is separated into a separate group, since this roof should perceive large and intense loads from transport; the load on the roof is already calculated in tons per 1 m^2, unlike other groups. (Borodina & Klevtsov 2016; EDILTEC.) Therefore, this type of roof will have its own features of the construction.

The construction of this roof in Russia is presented by options in the form of TSS-Operated Roof-Parking systems from TempStroySistema LLC (Russia), TN-Roof Auto from TechnoNICOL (Russia).

The roof has a typical inverted roof structure:

1. A reinforced concrete slab as a base.
2. A slope-forming layer.
3. A levelling screed.
4. A waterproofing.
5. A thermal insulation (XPS).
6. A geotextile as water flow reducing layer (WFRL).
7. An exploitable finish layer (asphalt concrete, airfield concrete).

As described above, for rooftop parking (Figure 19) there are the following features of the device related to the high intensity of the tested loads and functional purpose:

- enhanced protection of waterproofing layer material
- density of extruded polystyrene foam plates
- sufficient thickness of reinforced concrete slab as a base.

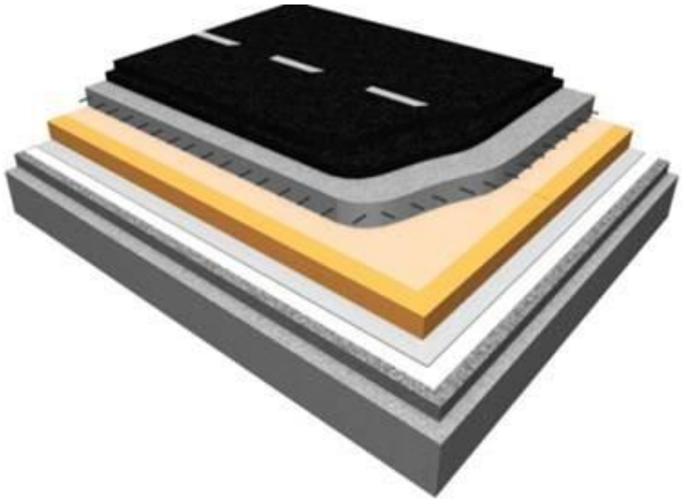

Figure 19. Inverted rooftop parking (PENOPLEX)

Coating of the finish layer

Waterproofing layer is protected by a layer of asphalt concrete (usually in two layers) in reason of protection against mechanical impact from movement and location of transport. It is worth considering the property of asphalt concrete to pass water, because it is on the distributing concrete slab that the entire climatic load falls: it is saturated with water in the absence of protection and thaws, losing load-bearing capacity and leading to the destruction of the asphalt surface from above (Kolesnik & Mantopkin 2017, 128—129).

It is possible to use an airfield concrete with additives (plasticizers) that prevent the defrosting of concrete of class C25/30 at least with reinforcing impregnation, worn by special locking machines with a rough anti-slip surface (Borodina & Klevtsov 2016).

Thus, the existing solutions of the inverted flat roof were systematized according to a structural peculiarity into three groups: inverted flat roof on supports (adjustable and unregulated), inverted flat roof without supports and inverted rooftop parking.

4.2 System of criteria for evaluating options of inverted flat roof construction with expert analysis method

Due to the existing solutions of the inverted flat roof construction that have been found, the study developed the system of criteria for evaluating the efficiency of each roof's option.

The development of system of criteria and expert analysis method were used in a Russian study of the operation of 3D printers in the field of civil engineering (Egorov & Gorovaia 2019, 178—182). The same principles of expert analysis, the development of system criteria and indicators combined with mathematical modelling of 3D printing research are taken as the basis for this study.

The method of expert analysis is actively used in technical and design problems, including in cases of solving problems for the choice of rational options for construction production (Badjin et al. 1989, 3; Lapidus & Demidov 2014, 164). The main sequence of expert analysis and mathematical modelling of the thesis work is shown in Figure 20.

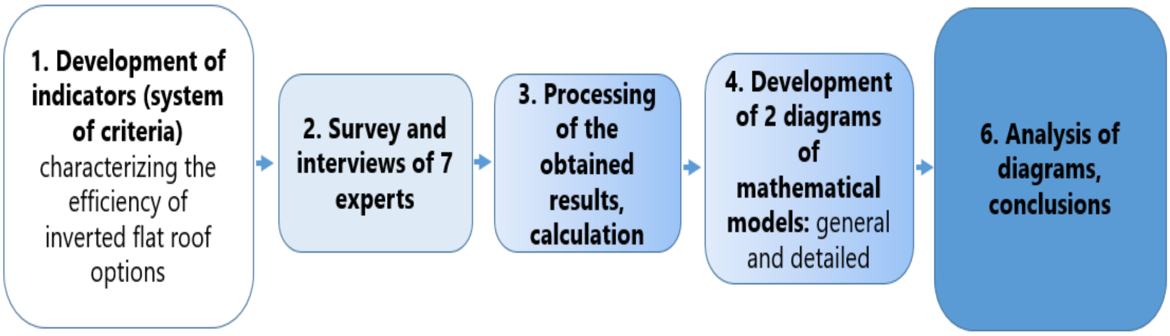

Figure 20. The main sequence of expert analysis and mathematical modelling in the thesis work

As it is possible to see, the implementation of these methods has many steps and includes a survey-interview, calculation, etc.

At the beginning of the study, the main indicators and criteria (system of criteria) were identified (Table 1), affecting the efficiency of inverted flat roof construction options. In our case, there are three main (enlarged) criteria:

- Technological efficiency is a criterion that allows assessing the production and operational characteristics of the roof, as well as the possibility of carrying out work in various construction conditions.
- Resource efficiency is a criterion that shows the level of consumption of roofing materials, resources and financial costs.
- Environmental friendliness is a criterion that makes it possible to assess the degree of impact on the environment and people.

These criteria and following expert analysis will make it possible to characterize the efficiency of inverted flat roof construction options. The analysis will help to understand which main criteria and indicators are most important for an inverted roof.

Code	Evaluation criterion	Weight coefficient, **λ**
1.	**Technological efficiency**	
1.1	Possibility to perform works in conditions of atmospheric precipitation	λ_1
1.2	Possibility of using for reconstruction the flat roof of existing buildings	λ_2
1.3	Possibility of using the roof in the construction of family houses	λ_3
1.4	Convenience of snow and ice removal from the roof surface during the usage phase	λ_4
1.5	Convenience of rain water removal from the roof surface during the usage phase	λ_5
2.	**Resource efficiency**	
2.1	Structural reliability of the roof	λ_6
2.2	Cost of use	λ_7
2.3	Roofing materials consumption	λ_8
2.4	Thermal capacity	λ_9
2.5	Volume (amount) of work	λ_{10}
3.	**Environmental friendliness**	
3.1	Lack of construction waste during work	λ_{11}
3.2	Possibility of using thermal insulation based on natural materials	λ_{12}

Table 1. Developed indicators characterizing the efficiency of construction of inverted flat roof options

Thus, 3 main criteria with 12 indicators (criteria) were identified.

At the first stage, the expert analysis method was applied in order to determine the weight of each criterion.

In the course of this research, the method of assigning points was applied. It consists in evaluating the criteria by experts on a ten-point scale. Criteria can be assigned the same score.

For the expert analysis, 7 experts from Russia with specialized civil engineering's education and experience in the field of construction and design for 10-15 years or more were involved. There were specialists as experts of following organizations that were interviewed:

- Novyj Dom Invest Ltd. Company (Saint Petersburg)
- Department of Construction Technology of Saint Petersburg State University of Architecture and Civil Engineering (Saint Petersburg)
- Ladoga Ltd. Company (Saint Petersburg).

Sheets with the indicators from Table 1 above were issued to each expert to assess the factors affecting the efficiency of inverted flat roof construction. Their task was to evaluate these factors from 1 to 10 points, where 1 is the smallest influence value, 10 is the maximum. The final evaluation results are shown in Table 2.

Criterion, j_n	**Expert 1, h_1**	**Expert 2, h_2**	**Expert 3, h_3**	**Expert 4, h_4**	**Expert 5, h_5**	**Expert 6, h_6**	**Expert 7, h_7**
j_1	9	8	9	10	7	10	10
j_2	6	6	6	7	8	5	2
j_3	7	3	2	5	2	7	1
j_4	10	5	9	10	8	9	10
j_5	10	10	9	10	8	9	9
j_6	10	10	10	10	10	10	10
j_7	7	9	9	10	9	8	7
j_8	7	8	7	10	9	7	5
j_9	7	10	8	9	9	7	6
j_{10}	7	7	7	9	8	7	6
j_{11}	6	9	8	9	5	10	6
j_{12}	5	9	5	6	5	6	4

Table 2. Results of expert analysis on the significance of criteria

As the next step, it is necessary to assign a weight depending on the influence and importance on the overall efficiency of the roof construction.

During the processing of the obtained expert analysis data, the weight of each criterion was found. It defines by the formula:

$$r_{ij} = \frac{h_{ij}}{\sum_{j=1}^{m} h_{ij}} \quad (1)$$

where h_{ij} is the score set by the i-expert on the j-criterion.

Obtained values of weights of criteria are given in Table 3.

r_{1j}	r_{2j}	r_{3j}	r_{4j}	r_{5j}	r_{6j}	r_{7j}	Σr_{ij}
1	2	3	4	5	6	7	8
0,0989	0,0879	0,0989	0,1099	0,0769	0,1099	0,1099	0,692
0,0659	0,0659	0,0659	0,0769	0,0879	0,0549	0,0220	0,440
0,0769	0,0330	0,0220	0,0549	0,0220	0,0769	0,0110	0,297
0,1099	0,0549	0,0989	0,1099	0,0879	0,0989	0,1099	0,670
0,1099	0,1099	0,0989	0,1099	0,0879	0,0989	0,0989	0,714
0,1099	0,1099	0,1099	0,1099	0,1099	0,1099	0,1099	0,769
0,0769	0,0989	0,0989	0,1099	0,0989	0,0879	0,0769	0,648
0,0769	0,0879	0,0769	0,1099	0,0989	0,0769	0,0549	0,582
0,0769	0,1099	0,0879	0,0989	0,0989	0,0769	0,0659	0,615
0,0769	0,0769	0,0769	0,0989	0,0879	0,0769	0,0659	0,560
0,0659	0,0989	0,0879	0,0989	0,0549	0,1099	0,0659	0,582
0,0549	0,0989	0,0549	0,0659	0,0549	0,0659	0,0440	0,440

Table 3. Weights of criteria

Final weight coefficients were calculated using the formula:

$$\lambda_j = \frac{\sum_{i=1}^{n} r_{ij}}{\sum_{i=1}^{n} \sum_{i=1}^{m} r_i} \quad (2)$$

where r_{ij} is the weight of the corresponding criterion.

As a result, the weight coefficients for each criterion were obtained, summarized in Table 4.

Criteria	**Weight coefficient**
λ_1	0,099
λ_2	0,063
λ_3	0,042
λ_4	0,096
λ_5	0,102
λ_6	0,110
λ_7	0,092
λ_8	0,083
λ_9	0,088
λ_{10}	0,080
λ_{11}	0,083
λ_{12}	0,063

Table 4. Weight coefficients of criteria

At that step, based on the results of the expert analysis before developed final diagrams, it can be concluded that the most significant indicators (criteria) are:

- criterion of structural reliability of the roof
- criterion of convenience of rainwater removal from the roof surface during the usage phase
- criterion of possibility to perform works in conditions of atmospheric precipitation
- criterion of convenience of snow and ice removal from the roof surface during the usage phase.

The next step was to conduct an expert analysis of the efficiency of the use of 3 grouped options for the inverted flat roof construction:

- Group 1. Inverted flat roof on supports.
- Group 2. Inverted flat roof without supports.
- Group 3. Inverted rooftop parking.

The method of expert analysis was also used to analyse the efficiency of grouped roof construction options. Experts gave estimates of 1 to 10 per criterion by degree of conformity and security, where 1 is the smallest influence value, 10 is the maximum. The results of the obtained expert assessments are given in Table 5, Table 6 and Table 7.

The presence of a large number of evaluation criteria does not make it possible to uniquely determine the optimal option of inverted flat roof construction. Therefore, at the first stage, weights were determined. As the criterion of optimality can be adopted generalized function F_i (h_{i1}; h_{i2}; h_{i3}; ... h_{in}), which is a monotonic function of h_{i1} criteria; h_{i2}; h_{i3}; ... h_{in}. This function is constructed using the additive optimization method. The method consists in the summation of particular criteria multiplied by the appropriate weight coefficient:

$$F_{ij} = \sum_{j=1}^{n} \lambda_j \cdot h_{ij} \qquad (3)$$

where F_{ij} is the generalized function of the mathematical model;

h_{ij} – the score given by the i-expert according to the j-criterion;

λ_j – weighting coefficient of the j-criterion, which determines the importance of the criterion.

The optimal option of inverted flat roof construction will be considered, in which the value of F is the largest.

Criterion, j_n	**Expert 1, h_1**	**Expert 2, h_2**	**Expert 3, h_3**	**Expert 4, h_4**	**Expert 5, h_5**	**Expert 6, h_6**	**Expert 7, h_7**
1	2	3	4	5	6	7	8
j_1	3	4	5	6	4	5	6
j_2	5	6	4	6	7	5	3
j_3	7	2	5	8	5	7	1
j_4	7	3	2	5	5	5	1
j_5	6	3	3	5	6	1	1
j_6	5	7	3	5	5	6	6
j_7	8	9	7	10	7	7	8
j_8	8	9	8	10	8	6	7
j_9	8	9	9	9	9	7	6
j_{10}	8	7	8	7	10	6	8
j_{11}	7	5	8	7	6	8	5
j_{12}	7	7	5	6	4	4	5
Σ	79	71	67	84	76	67	57

Table 5. Results of expert analysis of the inverted flat roof construction group 1 (the roof on supports)

Criterion, j_n	Expert 1, h_1	Expert 2, h_2	Expert 3, h_3	Expert 4, h_4	Expert 5, h_5	Expert 6, h_6	Expert 7, h_7
1	2	3	4	5	6	7	8
j_1	5	6	6	8	7	9	8
j_2	6	7	7	3	2	5	5
j_3	8	2	7	10	5	9	5
j_4	8	3	5	8	1	6	1
j_5	8	7	7	9	8	6	7
j_6	10	9	9	6	8	7	8
j_7	10	6	6	7	4	5	8
j_8	10	10	9	9	8	6	9
j_9	7	7	8	6	5	6	10
j_{10}	10	8	5	6	10	6	5
j_{11}	3	5	5	4	3	3	2
j_{12}	8	9	7	7	8	5	7
Σ	93	79	81	83	69	73	75

Table 6. Results of expert analysis of the inverted flat roof construction group 2 (the roof without supports)

Criterion, j_n	Expert 1, h_1	Expert 2, h_2	Expert 3, h_3	Expert 4, h_4	Expert 5, h_5	Expert 6, h_6	Expert 7, h_7
1	2	3	4	5	6	7	8
j_1	6	7	8	8	7	10	8
j_2	4	2	2	3	1	5	6
j_3	2	1	1	2	3	1	2
j_4	5	2	3	3	2	5	4
j_5	9	7	8	9	10	4	5
j_6	9	9	10	5	8	5	8
j_7	10	10	9	7	7	6	9
j_8	10	10	10	9	10	8	9
j_9	8	8	8	6	5	6	9
j_{10}	9	8	5	5	10	6	5
j_{11}	3	5	5	4	3	3	2
j_{12}	9	9	6	7	8	5	8
Σ	84	78	75	68	74	64	75

Table 7. Results of expert analysis of the inverted flat roof construction group 3 (the roof-top parking)

Knowing the value of the weights from the Table 4, it is possible to find the F-values for each expert according to Formula 3. This is by the sum of the experts' estimate multiplied by appropriate weight coefficients. As a result, criteria of optimality values for the grouped options of inverted flat roof construction were calculated in Table 8, Table 9 and Table 10.

$F_1(h_1)$	$F_1(h_2)$	$F_1(h_3)$	$F_1(h_4)$	$F_1(h_5)$	$F_1(h_6)$	$F_1(h_7)$
6,502	6,000	5,502	6,906	6,334	5,497	4,895

Table 8. Criteria of optimality for the inverted flat roof construction Group 1 (the roof on supports)

$F_2(h_1)$	$F_2(h_2)$	$F_2(h_3)$	$F_2(h_4)$	$F_2(h_5)$	$F_2(h_6)$	$F_2(h_7)$
7,806	6,723	6,765	6,914	5,840	6,066	6,371

Table 9. Criteria of optimality for the inverted flat roof construction Group 2 (the roof without supports)

$F_3(h_1)$	$F_3(h_2)$	$F_3(h_3)$	$F_3(h_4)$	$F_3(h_5)$	$F_3(h_6)$	$F_3(h_7)$
7,301	6,828	6,713	5,908	6,436	5,566	6,458

Table 10. Criteria of optimality for the inverted flat roof construction Group 3 (the rooftop parking)

The general opinion O_m of the expert group on the effectiveness of the grouped options of the flat roof construction can be found as the weighted average of its estimates:

$$O_m = \frac{\sum F_m(h_i)}{Ni} \quad (4)$$

where $F_m(h_i)$ – criteria of optimality from Table 8, Table 9 and Table 10;

N_i – amount of the experts.

The detailed calculation according to the Formula 4 for each group is provided in Appendix 1.

In the case of inverted flat roof construction Group 1, the general opinion O_1 will be to 5.948.

For the inverted flat roof construction Group 2, the general opinion will O_2 be equal to 6.641.

For the inverted flat roof construction Group 3, the general opinion O_3 will be equal to 6.458.

When analysing the obtained results of the indicators of the additive criterion, it can be concluded that the option of roofing construction without supports (Group 2) is the most effective because $O_2>O_3>O_1$ or 6.641 > 6.458 > 5.948.

4.3 Final diagrams of mathematical models

Detailed mathematical models as diagrams were built that reflect the properties of options of inverted flat roof construction:

$$F_i^{'} = \lambda_1 \cdot h_{i1} + \lambda_2 \cdot h_{i2} + \lambda_3 \cdot h_{i3} + ... + \lambda_n \cdot h_{in} \quad (5)$$

where h_{ij} is the average estimate of the h_{ij} criterion for assessing all experts for the each i-option of the roof construction (Table 11, Table 12, Table 13).

At first, a detailed mathematical model F'_1 was compiled according to the Formula 5, which displays the properties of the option of roofing construction on supports. The results are presented in Table 11. Auxiliary data for the construction of inverted roof Group 1 are represented in all 12 criteria.

Criterion, j_n	$\bar{h}_{ij}$	λ_i	$\bar{h}_{ij}\ \lambda_i$
j_1	4,7	0,0987	0,4655
j_2	5,1	0,0627	0,3224
j_3	5,0	0,0423	0,2116
j_4	4,0	0,0956	0,3824
j_5	3,6	0,1019	0,3639
j_6	5,3	0,1097	0,5799
j_7	8,0	0,0925	0,7398
j_8	8,0	0,0831	0,6646
j_9	8,1	0,0878	0,7147
j_{10}	7,7	0,0799	0,6167
j_{11}	6,6	0,0831	0,5459
j_{12}	5,4	0,0627	0,3403

Table 11. Auxiliary data for inverted roof construction: Group 1

After that, it is necessary to draw up a detailed mathematical model F'_2 that displays the properties of the option of roofing construction without supports. The results are presented in Table 12. Auxiliary data for the construction of inverted roof Group 2 are represented in all 12 indicators.

Criterion, j_n	$\hbar_{ij}$	λ_i	$\hbar_{ij}\ \lambda_i$
j_1	7,0	0,0987	0,6912
j_2	5,0	0,0627	0,3135
j_3	6,6	0,0423	0,2781
j_4	4,6	0,0956	0,4371
j_5	7,4	0,1019	0,7568
j_6	8,1	0,1097	0,8934
j_7	6,6	0,0925	0,6077
j_8	8,7	0,0831	0,7239
j_9	7,0	0,0878	0,6144
j_{10}	7,1	0,0799	0,5710
j_{11}	3,6	0,0831	0,2967
j_{12}	7,3	0,0627	0,4568

Table 12. Auxiliary data for inverted roof construction Group 2

The last step was to compile a detailed mathematical model F'_3 that displays the properties of the rooftop parking option. The results are presented in Table 13. Auxiliary data for the construction of inverted roof Group 3 there are represented in all 12 criteria.

Criterion, j_n	$\hbar_{ij}$	λ_i	$\hbar_{ij}\ \lambda_i$
j_1	7,7	0,0987	0,7618
j_2	3,3	0,0627	0,2060
j_3	1,7	0,0423	0,0725
j_4	3,4	0,0956	0,3278
j_5	7,4	0,1019	0,7568
j_6	7,7	0,1097	0,8464
j_7	8,3	0,0925	0,7662
j_8	9,4	0,0831	0,7833
j_9	7,1	0,0878	0,6270
j_{10}	6,9	0,0799	0,5481
j_{11}	3,6	0,0831	0,2967
j_{12}	7,4	0,0627	0,4657

Table 13. Auxiliary data for inverted roof construction Group 3

Then it was necessary to construct a detailed diagram that clearly demonstrates and helps to track the distribution of expert assessments for all 12 criteria based on their weight (Chart 1).

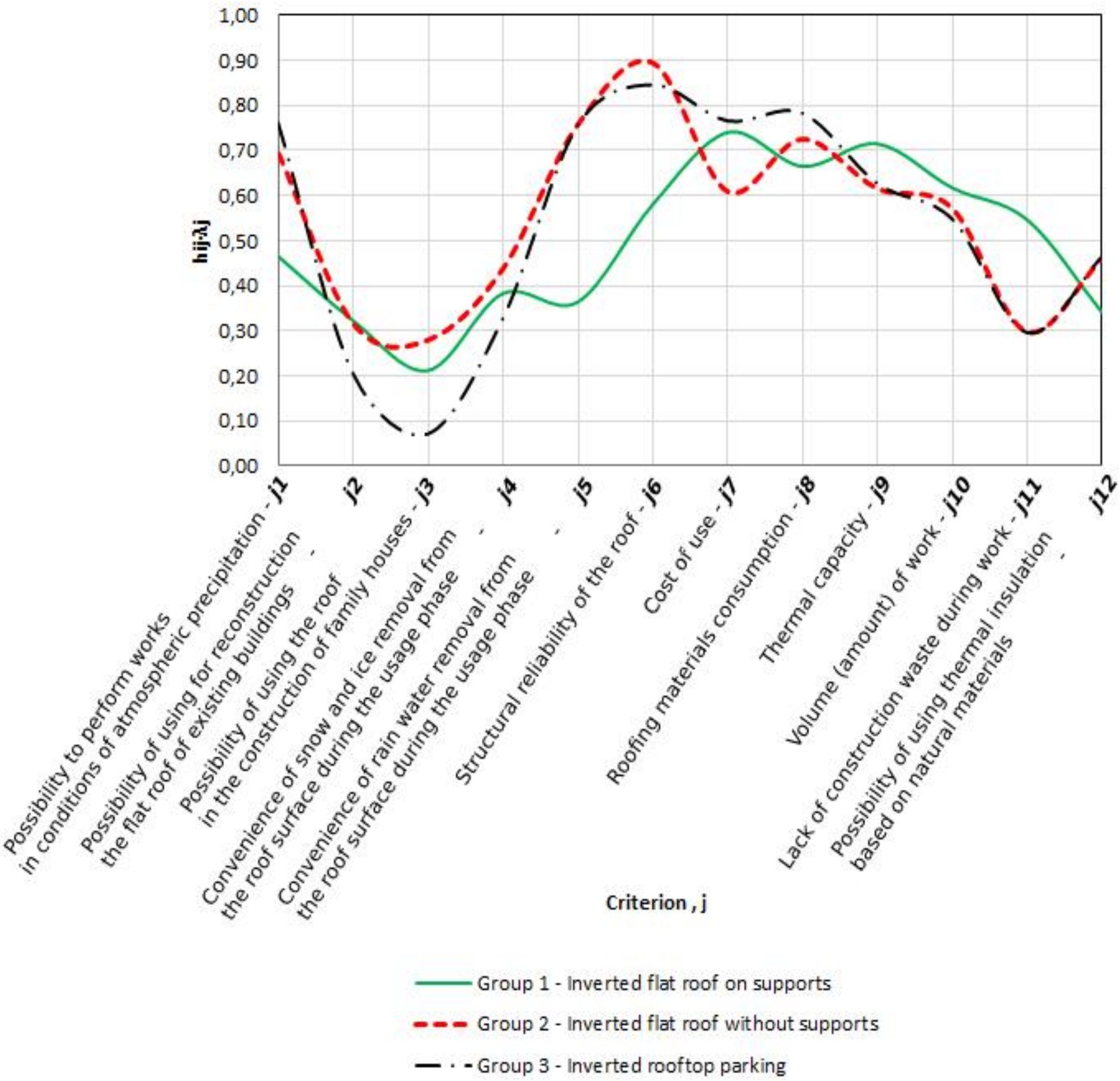

Chart 1. Final detailed diagram

Analysing the detailed diagram, it can be concluded that all options of inverted flat roof construction have the following rather low parameters:

- possibility of using to reconstruct the flat roof of existing buildings
- possibility of using the roof in the construction of family houses
- convenience of snow and ice removal from the roof surface during the usage phase.

The option of roofing with the use of supports and the rooftop parking option received the lowest values of the parameter of the lack of construction waste during work. Maximum values are for the parameters of availability and convenience of rainwater removal from the roof surface during the usage phase, structural reliability of the roof.

It should be noted that the roofing option with the use of supports in comparison with the rest of the options received the lowest values of the following parameters:

- convenience of snow and ice removal from the roof surface during the usage phase
- convenience of rainwater removal from the roof surface during the usage phase
- structural reliability of the roof.

In the course of the study, a mathematical model was obtained that shows the effectiveness of the inverted flat roof construction into account 3 main enlarged criteria:

- K_1 – technological efficiency
- K_2 – resource efficiency
- K_3 – environmental friendliness.

Thus, the general mathematical model for the inverted roof construction Group 1 is defined as:

$$H_0^1 = K_1^1 + K_2^1 + K_3^1, \qquad (6)$$

where $K_1^1 = \sum_{j=1}^{5} h_{1j} \cdot \lambda_j$,

$K_2^1 = \sum_{j=6}^{10} h_{1j} \cdot \lambda_j$,

$K_3^1 = \sum_{j=11}^{12} h_{1j} \cdot \lambda_j$.

h_{1j} is the average rating of all experts according to criterion j for the Group 1.

The general mathematical model for the inverted roof construction Group 2 is defined as:

$$H_0^2 = K_1^2 + K_2^2 + K_3^2, \qquad (7)$$

where $K_1^2 = \sum_{j=1}^{5} h_{2j} \cdot \lambda_j$;

$K_2^2 = \sum_{j=6}^{10} h_{2j} \cdot \lambda_j$;

$K_3^2 = \sum_{j=11}^{12} h_{2j} \cdot \lambda_j$;

h_{2j} is the average rating of all experts according to criterion j for the Group 2.

The general mathematical model for the inverted roof construction Group 3 is defined as:

$$H_0^3 = K_1^3 + K_2^3 + K_3^3, \quad (8)$$

where $K_1^3 = \sum_{j=1}^{5} h_{3j} \cdot \lambda_j$;

$K_2^3 = \sum_{j=6}^{10} h_{3j} \cdot \lambda_j$;

$K_3^3 = \sum_{j=11}^{12} h_{3j} \cdot \lambda_j$;

h_{3j} is the average rating of all experts according to criterion j for the Group 3.

As a result, a general diagram was built based on the developed mathematical models, which reflects the properties of the investigated roof construction (Chart 2).

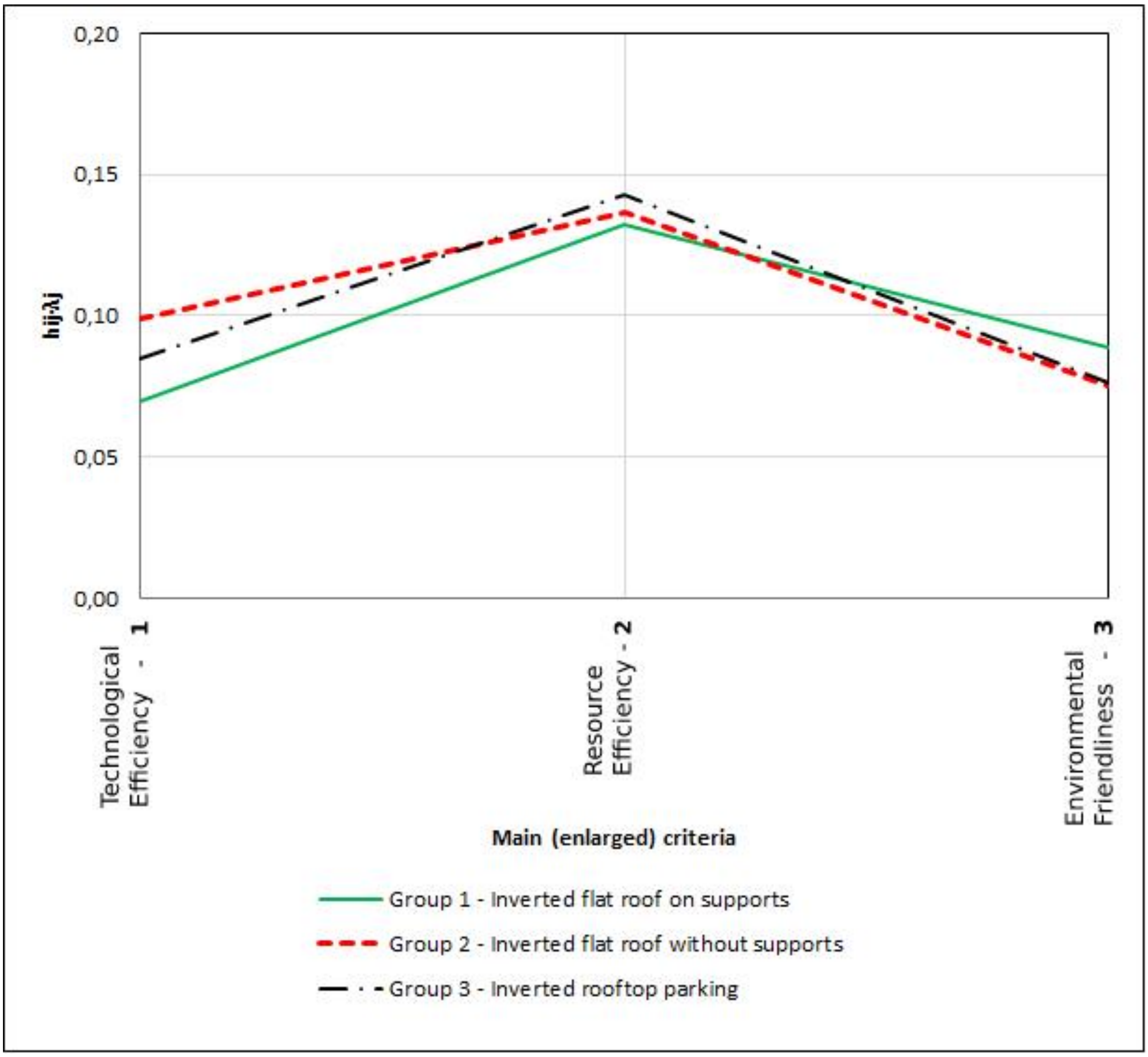

Chart 2. Final general diagram

Analyzing the general diagram, it is possible to conclude that the option of the inverted roof construction with the use of supports is inferior to the rest by most of the criteria. Of all 3 options of roofing, the main (enlarged) criterion of the resource efficiency received the greatest assessment. This is due to the importance of cost, roofing material consumption, the thermal capacity, the volume of work, structural reliability of the roof for any type of roof.

The developed system of evaluation criteria of inverted roof options and the analysis performed to help customers and designers to take into account the peculiarities of such a roof in their own projects.

5 Improvement of inverted flat roof technology and construction

5.1 Alternative construction method of inverted flat roof on unregulated supports

5.1.1 Existing solutions and their disadvantages

Traditionally, to create inverted roof on supports, separate elements are used: supports and, in the case of a composite decking boards as a finishing layer, guides elements: steel guides or timber elements that are attached to the supports (Figure 21).

Figure 21. Separate support elements: guide joists and supports (Roofinglines 2018)

Such solutions have their disadvantages — there are long-term assembly and large volume of work for the assembly of supporting elements: placement of freestanding adjustable plastic supports at the desired equal distance according to the project, the location and assembly of steel guides or timber elements, and in some cases their trimming.

During the research, a review of technical and patent information was carried out. Technical solutions for the rooftop terrace support system were found partially solving the problem, but having their own disadvantages.

Set of elements for raised floor and open terraces (patent EP0362718B1)

A set of elements was found for an adjustable floor stand and open terraces. It contains a threaded rod with a nut screwed onto it, one end connected to the base plate for mounting the supporting floor structures on it, and a cylindrical element connected at one end to the plate for fixing it to the floor base (Figure 22).

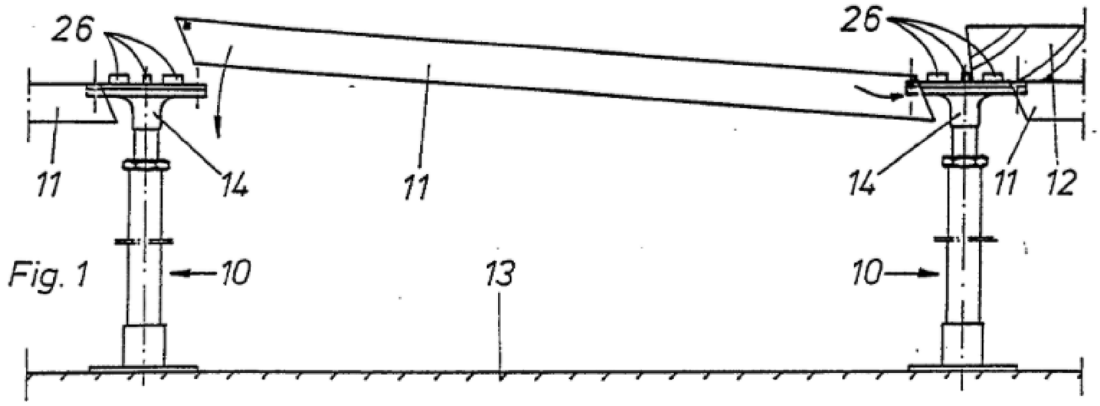

Figure 22. Set of elements from the European patent EP0362718B1: supports (10) and connecting steel element (11) (Hiller 1992, 5)

From the same source of information, a method for assembling an adjustable floor stand is known, including the assembling on the floor base of a cylindrical element rigidly connected to a plate attached to the floor base. (Hiller 1992, 2—5.)

The disadvantage of solution is a large number of elements that will take assembly time, and will increase the construction period of the roof. In addition, there is a gap between the connected parts of the rack — the cylindrical element and the threaded rod, which leads to misalignment of the cylindrical mating surfaces and thereby reduces the quality of the connection. The found development is not able to reduce the level of vibration from roofing (exploitable finish layer).

Loadbearing structure for raised floor (Patent RU 126352 U1)

A solution was found in the form of a created supporting structure for creating roof terraces and a raised floor (Figure 23). It could be used for construction of inverted roofs on supports.

A set of supports consists of a large number of parts and elements: steel bearing supports, washers, screw supports, braces made in the form of a steel, locknuts on the screws etc. (Zhilnikov et al 2013, 2—5).

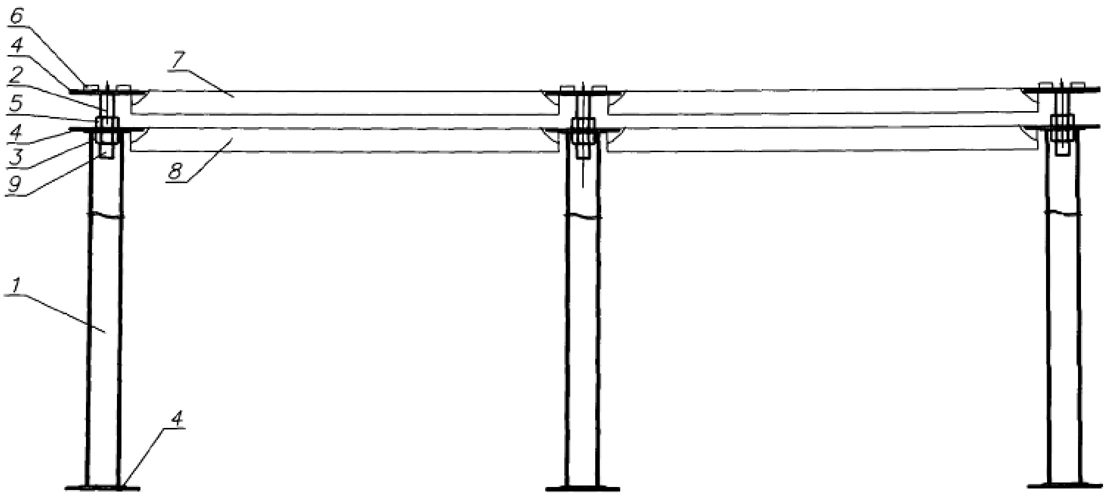

Figure 23. Set of elements from the Russian patent RU 126352 U1: supports (1), connecting steel U-shaped cross-section elements (7, 8) (Zhilnikov et al 2013, 1)

However, this construction has the following disadvantages: a narrow range of adjustment of the floor height due to the fixed dimensions of the stringer, a fixed distance between the stringers, due to the size of the U-shaped cross-section element. Similar to the previous design, it poorly reduces the level of vibration from the roof to the lower layers of roofs.

In addition, the use of timber elements as elements of roof supports — also has its disadvantages. There are the following disadvantages of using metal guides:

- Timber has a shorter lifespan than metal, so it can deteriorate faster than a roof covering.
- Timber requires additional processing and protection: protection of surfaces from pests, protection from moisture, fire protection.

Therefore, when constructing a system of roof supports with composite decking boards on supports, it is rational to use aluminium guides elements.

The use of elements in the structure of a support made lightweight steel profiles or aluminium elements has its advantages:

- materials do not corrode and do not require additional protection against it
- light weight of all structures.

It is possible to conclude, that prefabricated corrosion-resistant materials are essential especially for use in northern conditions and in rainy, snowy weather condition. Possible improvement should be based on such materials.

5.1.2 Alternative technical model of the roof support system

After analysing technical solutions and materials, a set of four sliding unregulated supports of stainless steel with connecting elements made of aluminium was developed for the construction of the inverted roof on supports with composite decking boards. This development is able to improve the technology of inverted roof construction, because it reduces the weight of the structure, increases the speed of assembling of elements, and the connecting elements do not need additional protection — elements are not subject to corrosion and are resistant to harsh climatic conditions.

The technical results of the development are following:

- Ensuring an increase in the speed of assembling of elements of the roof supports.
- Lightening the weight of the support structure.
- Prefabricated corrosion protection.
- Reducing vibration, reducing noise and protecting the covering on which the support will be placed.
- Convenience when repairing the roof: there is no need to disassemble all the supports and the entire finishing layer.

The four supports of the sliding system are connected to each other at a distance of 500 to 1100 mm by four guides.

Aluminium guides have the following dimensions: two elements have length from 500 to 1100 mm, width 40 mm, height 40 mm, thickness 1.5 mm, and last two elements have the same dimensions, except the height – 39.5 mm. The weight of the one connecting element be from 0.642 to 1.177 kg (depending on length). They are attached with each other and to the stainless steel supports with special stainless anchor stud bolt in round aluminium bushing. The round aluminium bushing needed to redistribute loads from above.

Such a structure is capable of moving from a folded position to a sliding position at an angle of 90 degrees due to one movement according to the principle of a rhombic jack device. For 3D modelling, Autodesk Solidworks 2016 was used (Figure 24).

Stainless steel supports has a height 40 mm and the diameter of the support is 200 mm. The top and bottom surfaces of the support are rubber shims (2.5 mm thickness). This is necessary to reduce vibrations between the support elements, reduce noise and protect the covering on which the support will be placed.

Next, the connecting elements are assembled in the form of separate aluminium guides, which connect the sliding structures to each other due to stainless bolts, which are twisted into the holes of the connecting aluminium guide and support.

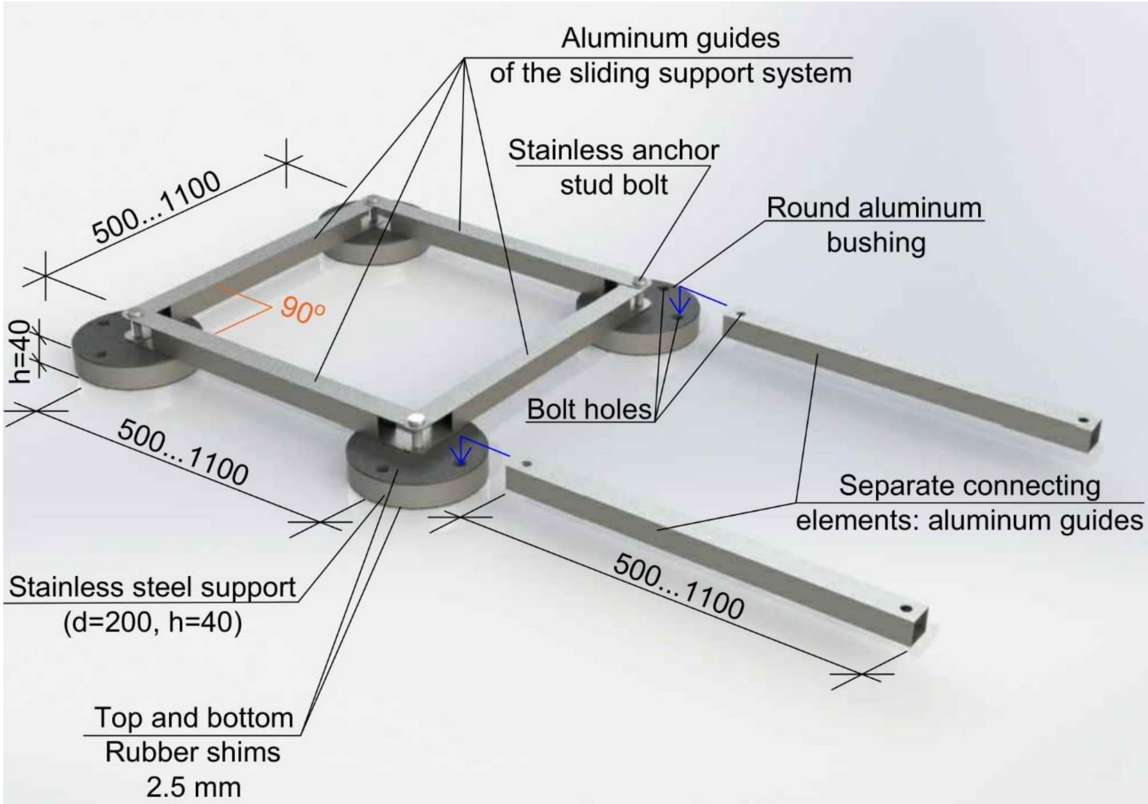

Figure 24. Alternative technical model set of support elements of the roof system: sliding support system and intermediate connecting elements (designed in Autodesk Solidworks 2016)

All elements will be prefabricated and can be transported to the construction site, the amount of those elements — according to the designer’s calculations. It is possible to manufacture these supporting elements in different sizes.

5.1.3 Method of assembling support elements for alternative technical model

The optimal method and scheme of assembling support elements are proposed.

1. On Figure 25, it is possible to see that the arrangement of elements in the form of a sliding system of four stainless supports is carried out through one: two sliding systems of four stainless supports are assembled at a distance from each other from about 500 mm to 1100 mm depending on the project.

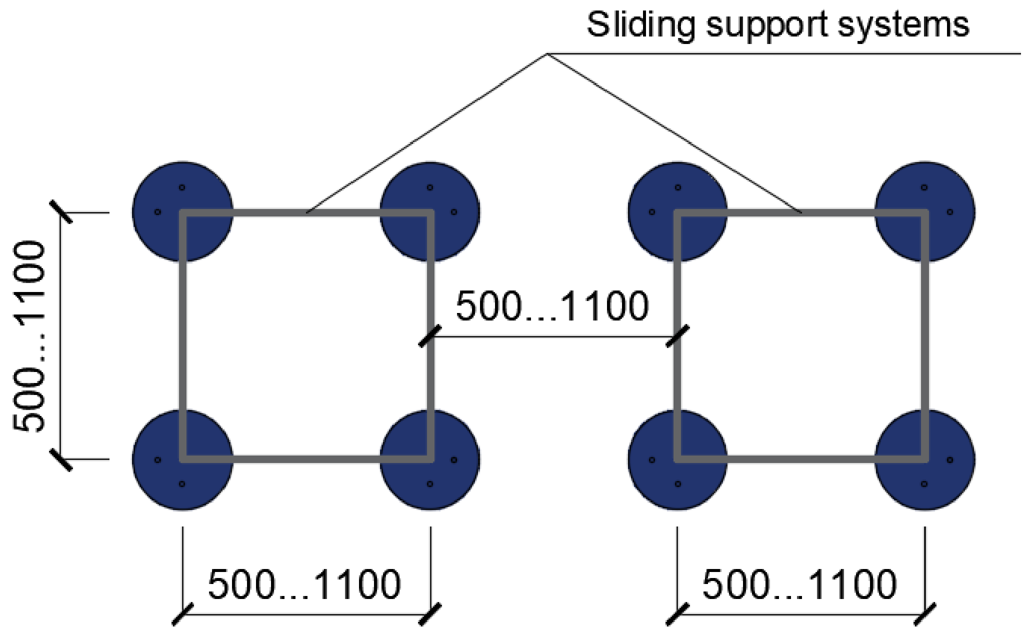

Figure 25. Method of assembling support elements: the first step

2. Next step it is presented in Figure 26. Between two sliding systems of four stainless supports, an intermediate connecting elements made of aluminium are assembled, connected to the supports with stainless bolts.

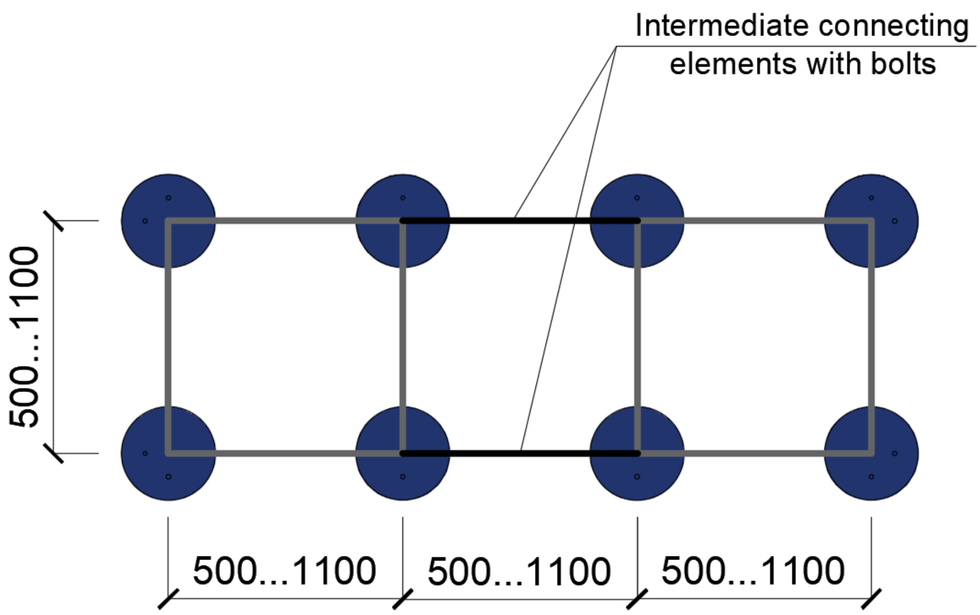

Figure 26. Method of assembling support elements: the second step

3. After that, the next step it is presented in Figure 27. Here an approximate distance from 500 mm to 1100 mm is laid from the last assembled sliding element with four supports, and another sliding element with four supports is placed again and intermediate ones are placed between them.

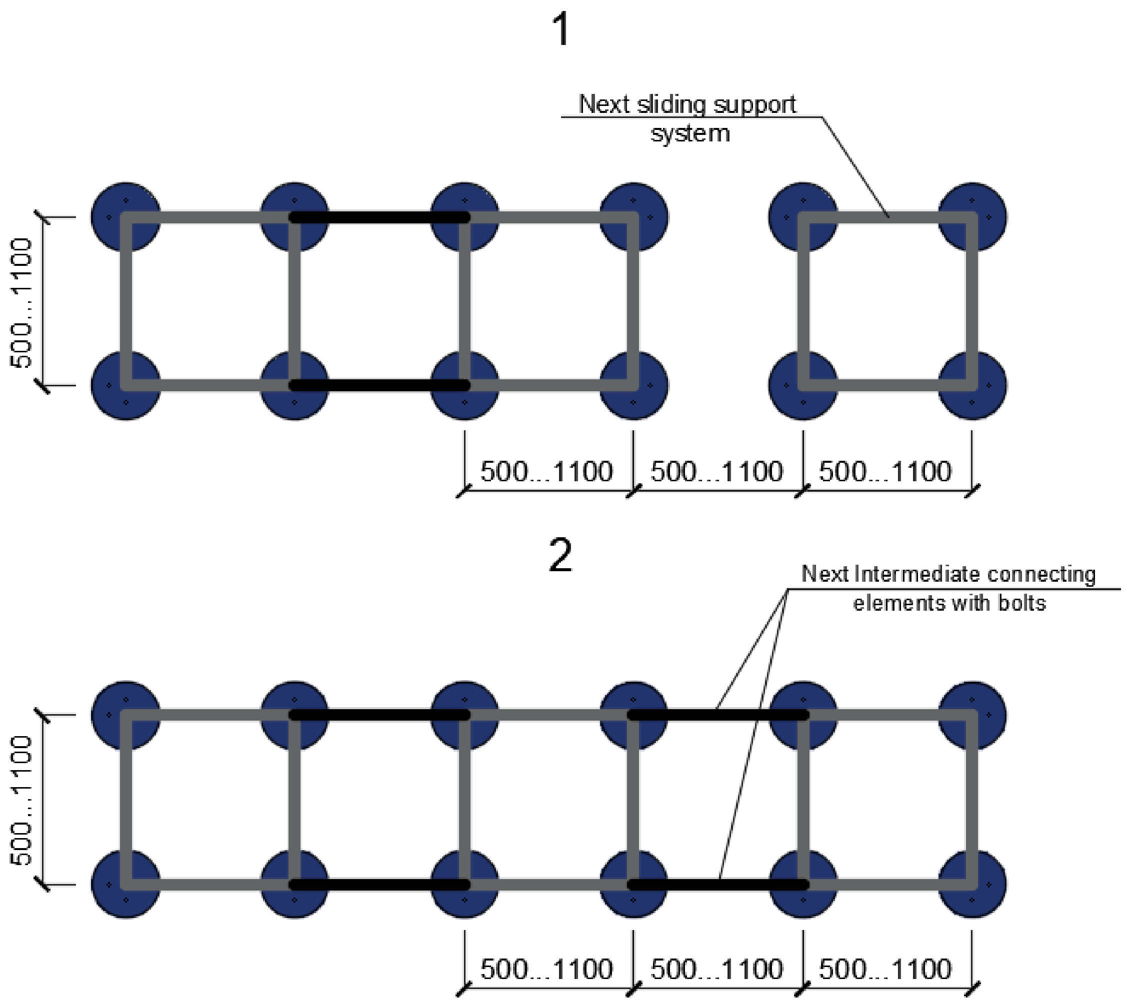

Figure 27. Method of assembling support elements: the third step

4. Then, as it presented in Figure 28, it is possible to assemble the next row of elements, and connect them with intermediate connecting elements with bolts.

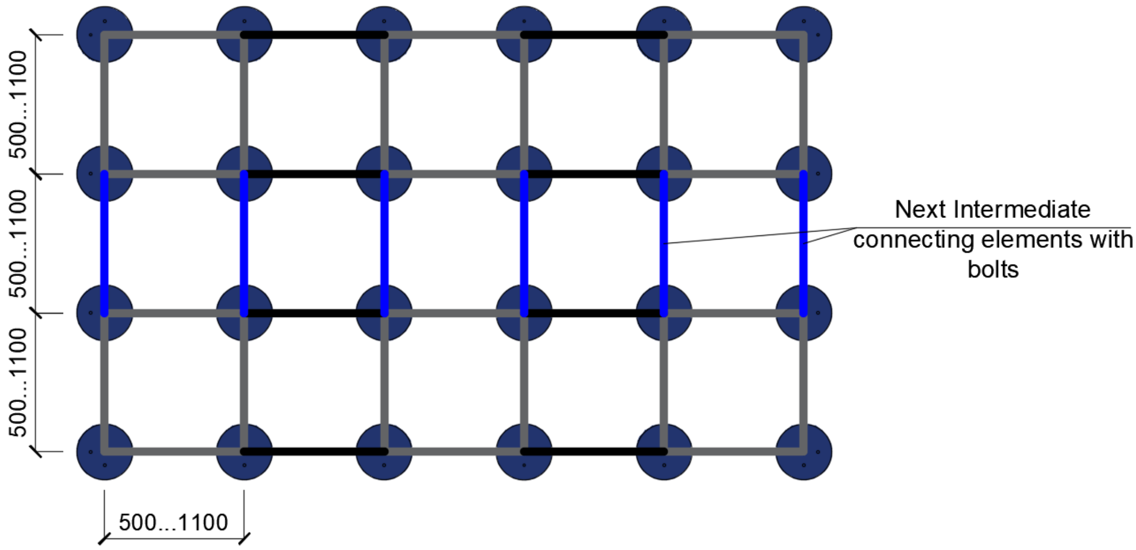

Figure 28. Method of assembling support elements: the fourth step

Then the process is repeated until all roof support elements are fully assembled.

As the final step composite decking boards are laid, which are fastened with special connections or self-tapping screws to the aluminium structures of the support system.

5.2 Modern and versatile insulation materials for construction of inverted flat roof with thermal calculation

5.2.1 Multifunctional insulation materials as a replacement for traditional insulation

In the course of the study, modern multifunctional and versatile insulation materials were found that could play the role of waterproofing, vapour barrier and additional thermal insulation in order to create an optimal design of an inverted roof with an exploited coating.

As an improved waterproofing, a bitumen-polymer material with a multilayer structure and SBS-modified (styrene-butadiene-styrene) bitumen will be optimal. The most interesting example of such material is a Russian insulation material Dneprotex PE. Unlike traditional bitumen roll materials that do not contain a polymer modifier, it has increased durability, flexibility, heat and frost resistance, elasticity, and weather resistance (TY 5774-001-51070686-2003, Section 1; Zelmanovich & Mogilevsky 2010, 41—43).

The main advantage of the material is its unique multiple application: waterproofing, sound and thermal insulation of structures. It is used for waterproofing buildings and engineering structures, transport tunnels and subways, road (transport construction) waterproofing coatings of overpass subway lines.

In Figure 29 the structure of the Dneprotex material is presented as five-layer roll material on a polyester or fiberglass carrier base and modified bitumen, the front surface of which is protected by a geotextile cloth with a density of 400-700 g / m^2 made of polyester fibers. Available in rolls 1 m wide and 4 to 10 m long. The thickness of Dneprotex is 8.1 mm. (Zelmanovich & Mogilevsky 2010, 41—43.)

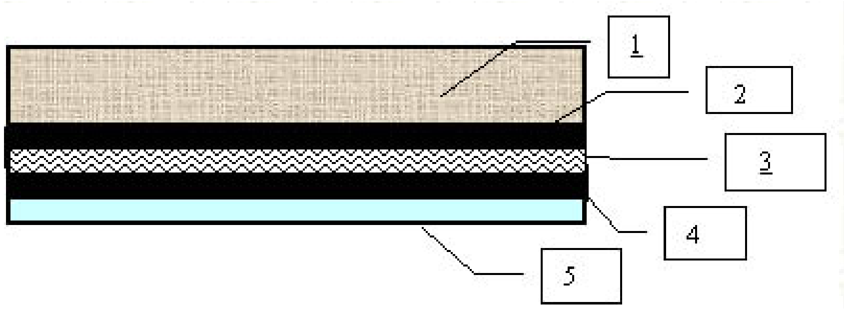

Figure 29. Structure of the Dneprotex insulation material (CJSC Corporation of Building Materials 2004)

According to Figure 29, it is possible to see that the structure has a multi-layer structure with following layers:

1. A nonwoven geotextile fabric made of polymer fibres with a density of 400-700 g / m^2.
2. A bonding bitumen (bitumen-elastomeric) SBS-modified layer.
3. A carrier layer impregnated with a bitumen-polymer (bitumen) binder made of durable non-woven polyester fabric, basalt or glass fabric.
4. A waterproofing deposited bitumen (bitumen-elastomeric) SBS-modified layer.
5. An anti-adhesive polymer film.

It is possible to lay and attach Dnerpotex PE to concrete, asbestos-cement and other bases or surfaces by melting method. In addition, it is possible to lay the material on an existing bituminous waterproofing carpet. Dneprotex PE is biostable material. (LLC STC Gidrol-Krovlya.)

As Zelmanovich and Mogilevsky (2010, 41) described in their article, in 2004 Dneprotex was used for waterproofing spans of the Butovskaya flyover line of the Moscow Metro over 4 km long. However, the creators of this material mention only the possibility of using it to create an inverted roof, but in the course of the thesis work real cases of using Dneprotex as an insulation material for any types of flat roofs was not found

According to the description of its properties, which are given above, it is possible to use this material as an additional layer of waterproofing, which is especially important during construction and use of roof in climatic conditions of Central Finland. This statement must be proved by further thermal engineering calculation and analysis.

Thus, there is no need to lay several, few layers of traditional bituminous materials, membranes. It is enough to lay one layer of Dneprotex PE.

As an alternative option, instead of exporting material from Russia, it is possible to develop an analogue material with similar properties, but with some improvements and changes: additional layers of geotextiles, bitumen and film, etc.

Moreover, as a vapour barrier and waterproofing for sublayers (under layers), the optimal material will be a material that has a multilayer structure, including a film one, as well as an outer surface that reflects heat.

A similar example is SuperFOIL SFUF insulation by the British company SuperFOIL. The British insulation material SuperFOIL SFUF was used in all three solutions as additional waterproofing and separating layer of the loadbearing concrete hollow core slab (Figure 30).

Figure 30. SuperFOIL SFUF insulation material (SuperFOIL)

This is necessary to protect the loadbearing concrete slab from moisture and transfer water from the upper layers of the roof. This unique material consists of 13 layers of reflective foil, thermofoam separation layers and topped with a polyethylene layer (Insulation Superstore). The thermal resistance of the SuperFOIL SFUF is 0.8 $m^2 \cdot K / W$ and the thickness is 6.0 mm. This material is a versatile and optimal alternative to the traditional insulation materials of the roof: water and vapour barrier protection, sound insulation and impact noise reduction up to about 22 decibels. (SuperFOIL.)

In addition to the properties described above, SuperFOIL SFUF is easy to install and does not require any special tools. The use of this material can replace several layers of traditional film, geotextile. It is rather difficult to damage it during construction or use, since the material is multi-layered.

5.2.2 Designed roof structures and their main features

As part of the study, the optimal structures were compiled for three systematized groups of inverted roof: the roof on supports (group 1), the roof without supports (group 2) and the rooftop parking (group 3).

In addition, as part of the study, it was necessary to select modern and versatile materials for the roof: both available for purchase in Finland and for export from other European countries and Russia.

In our cases, in thermal insulation layer (XPS) uses shiplap (as known as “overlapped”) joints of XPS-boards. Arrangement of thermal insulation materials in 2 layers, the seams between the slabs are spaced apart: the joints of the slabs of the first and second layers must not match. This will reduce the transfer of moisture and water from the upper layers of the roof.

For roof groups 1 and 2, the use of XPS-boards from Finnofoam company is provided (Finnfoam FL-400). This is because such XPS-boards are suitable for light, pedestrian (human) traffic. However, for the inverted rooftop parking (group 3) a more durable thermal insulation material is needed that can withstand high and ultra-high loads from the transport. In that case, URSA XPS PROF 500 N-V-L is more durable for the inverted roof structure. This thermal insulation material is frost-resistant and it can handle loads of up to 50 tons per m^2 (URSA Insulation). Due to this characteristic, it is indispensable in road construction and for rooftop parking.

In all three cases, it is envisaged to use a concrete hollow floor slab C25/30 with a thickness of 265 and 320 mm, depending on the roof’s group.

5.2.3 Thermal calculation and analysis

In the process of choosing the composition of the optimal roof structure and its materials, the most important thing was to ensure good thermal insulation and protection from moisture, condensation, which is important in the climatic conditions of Central Finland.

As part of the calculation of heating were necessary to calculate thermal transmittance ($W/m^2 \cdot K$) of the roof structure and the total thermal resistance ($m^2 \cdot K/W$). For this purpose, the thermal (heat) engineering calculation of the roof was carried out in accordance with SFS EN ISO 6946:2017 “Building components and building elements. Thermal resistance and thermal transmittance. Calculation methods”.

A simplified method was chosen for the thermal calculation. Central region of Finland was chosen as a conditional construction site. Direction of heat flow (D) is upwards.

In all three cases, the internal surface resistance is assumed to be 0.10 $m^2 \cdot K/W$, and the external surface resistance is assumed to be 0.04 $m^2 \cdot K/W$ (SFS EN ISO 6946:2017, Section 6.8).

The designed template in Microsoft Excel was used for thermal transmittance and total thermal resistance calculations in accordance with Finnish standard. The German online engineering tool — Ubakus online calculator — was used for detailed calculation of U-value, total thermal resistance, moisture proofing analyzation, humidity analyzation of the roof structures with graphs (Ubakus 2021). The calculation in this case does not include various correction factors for flat roofs.

In the calculation process in Excel, the values of thermal conductivity and thermal resistance from the technical documentation of building materials and from scientific research were used. The calculation in this case includes various correction factors in accordance with SFS EN ISO 6946:2017.

Group 1. Inverted flat roof on supports

The optimal roof structure developed for conditions of Central Finland (Figure 31).

The detailed calculation of U-value and total thermal resistance in accordance with SFS EN ISO 6946:2017 for the roof structure 1 are shown in Appendix 2. General results of Excel sheet are shown below.

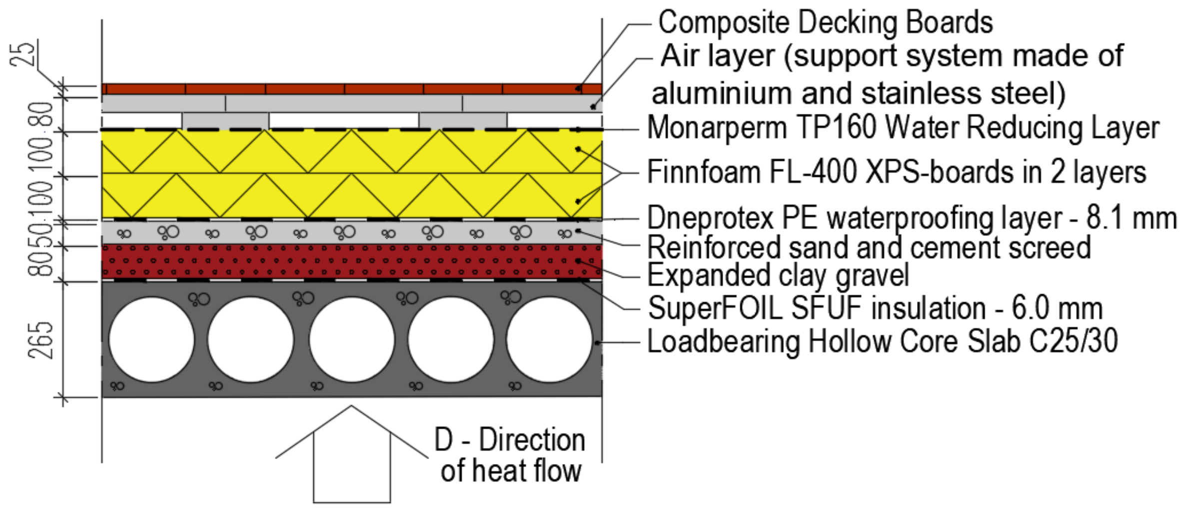

Figure 31. Optimal structure of inverted flat roof on supports

The total thickness of the roof ranges from 700.0 to 714.5 mm because the layers of waterproofing materials are compressed by the load of the upper layers.

The input data for the thermal calculation, modern and versatile building materials with thermal resistance of each layer are presented in Table 14.

№	Material	Thickness of material layer in the component *d*, m	Thermal conductivity *λ*, W/(m·K)	Thermal resistance *R*, (m^2·K)/W
1	External Surface	-	-	0,040
2	Composite Decking Boards	0,025	0,310	0,081
3	Air layer	0,08	-	0,160
4	Monarperm TP160 Water Reducing Layer	0,0004	0,079	0,005
5	Finnfoam FL-400 XPS-boards (in 2 layers)	0,2	0,037	5,405
6	Dneprotex PE waterproofing layer	0,0081	0,030	0,270
7	Reinforced sand and cement screed	0,05	1,200	0,042
8	Expanded clay gravel	0,08	0,160	0,500
9	SuperFOIL SFUF insulation	0,006	-	0,800
10	Loadbearing Hollow Core Slab C25/30	0,265	1,290	0,205
11	Internal Surface	-	-	0,100

Table 14. Thermal conductivity, thermal resistance values and thickness of material layer in roof's component (Group 1)

The total thermal resistance R_{tot} of the roof structure is 7.61 m^2·K/W.

Final thermal transmittance of the roof structure with the corrections is 0.16 W/m^2·K, which is acceptable for a flat roof.

The detailed calculation of U-value, total thermal resistance, moisture proofing analyzation, humidity analyzation of the roof structure 1 with graphs in Ubakus Calculator are shown in Appendix 3. General results are described below.

In the case of thermal calculation and analyzation in Ubakus, the total thermal resistance R_{tot} of the roof structure is 7.42 $m^2 \cdot K/W$.

Final thermal transmittance of the roof structure without the correction is 0.13 $W/m^2 \cdot K$, which is acceptable for a flat roof.

The temperature of the inside surface is 18.9 °C leading to a relative humidity on the surface of 54%. Mould formation is not expected under conditions of inside temperature 20°C and 50% Humidity; outside temperature -12.0°C and 80% Humidity.

This structure is free of condensate due moisture under the given climatic conditions.

Group 2. Inverted flat roof without supports

The optimal structure of roof without supports was developed (Figure 32). General results of Excel sheet are shown below.

The detailed calculation of U-value and total thermal resistance for the roof structure 2 are shown in Appendix 4.

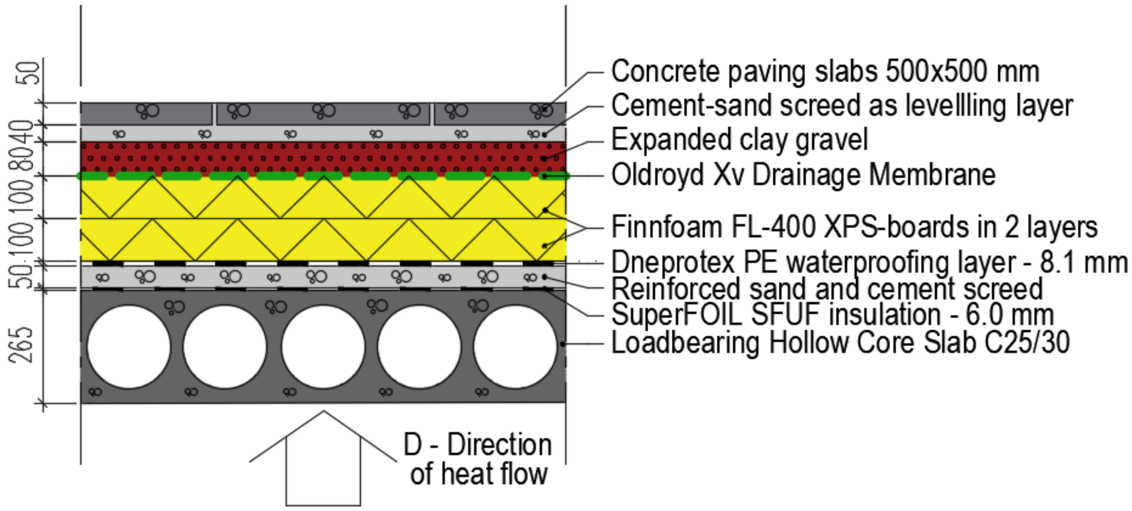

Figure 32. Optimal structure of inverted flat roof without supports

The total thickness of the roof ranges from 685.0 to 699.6 mm because the layers of waterproofing materials are compressed by the load of the upper layers. The input data for the thermal calculation, modern and versatile building materials with thermal resistance of each layer are presented in Table 15.

№	Material	Thickness of material layer in the component *d*, m	Thermal conductivity *λ*, W/(m·K)	Thermal resistance *R*, (m²·K)/W
1	External Surface	-	-	0,040
2	Concrete paving slabs	0,05	0,450	0,111
3	Cement-sand screed as levelling layer	0,04	1,200	0,033
4	Expanded clay gravel	0,08	0,160	0,500
5	Oldroyd XV Drainage Membrane	0,0005	0,021	0,024
6	Finnfoam FL-400 XPS-boards (in 2 layers)	0,2	0,037	5,405
7	Dneprotex PE waterproofing layer	0,0081	0,030	0,270
8	Reinforced sand and cement screed	0,05	1,200	0,042
9	SuperFOIL SFUF insulation	0,006	-	0,800
10	Loadbearing Hollow Core Slab C25/30	0,265	1,290	0,205
11	Internal Surface	-	-	0,100

Table 15. Thermal conductivity, thermal resistance values and thickness of material layer in roof's component (Group 2)

The total thermal resistance R_{tot} of the roof structure is 7.53 $m^2 \cdot K/W$.

Final thermal transmittance of the roof structure with the corrections is 0.16 $W/m^2 \cdot K$, which is acceptable for a flat roof.

The detailed calculation of U-value, total thermal resistance, moisture proofing analyzation, humidity analyzation of the roof structure 1 with graphs in Ubakus-Calculator are shown in Appendix 5. General results are described below.

In the case of thermal calculation and analyzation in Ubakus, the total thermal resistance R_{tot} of the roof structure is 7.53 $m^2 \cdot K/W$.

Final thermal transmittance of the roof structure without the correction is 0.13 $W/m^2 \cdot K$, which is acceptable for a flat roof.

The temperature of the inside surface is 19.0 °C leading to a relative humidity on the surface of 53%. Mould formation is not expected under conditions of inside temperature 20°C and 50% Humidity; outside temperature -12.0°C and 80% Humidity.

This structure is free of condensate due moisture under the given climate conditions.

Group 3. Inverted rooftop parking

The optimal structure of inverted rooftop parking (Figure 33). General results of Excel sheet are shown below.

The detailed calculation of U-value and total thermal resistance for the roof structure 2 are shown in Appendix 6.

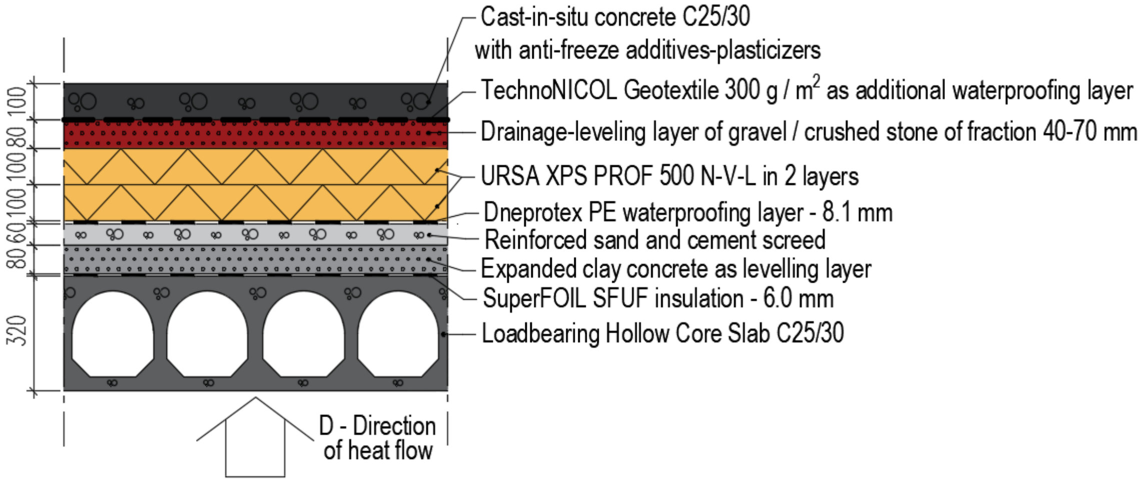

Figure 33. Optimal structure of inverted rooftop parking

The total thickness of the roof ranges from 840.0 to 856.1 mm because the layers of waterproofing materials are compressed by the load of the upper layers. The input data for the thermal calculation, modern and versatile building materials with thermal resistance of each layer are presented in Table 16.

№	Material	Thickness of material layer in the component *d,* m	Thermal conductivity *λ*, W/(m·K)	Thermal resistance *R*, (m²·K)/W
1	External Surface	-	-	0,040
2	Cast-in-situ concrete C25/30 with anti-freeze additives-plasticizers	0,1	1,300	0,077
3	TechnoNICOL Geotextile 300 g/m² as additional waterproofing layer	0,002	0,080	0,025
4	Drainage-levelling layer of gravel / crushed stone of fraction 40-70 mm	0,08	0,180	0,444
5	URSA XPS PROF 500 N-V-L (in 2 layers)	0,2	0,032	6,250
6	Dneprotex PE waterproofing layer	0,0081	0,030	0,270
7	Reinforced sand and cement screed	0,06	1,200	0,050
8	Expanded clay concrete as levelling layer	0,08	0,140	0,571
9	SuperFOIL SFUF insulation	0,006	-	0,800
10	Loadbearing Hollow Core Slab C25/30	0,32	1,310	0,244
11	Internal Surface	-	-	0,100

Table 16. Thermal conductivity, thermal resistance values and thickness of material layer in roof's component (Group 3)

The total thermal resistance R_{tot} of the roof structure is 8.87 m^2·K/W.

Final thermal transmittance of the roof structure with the corrections is 0.14 W/m^2·K, which is acceptable for a flat roof.

The detailed calculation of U-value, total thermal resistance, moisture proofing analyzation, humidity analyzation of the roof structure 1 with graphs in Ubakus Calculator are shown in Appendix 7. General results are described below.

In the case of thermal calculation and analyzation in Ubakus, the total thermal resistance R_{tot} of the roof structure is 8.87 m^2·K/W.

Final thermal transmittance of the roof structure without the correction is 0.11 W/m^2·K, which is acceptable for a flat roof.

The inner surface temperature is 19.1° C, which provides 53% relative humidity at the surface. Mould formation is not expected under conditions of an internal temperature of 20 °C and a humidity of 50%; outdoor temperature -12.0° C and humidity 80%.

This structure could has minimum condensate at the surface of geotextile (by TechnoNICOL) due moisture under the given climate conditions. However, as analyzation has shown that it is not dangerous for the structure because drainage-levelling gravel layer is placed under this geotextile. Furthermore, geotextile has enough properties to absorb actions of moisture and condensation.

Results for each structure of the group in Excel and in Ubakus Calculator are presented in Table 17.

№	**Group**	**Excel Sheet**		**Ubakus Calculator**	
		Final Thermal Transmittance of the roof structure with the correction, in W/m^2·K	**Total Thermal Resistance R_{tot}, in m^2·K/W**	**Final Thermal Transmittance of the roof structure, in W/m^2·K**	**Total Thermal Resistance R_{tot}, in m^2·K/W**
1	Inverted roof on supports	0.16	7.61	0.13	7.42
2	Inverted roof without supports	0.16	7.53	0.13	7.53
3	Inverted rooftop parking	0.14	8.87	0.11	8.87

Table 17. Results for each structure of the groups in Excel and in Ubakus Calculator

The difference between the calculated values obtained by calculations in Excel and in Ubakus Calculator does not differ much. Because correction factors are not taken into account in Ubakus Calculator, there is a difference in final thermal transmittances.

However, all final thermal transmittance and total thermal resistance values of the roof structures show that they are acceptable for a flat roof. It was achieved through the selection of optimal, modern and versatile roofing materials with enough thickness of layers. Calculation in Excel and calculation with analyzation in Ubakus Calculator have shown that the developed roof structures can be applied in the conditions of Central Finland.

6 Summary

Existing interesting use cases of inverted (turned) flat roof in were found in Norway, Sweden, Finland and Russia. Many use cases are with pavement slabs for walking space, green roofs. It can be concluded that inverted roofs are possible for construction and use in the harsh climatic conditions of the Northern countries. Existing use cases may motivate active using and construction of this roof.

Existing engineering solutions of the inverted flat roof were systematized according to a structural peculiarity into 3 main groups: roof on supports, roof without supports and rooftop parking. The developed system of evaluation criteria and expert analysis performed to help customers and designers to take into account the peculiarities of inverted roof in their projects. As a result of expert analysis, the developed main criterion of resource efficiency is the most important in the construction of the investigated roof.

The developed model of new roof supports made of aluminium and stainless steel can be useful in modern construction, especially in the construction of inverted roofs with composite decking boards. This development is able to improve the technology of inverted roof construction on supports, because it reduces the weight of structure, increases the speed of assembling of elements, and the connecting elements do not need any additional protection.

Thermal calculation and analysis showed that multifunctional insulation materials with unique composition such as Dneprotex PE and SuperFOIL SFUS could be used in the structure of the inverted roof. The use of such materials can replace several layers of traditional insulation. The use of these materials in the climatic conditions of Central Finland was proved. In the course of the work, there was an acquaintance with Finnish Standards. In addition, a simple tool for thermal calculation and analysis was found — Ubakus U-value Calculator.

All materials used in calculations and in roof structures are available in Europe, in Finland and in Russia. Some of them could be imported from Europe and UK, some of them are available in Finland. In the case of using Dneprotex PE — it could be exported from Russia. Instead of exporting, it is possible to develop an analogue, but with some changes.

It is also advisable to perform an economic calculation according to Russian pricing for improvements. Some improvements for inverted flat roof technology are needed for control of works on the construction site. Future researches should be focused on improving the roofing process at the construction site with the using of modern tools and IT.

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Appendices

Appendix 1. Calculation of general opinions for inverted roof groups

Input data:

$F_1(h_1)$	$F_1(h_2)$	$F_1(h_3)$	$F_1(h_4)$	$F_1(h_5)$	$F_1(h_6)$	$F_1(h_7)$
6,502	6,000	5,502	6,906	6,334	5,497	4,895

Table 1. Criteria of optimality for the inverted flat roof construction Group 1 (the roof on supports)

$F_2(h_1)$	$F_2(h_2)$	$F_2(h_3)$	$F_2(h_4)$	$F_2(h_5)$	$F_2(h_6)$	$F_2(h_7)$
7,806	6,723	6,765	6,914	5,840	6,066	6,371

Table 2. Criteria of optimality for the inverted flat roof construction Group 2 (the roof without supports)

$F_3(h_1)$	$F_3(h_2)$	$F_3(h_3)$	$F_3(h_4)$	$F_3(h_5)$	$F_3(h_6)$	$F_3(h_7)$
7,301	6,828	6,713	5,908	6,436	5,566	6,458

Table 3. Criteria of optimality for the inverted flat roof construction Group 3 (the rooftop parking)

Calculation:

The general opinion O_m of the expert group on the effectiveness of the grouped options of the flat roof construction can be found as the weighted average of its estimates:

$$O_m = \frac{\sum F_m(h_i)}{Ni}$$

where $F_m(h_i)$ – criteria of optimality from Tables 1-3;

N_i – amount of the experts (7).

For the inverted flat roof construction Group 1, the general opinion O_1 will be:

$$O_1 = \frac{6.502+6.000+5.502+6.906+6.334+5.497+4.895}{7} = 5.948$$

For the inverted flat roof construction Group 2, the general opinion will O_2 will be:

$$O_2 = \frac{7.806+6.723+6.765+6.914+5.840+6.066+6.371}{7} = 6.641$$

For the inverted flat roof construction Group 3, the general opinion O_3 will be:

$$O_3 = \frac{7.301+6.828+6.713+5.908+6.436+5.566+6.458}{7} = 6.458$$

.

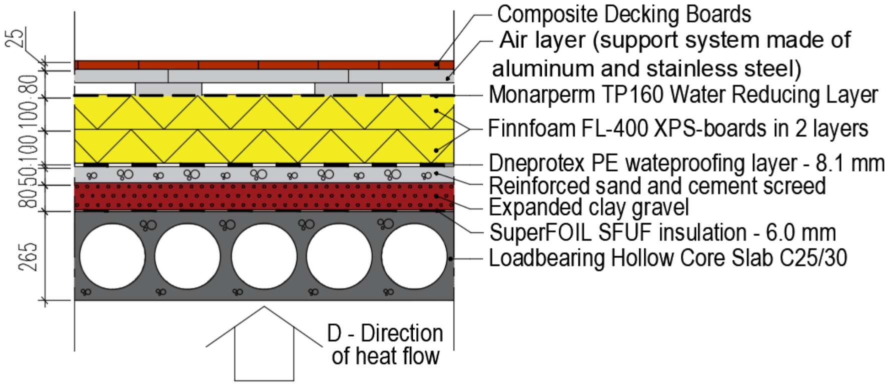
Results:

Groups	**General opinion O_n**
Group 1: roof on supports	5.948
Group 2: roof without supports	6.641
Group 3: rooftop parking	6.458

Appendix 2. Excel sheet of thermal calculation for inverted roof on supports

Input data		
Roof type:	Inverted Flat Roof on Supports	
Simplified calculation method;	**Maximum error for simplified method:** No	
Surface resistances for specific boundary conditions (Annex C of *SFS EN ISO 6946:2017*): No		
Conditional place of	Central Finland	
Conventional surface resistances (Table 7 of *SFS EN ISO 6946:2017)*		

Surface resistance m2·K/W	Direction of heat flow Upwards	
Rsi	0,10	internal surface resistance
Rse	0,04	external surface resistance



Calculation

1. **Thermal Resistance and U-Value without corrections Calculation**

Thermal conductivity, thermal resistance values and thickness of material layer in roof's component

№ position	Material	Thickness of material layer in the component *d*, m	Thermal conductivity *λ*, W/(m·K)	Thermal resistance *R*, m2·K/W
1	External Surface	-	-	0,040
2	Composite Decking Boards	0,025	0,310	0,081
3	Air layer *	0,08	-	0,160
4	Monarperm TP160 Water Reducing Layer	0,0004	0,079	0,005
5	Finnfoam FL-400 XPS-boards (in 2 layers)	0,2	0,037	5,405
6	Dneprotex PE waterproofing layer	0,0081	0,030	0,270
7	Reinforced sand and cement screed	0,05	1,200	0,042
8	Expanded clay gravel	0,08	0,160	0,500
9	SuperFOIL SFUF insulation	0,006	-	0,800
10	Loadbearing Hollow Core Slab C25/30	0,265	1,290	0,205
11	Internal Surface	-	-	0,100
			Total Thermal Resistance *Rtot*, m2·K/W	**7,61**

* According to 6.9.1 and 6.9.2, there is air layer which is bounded by two faces that are effectively parallel and perpendicular to the direction of heat flow and
that have emissivities not less than 0,8
— has a thickness (in the direction of heat flow) of less than 0,1 times each one of the other two dimensions, and not greater than 0,3 m, and
— has no air interchange with the internal environment. there is an unventilated air layer where the support system of the compsite decking boards are placed. This air layer is one in which there is no express provision for air flow through it.

Appendix 2. Excel sheet of thermal calculation for inverted roof on supports

This layer of air is not completely ventilated, as it is closed by parapets on all 4 sides. But this layer all the same perceives the action of air air, albeit partially.

In order **to simplify** the calculation, the following values are accepted here below. According to the *Table 8* of *SFS EN ISO 6946:2017,* the Thermal Resistance of the unventilated **air layer (80 mm)** in *m2·K/W* was assumed:

Table 7 of SFS EN ISO 6946:2017

Thickness of air layer	**Thermal resistance m2·K/W**
	Direction of heat flow
mm	**Upwards**
50	0,16
100	0,16

Thus, Thermal resistance of the air layer is **0.16 m2·K/W**

NOTE: This air *and partially ventilated* ***layer is taken into account in the calculation of the Ubuakus Calculator without this simplification.***

***U*-Value without corrections:**	***U* = 1 / *Rtot* =**	**0,13**	**W/m2·K**

2.	**Correction due to water flowing between the insulation and the waterproofing membrane**			
	ΔUr = p · f · x · ***((R1/Rtot) ^2)***	0,030	W/m2·K	
	where			
	p	is the average rate of precipitation during the heating season, based on data relevant for the location (e.g. weather station) or given through local, regional or national regulations, or other national documents, in mm/day		
	Average precipitation			
	Item	**Choices**		
	Average rate of precipitation during heating season	3 mm/day	Table B.7 of *SFS EN ISO 6946:2017*	
	p =	3	mm/day	
	f	is the drainage factor giving the fraction of p reaching the waterproofing membrane		
	x	is the factor for increased heat loss caused by rainwater flowing on the membrane, in (W·day)/(m2·K·mm)		
	R1	is the thermal resistance of the layer of XPS-insulation above the waterproofing membrane, in m2·K/W		
	and *R1 =*	5,405	m2·K/W	
	Rtot =	7,61	m2·K/W	*Rtot* - is the total thermal resistance of the construction before application of the correction.
	In our case, the different jointing arrangements of thermal insulation layer (XPS) is used (such as shiplap or tongue-and-groove joints). In our case, value **0.02** for *f·x* may be used:			
	f · x =	0,02		

Appendix 2. Excel sheet of thermal calculation for inverted roof on supports

3.	**<u>Corrected Thermal Transmittance</u>**			
	Uc = U + ΔU =	**0,16**	**W/m2·K**	
	where			
	ΔU = ΔUg + ΔUf + ΔUr =	0,03	W/m2·K	
	ΔUg is the correction for air voids in accordance with F.2 *(SFS EN ISO 6946:2017)*			
	In our case, there are no air voids within the insulation, or there are only minor air voids are present that have no significant effect on the thermal transmittance.			
	Thus, *ΔUg =*	0,00	W/m2·K	
	ΔUf is the correction for mechanical fasteners in accordance with F.3			
	In our case, no correction shall be applied because there are wall ties across an empty cavity. In addition, with mechanical fastening of insulation, it is possible to use fasteners (e.g. 2 fasteners per 1 m2) from *Paroc, TechnoNIKOL Company* with the thermal conductivity of the fastener less than 1 W/(m·K).			
	Thus, *ΔUf =*	0,00	W/m2·K	
	ΔUr is the correction for inverted roofs in accordance with F.4.			
	ΔUr =	0,03	W/m2·K	
	Final Thermal Transmittance of the roof structure with the correction:		**0,16**	**W/m2·K**
	Total Thermal Resistance *Rtot:*		**7,61**	**m2·K/W**

Appendix 3. Ubakus-calculation for inverted roof on supports

ubakus

All statements without guarantee

1-Group 1: supports N

Flat roof
created on 18.2.2021

Thermal protection

U = 0,13 W/(m²K)

EnEV Bestand*: U<0,2 W/(m²K)

excellent insufficient

Moisture proofing

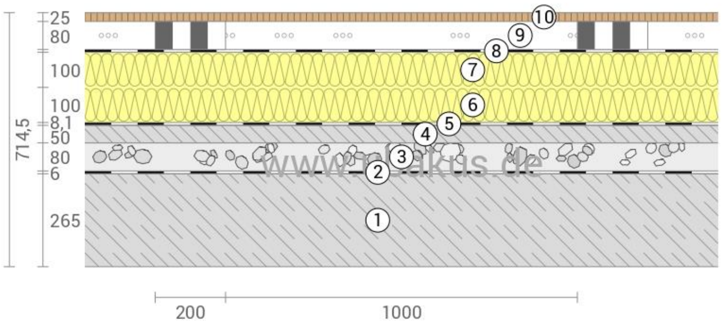
No condensate

excellent insufficient

Heat protection

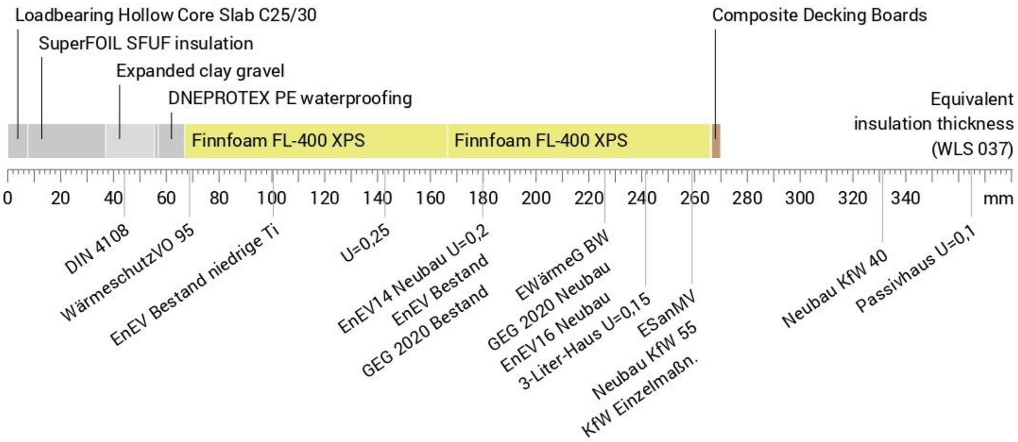
Temperature amplitude damping: >100
phase shift: non relevant
Thermal capacity inside: 758 kJ/m²K

excellent insufficient



1. Loadbearing Hollow Core Slab C25/30 (265 mm)
2. SuperFOIL SFUF insulation
3. Expanded clay gravel (80 mm)
4. Reinforced sand and cement screed (50 mm)
5. DNEPROTEX PE waterproofing
6. Finnfoam FL-400 XPS (100 mm)
7. Finnfoam FL-400 XPS (100 mm)
8. Monarperm TP160 WFRL
9. Outside air (80 mm)
10. Composite Decking Boards (25 mm)

Impact of each layer and comparison to reference values



Inside air :	20,0°C / 50%		Thickness:	71,5 cm
Outside air:	-12,0°C / 80%	sd-value: 286,2 m	Weight:	1046 kg/m²
Surface temperature.:	18,9°C / -12,0°C		Heat capacity:	934 kJ/m²K

*Comparison to the maximum U-value according to the german EnEV 2014/2016 for first-time installation or renewal of Dachflächen mit Abdichtung (Anlage 3, Tabelle 1, Zeile 4b).

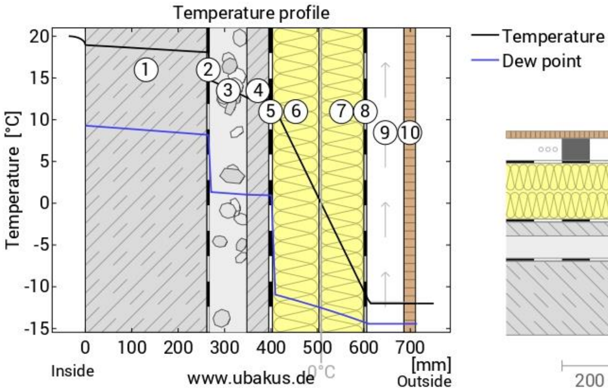
Appendix 3. Ubakus-calculation for inverted roof on supports

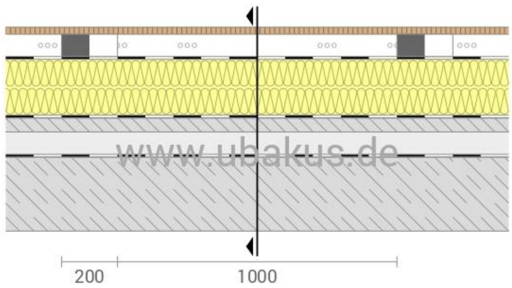
ubakus

All statements without guarantee

1-Group 1: supports N, U=0,13 W/(m²K)

Temperature profile





① Loadbearing Hollow Core Slab C25...
② SuperFOIL SFUF insulation
③ Expanded clay gravel (80 mm)
④ Reinforced sand and cement scree...
⑤ DNEPROTEX PE waterproofing
⑥ Finnfoam FL-400 XPS (100 mm)
⑦ Finnfoam FL-400 XPS (100 mm)
⑧ Monarperm TP160 WFRL
⑨ Outside air (80 mm)
⑩ Composite Decking Boards (25 mm)

Left: Temperature and dew-point temperature at the place marked in the right figure. The dew-point indicates the temperature, at which water vapour condensates. As long as the temperature of the component is everywhere above the dew point, no condensation occurs. If the curves have contact, condensation occurs at the corresponding position.
Right: The component, drawn to scale.

Layers (from inside to outside)

#		Material	λ [W/mK]	R [m²K/W]	Temperatur [°C] min	max	Weight [kg/m²]
		Thermal contact resistance*		0,100	18,9	20,0	
1	26,5 cm	Loadbearing Hollow Core Slab C25/30	1,290	0,205	18,1	18,9	609,5
2	0,6 cm	SuperFOIL SFUF insulation	0,008	0,800	14,7	18,1	6,6
3	8 cm	Expanded clay gravel	0,160	0,500	12,6	14,7	176,0
4	5 cm	Reinforced sand and cement screed	1,200	0,042	12,4	12,6	100,0
5	0,81 cm	DNEPROTEX PE waterproofing	0,030	0,270	11,3	12,4	8,9
6	10 cm	Finnfoam FL-400 XPS	0,037	2,703	-0,2	11,3	3,0
7	10 cm	Finnfoam FL-400 XPS	0,037	2,703	-11,7	-0,1	3,0
8	0,04 cm	Monarperm TP160 WFRL	0,079	0,005	-11,7	-11,6	0,3
9	8 cm	Outside air			-12,0	-11,6	
	8 cm	Stainless Steel (austenitic) (17%)	17,000	0,005	-11,8	-11,7	105,3
10	2,5 cm	Composite Decking Boards	0,310	0,081	-12,0	-11,8	33,8
		Thermal contact resistance*		0,040	-12,0	-11,9	
	71,45 cm	Whole component		7,420			1.046,4

*Thermal contact resistances according to DIN 6946 for the U-value calculation. Rsi=0,25 and Rse=0,04 according to DIN 4108-3 were used for moisture proofing and temperature profile.

Surface temperature inside (min / average / max):	18,9°C	18,9°C	18,9°C
Surface temperature outside (min / average / max):	-12,0°C	-12,0°C	-11,9°C

Appendix 3. Ubakus-calculation for inverted roof on supports

ubakus

All statements without guarantee

1-Group 1: supports N, U=0,13 W/(m²K)

Moisture proofing

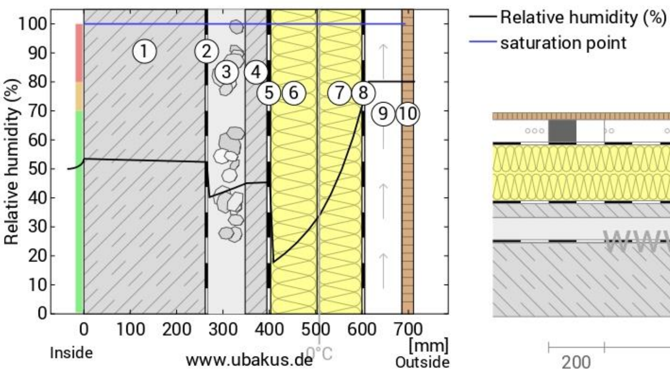
For the calculation of the amount of condensation water, the component was exposed to the following constant climate for 90 days: inside: 20°C und 50% Humidity; outside: -12°C und 80% Humidity (Climate according to user input).

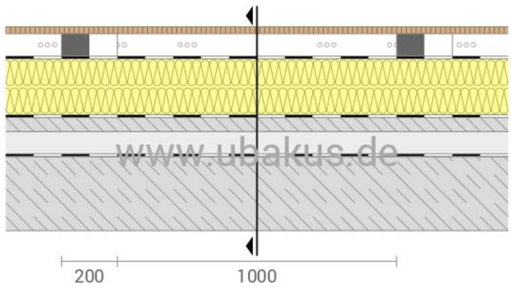
This component is free of condensate under the given climate conditions.

#		Material	sd-value [m]	Condensate [kg/m²]	[Gew.-%]	Weight [kg/m²]
1	26,5 cm	Loadbearing Hollow Core Slab C25/30	21,20	-		609,5
2	0,6 cm	SuperFOIL SFUF insulation	104,00	-		6,6
3	8 cm	Expanded clay gravel	4,00	-		176,0
4	5 cm	Reinforced sand and cement screed	0,75	-		100,0
5	0,81 cm	DNEPROTEX PE waterproofing	104,00	-		8,9
6	10 cm	Finnfoam FL-400 XPS	8,00	-		3,0
7	10 cm	Finnfoam FL-400 XPS	8,00	-		3,0
8	0,04 cm	Monarperm TP160 WFRL	0,10	-		0,3
9	8 cm	Outside air		-		
	8 cm	Stainless Steel (austenitic) (17%)	1500	-		105,3
10	2,5 cm	Composite Decking Boards	430,00	-	-	33,8
	71,45 cm	Whole component	286,21			1.046,4

Humidity

The temperature of the inside surface is 18,9 °C leading to a relative humidity on the surface of 54%.Mould formation is not expected under these conditions.
The following figure shows the relative humidity inside the component.





① Loadbearing Hollow Core Slab C25...
② SuperFOIL SFUF insulation
③ Expanded clay gravel (80 mm)
④ Reinforced sand and cement scree...
⑤ DNEPROTEX PE waterproofing
⑥ Finnfoam FL-400 XPS (100 mm)
⑦ Finnfoam FL-400 XPS (100 mm)
⑧ Monarperm TP160 WFRL
⑨ Outside air (80 mm)
⑩ Composite Decking Boards (25 mm)

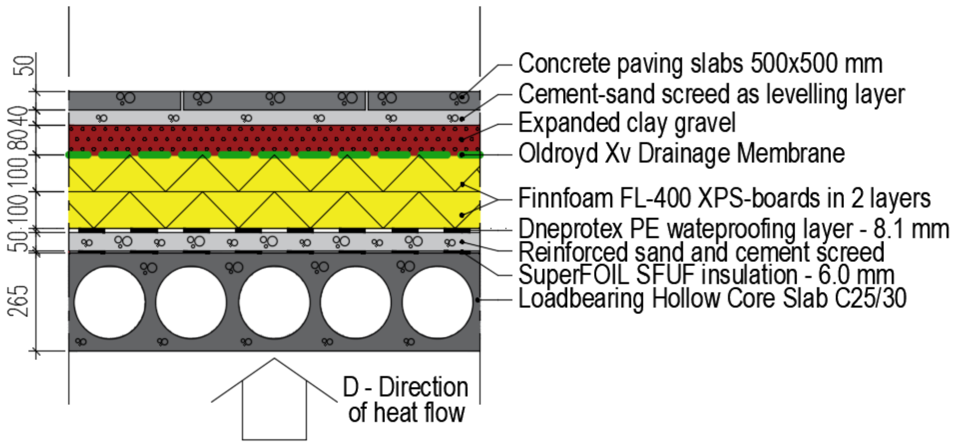
Notes: Calculation using the Ubakus 2D-FE method. Convection and the capillarity of the building materials were not considered. The drying time may take longer under unfavorable conditions (shading, damp / cool summers) than calculated here.

Appendix 4. Excel sheet of thermal calculation for inverted roof without supports

Input data		
Roof type:	Inverted Flat Roof without Supports	
Simplified calculation method;	**Maximum error for simplified method:** No	
Surface resistances for specific boundary conditions (Annex C of *SFS EN ISO 6946:2017*): No		
Conditional place of	Central Finland	

Conventional surface resistances (Table 7 of *SFS EN ISO 6946:2017)*

Surface resistance m2·K/W	**Direction of heat flow Upwards**	
Rsi	0,10	internal surface resistance
Rse	0,04	external surface resistance



Calculation

1. **Thermal Resistance and U-Value without corrections Calculation**

Thermal conductivity, thermal resistance values and thickness of material layer in roof's component

№ position	**Material**	**Thickness of material layer in the component *d*, m**	**Thermal conductivity *λ*, W/(m·K)**	**Thermal resistance *R*, m2·K/W**
1	External Surface	-	-	0,040
2	Concrete paving slabs	0,05	0,450	0,111
3	Cement-sand screed as levelling layer	0,04	1,200	0,033
4	Expanded clay gravel	0,08	0,160	0,500
5	Oldroyd XV Drainage Membrane	0,0005	0,021	0,024
6	Finnfoam FL-400 XPS-boards (in 2 layers)	0,2	0,037	5,405
7	Dneprotex PE wateproofing layer	0,0081	0,030	0,270
8	Reinforced sand and cement screed	0,05	1,200	0,042
9	SuperFOIL SFUF insulation	0,006	-	0,800
10	Loadbearing Hollow Core Slab C25/30	0,265	1,290	0,205
11	Internal Surface	-	-	0,100
	Total Thermal Resistance *Rtot*, m2·K/W			**7,53**
	***U*-Value without corrections:**	***U* = 1 / *Rtot* =**	**0,13**	**W/m2·K**

Appendix 4. Excel sheet of thermal calculation for inverted roof without supports

2.	**Correction due to water flowing between the insulation and the waterproofing membrane**			
	ΔUr = p · f · x · ***((R1/Rtot) ^2)***	0,031	W/m2·K	
	where			
	p	is the average rate of precipitation during the heating season, based on data relevant for the location (e.g. weather station) or given through local, regional or national regulations, or other national documents, in mm/day		
	Average precipitation			
	Item	**Choices**		
	Average rate of precipitation during heating season	3 mm/day	Table B.7 of *SFS EN ISO 6946:2017*	
	p =	3	mm/day	
	f	is the drainage factor giving the fraction of p reaching the waterproofing membrane		
	x	is the factor for increased heat loss caused by rainwater flowing on the membrane, in (W·day)/(m2·K·mm)		
	R1	is the thermal resistance of the layer of XPS-insulation above the waterproofing membrane, in m2·K/W		
	and *R1* =	5,405	m2·K/W	
	Rtot =	7,53	m2·K/W	*Rtot* - is the total thermal resistance of the construction before application of the correction.
	In our case, the different jointing arrangements of thermal insulation layer (XPS) is used (such as shiplap or tongue-and-groove joints). In our case, value **0.02** for *f·x* may be used:			
	f · x =	0,02		

Appendix 4. Excel sheet of thermal calculation for inverted roof without supports

3.	**Corrected Thermal Transmittance**			
	Uc = U + ΔU =	**0,16**	**W/m2·K**	
	where			
	ΔU = ΔUg + ΔUf + ΔUr =	0,03	W/m2·K	
	ΔUg is the correction for air voids in accordance with F.2 *(SFS EN ISO 6946:2017)*			
	In our case, there are no air voids within the insulation, or there are only minor air voids are present that have no significant effect on the thermal transmittance.			
	Thus, *ΔUg =*	0,00	W/m2·K	
	ΔUf is the correction for mechanical fasteners in accordance with F.3			
	In our case, no correction shall be applied because there are wall ties across an empty cavity. In addition, with mechanical fastening of insulation, it is possible to use fasteners (e.g. 2 fasteners per 1 m2) from *Paroc, TechnoNIKOL Company* with the thermal conductivity of the fastener less than 1 W/(m·K).			
	Thus, *ΔUf =*	0,00	W/m2·K	
	ΔUr is the correction for inverted roofs in accordance with F.4.			
	ΔUr =	0,03	W/m2·K	
	Final Thermal Transmittance of the roof structure with the correction:		**0,16**	**W/m2·K**
	Total Thermal Resistance *Rtot:*		**7,53**	**m2·K/W**

Appendix 5. Ubakus-calculation for inverted roof without supports

ubakus

2-Group 2 without supports

Flat roof
created on 18.2.2021

Thermal protection

U = 0,13 W/(m²K)

EnEV Bestand*: U<0,2 W/(m²K)

excellent insufficient

Moisture proofing

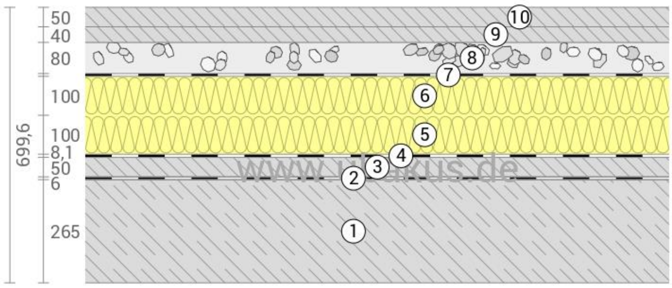
No condensate

excellent insufficient

Heat protection

Temperature amplitude damping: >100
phase shift: non relevant
Thermal capacity inside: 639 kJ/m²K

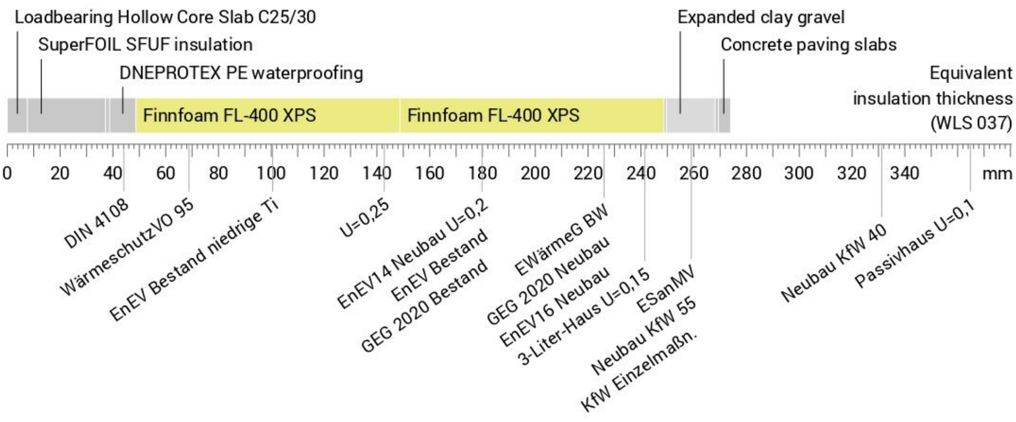
excellent insufficient



1. Loadbearing Hollow Core Slab C25/30 (265 mm)
2. SuperFOIL SFUF insulation
3. Reinforced sand and cement screed (50 mm)
4. DNEPROTEX PE waterproofing
5. Finnfoam FL-400 XPS (100 mm)
6. Finnfoam FL-400 XPS (100 mm)
7. Oldroyd XV Frainage membrane
8. Expanded clay gravel (80 mm)
9. Cement-sand screed (40 mm)
10. Concrete paving slabs (50 mm)

Impact of each layer and comparison to reference values

For the following figure, the thermal resistances of the individual layers were converted in millimeters insulation. The scale refers to an insulation of thermal conductivity 0,037 W/mK.



Inside air :	20,0°C / 50%		Thickness:	70,0 cm
Outside air:	-12,0°C / 80%	sd-value: 257,9 m	Weight:	1107 kg/m²
Surface temperature.:	19,0°C / -11,8°C		Heat capacity:	1041 kJ/m²K

*Comparison to the maximum U-value according to the german EnEV 2014/2016 for first-time installation or renewal of Dachflächen mit Abdichtung (Anlage 3, Tabelle 1, Zeile 4b).

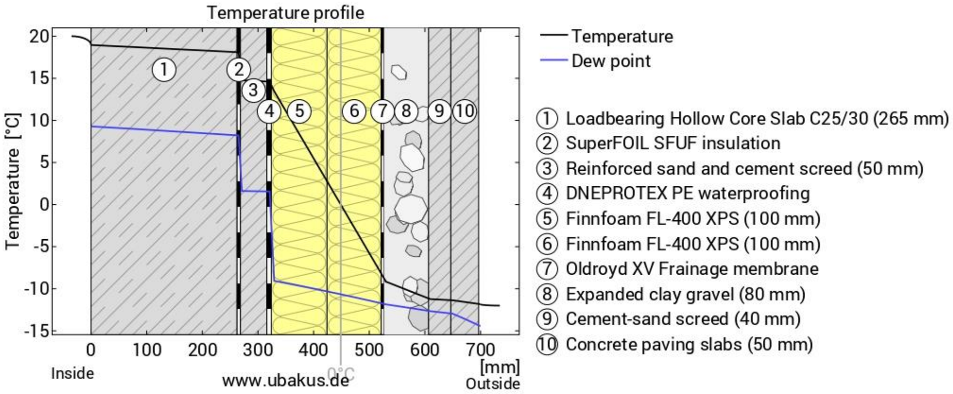
Appendix 5. Ubakus-calculation for inverted roof without supports

ubakus

All statements without guarantee

2-Group 2 without supports, U=0,13 W/(m²K)

Temperature profile



Temperature and dew-point temperature in the component. The dew-point indicates the temperature, at which water vapour condensates. As long as the temperature of the component is everywhere above the dew-point temperature, no condensation occurs. If the curves have contact, condensation occurs at the corresponding position.

Layers (from inside to outside)

#		Material	λ [W/mK]	R [m²K/W]	Temperatur [°C] min	max	Weight [kg/m²]
		Thermal contact resistance*		0,100	19,0	20,0	
1	26,5 cm	Loadbearing Hollow Core Slab C25/30	1,290	0,205	18,1	19,0	609,5
2	0,6 cm	SuperFOIL SFUF insulation	0,008	0,800	14,8	18,1	6,6
3	5 cm	Reinforced sand and cement screed	1,200	0,042	14,6	14,8	100,0
4	0,81 cm	DNEPROTEX PE waterproofing	0,030	0,270	13,5	14,6	8,9
5	10 cm	Finnfoam FL-400 XPS	0,037	2,703	2,2	13,5	3,0
6	10 cm	Finnfoam FL-400 XPS	0,037	2,703	-9,0	2,2	3,0
7	0,05 cm	Oldroyd XV Frainage membrane	0,021	0,024	-9,1	-9,0	0,0
8	8 cm	Expanded clay gravel	0,160	0,500	-11,2	-9,1	176,0
9	4 cm	Cement-sand screed	1,200	0,033	-11,4	-11,2	80,0
10	5 cm	Concrete paving slabs	0,450	0,111	-11,8	-11,4	120,0
		Thermal contact resistance*		0,040	-12,0	-11,8	
	69,96 cm	Whole component		7,531			1.107,0

*Thermal contact resistances according to DIN 6946 for the U-value calculation. Rsi=0,25 and Rse=0,04 according to DIN 4108-3 were used for moisture proofing and temperature profile.

Surface temperature inside (min / average / max): 19,0°C 19,0°C 19,0°C
Surface temperature outside (min / average / max): -11,8°C -11,8°C -11,8°C

Appendix 5. Ubakus-calculation for inverted roof without supports

ubakus

All statements without guarantee

2-Group 2 without supports, U=0,13 W/(m²K)

Moisture proofing

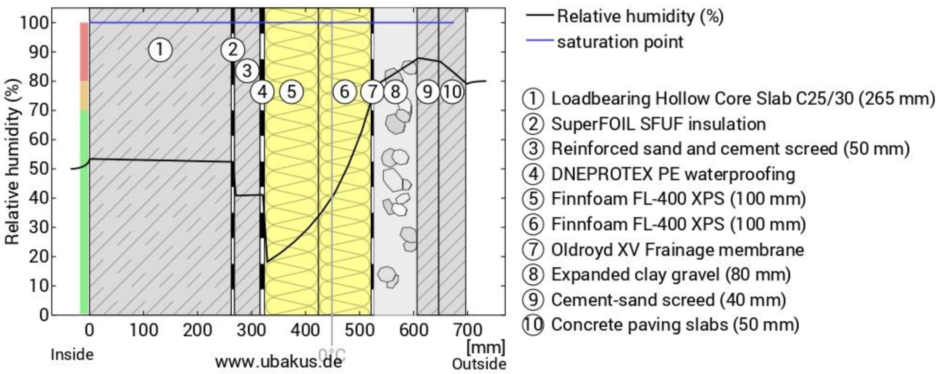
For the calculation of the amount of condensation water, the component was exposed to the following constant climate for 90 days: inside: 20°C und 50% Humidity; outside: -12°C und 80% Humidity (Climate according to user input).

This component is free of condensate under the given climate conditions.

#		Material	sd-value [m]	Condensate [kg/m²]	Condensate [Gew.-%]	Weight [kg/m²]
1	26,5 cm	Loadbearing Hollow Core Slab C25/30	21,20	-		609,5
2	0,6 cm	SuperFOIL SFUF insulation	104,00	-		6,6
3	5 cm	Reinforced sand and cement screed	0,75	-		100,0
4	0,81 cm	DNEPROTEX PE waterproofing	104,00	-		8,9
5	10 cm	Finnfoam FL-400 XPS	8,00	-		3,0
6	10 cm	Finnfoam FL-400 XPS	8,00	-		3,0
7	0,05 cm	Oldroyd XV Frainage membrane	0,00	-		0,0
8	8 cm	Expanded clay gravel	4,00	-		176,0
9	4 cm	Cement-sand screed	1,40	-		80,0
10	5 cm	Concrete paving slabs	6,50	-		120,0
	69,96 cm	Whole component	257,85			1.107,0

Humidity

The temperature of the inside surface is 19,0 °C leading to a relative humidity on the surface of 53%.Mould formation is not expected under these conditions.
The following figure shows the relative humidity inside the component.



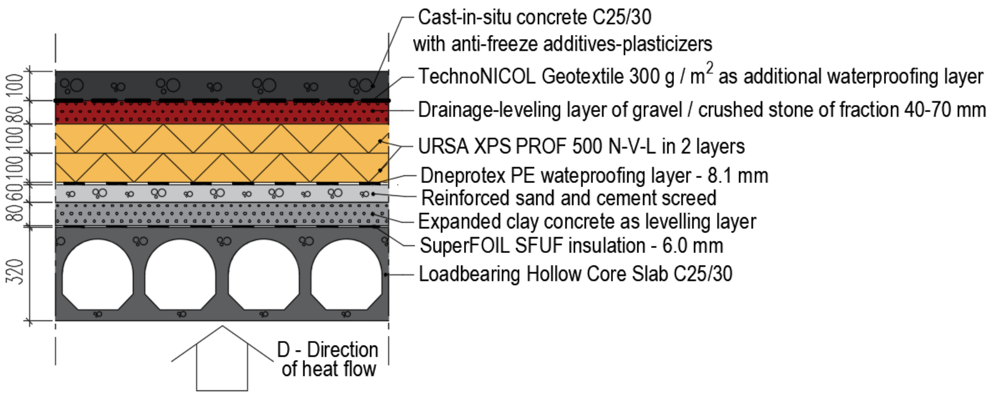
Notes: Calculation using the Ubakus 2D-FE method. Convection and the capillarity of the building materials were not considered. The drying time may take longer under unfavorable conditions (shading, damp / cool summers) than calculated here.

Appendix 6. Excel sheet of thermal calculation for inverted rooftop parking

Input data		
Roof type:	Inverted Rooftop Parking	
Simplified calculation method;	**Maximum error for simplified method:** No	
Surface resistances for specific boundary conditions (Annex C of *SFS EN ISO 6946:2017*): No		
Conditional place of construction:	Central Finland	

Conventional surface resistances (Table 7 of *SFS EN ISO 6946:2017)*

Surface resistance	Direction of heat flow	
m2·K/W	**Upwards**	
Rsi	0,10	internal surface resistance
Rse	0,04	external surface resistance



Calculation

1. **Thermal Resistance and U-Value without corrections Calculation**

Thermal conductivity, thermal resistance values and thickness of material layer in roof's component

№ position	Material	Thickness of material layer in the component *d*, m	Thermal conductivity *λ*, W/(m·K)	Thermal resistance *R*, m2·K/W
1	External Surface	-	-	0,040
2	Cast-in-situ concrete C25/30 with anti-freeze additives-plasticizers	0,1	1,300	0,077
3	TechnoNICOL Geotextile 300 g/m2 as additional waterproofing layer	0,002	0,080	0,025
4	Drainage-leveling layer of gravel / crushed stone of fraction 40-70 mm	0,08	0,180	0,444
5	URSA XPS PROF 500 N-V-L (in 2 layers)	0,2	0,032	6,250
6	Dneprotex PE wateproofing layer	0,0081	0,030	0,270
7	Reinforced sand and cement screed	0,06	1,200	0,050
8	Expanded clay concrete as levelling layer	0,08	0,140	0,571
9	SuperFOIL SFUF insulation	0,006	-	0,800
10	Loadbearing Hollow Core Slab C25/30	0,32	1,310	0,244
11	Internal Surface	-	-	0,100
	Total Thermal Resistance *Rtot*, m2·K/W			**8,87**

***U*-Value without corrections:** ***U* = 1 / *Rtot* =** **0,11** **W/m2·K**

Appendix 6. Excel sheet of thermal calculation for inverted rooftop parking

2.	**Correction due to water flowing between the insulation and the waterproofing membrane**			
	ΔUr = p · f · x · ***((R1/Rtot) ^2)***	0,030	W/m2·K	
	where			
	p	is the average rate of precipitation during the heating season, based on data relevant for the location (e.g. weather station) or given through local, regional or national regulations, or other national documents, in mm/day		
	Average precipitation			
	Item	**Choices**		
	Average rate of precipitation during heating season	3 mm/day	Table B.7 of *SFS EN ISO 6946:2017*	
	p =	3	mm/day	
	f	is the drainage factor giving the fraction of p reaching the waterproofing membrane		
	x	is the factor for increased heat loss caused by rainwater flowing on the membrane, in (W·day)/(m2·K·mm)		
	R1	is the thermal resistance of the layer of XPS-insulation above the waterproofing membrane, in m2·K/W		
	and *R1 =*	6,250	m2·K/W	
	Rtot =	8,87	m2·K/W	*Rtot* - is the total thermal resistance of the construction before application of the correction.
	In our case, the different jointing arrangements of thermal insulation layer (XPS) is used (such as shiplap or tongue-and-groove joints). In our case, value **0.02** for *f·x* may be used:			
	f · x =	0,02		

Appendix 6. Excel sheet of thermal calculation for inverted rooftop parking

3.	**Corrected Thermal Transmittance**			
	Uc = U + ΔU =	**0,14**	**W/m2·K**	
	where			
	ΔU = ΔUg + ΔUf + ΔUr =	0,03	W/m2·K	
	ΔUg is the correction for air voids in accordance with F.2 *(SFS EN ISO 6946:2017)*			
	In our case, there are no air voids within the insulation, or there are only minor air voids are present that have no significant effect on the thermal transmittance.			
	Thus, *ΔUg =*	0,00	W/m2·K	
	ΔUf is the correction for mechanical fasteners in accordance with F.3			
	In our case, no correction shall be applied because there are wall ties across an empty cavity. In addition, with mechanical fastening of insulation, it is possible to use fasteners (e.g. 2 fasteners per 1 m2) from *Paroc, TechnoNIKOL Company* with the thermal conductivity of the fastener less than 1 W/(m·K).			
	Thus, *ΔUf =*	0,00	W/m2·K	
	ΔUr is the correction for inverted roofs in accordance with F.4.			
	ΔUr =	0,03	W/m2·K	
	Final Thermal Transmittance of the roof structure with the correction:		**0,14**	**W/m2·K**
	Total Thermal Resistance *Rtot:*		**8,87**	**m2·K/W**

Appendix 7. Ubakus-calculation for inverted rooftop parking

ubakus

All statements without guarantee

3-Group 3: rooftop parking N

Flat roof
created on 18.2.2021

Thermal protection

U = 0,11 W/(m²K)

EnEV Bestand*: U<0,2 W/(m²K)

excellent insufficient

Moisture proofing

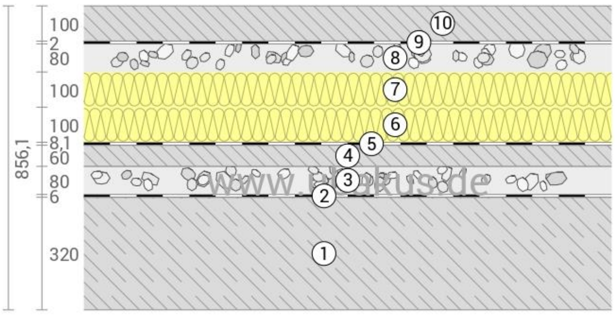
No condensate

excellent insufficient

Heat protection

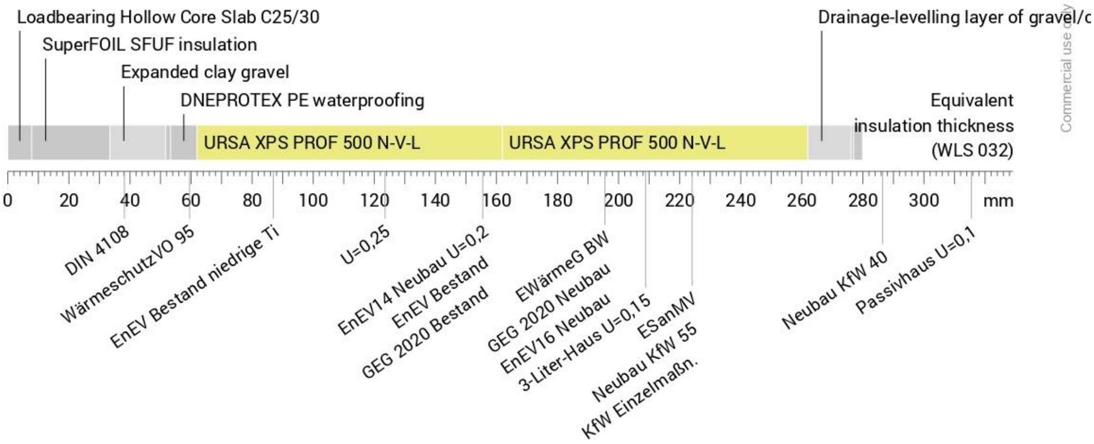
Temperature amplitude damping: >100
phase shift: non relevant
Thermal capacity inside: 901 kJ/m²K

excellent insufficient



1. Loadbearing Hollow Core Slab C25/30 (320 mm)
2. SuperFOIL SFUF insulation
3. Expanded clay gravel (80 mm)
4. Reinforced sand and cement screed (60 mm)
5. DNEPROTEX PE waterproofing
6. URSA XPS PROF 500 N-V-L (100 mm)
7. URSA XPS PROF 500 N-V-L (100 mm)
8. Drainage-levelling layer of gravel/crushed stone o (80 mm)
9. TechnoNICOL Geotextile 300 g
10. Cast-in-situ concrete slab C25/30 with anti-freeze (100 mm)

Impact of each layer and comparison to reference values



Inside air :	20,0°C / 50%		Thickness:	85,6 cm
Outside air:	-12,0°C / 80%	sd-value: 273,3 m	Weight:	1470 kg/m²
Surface temperature.:	19,1°C / -11,9°C		Heat capacity:	1383 kJ/m²K

*Comparison to the maximum U-value according to the german EnEV 2014/2016 for first-time installation or renewal of Dachflächen mit Abdichtung (Anlage 3, Tabelle 1, Zeile 4b).

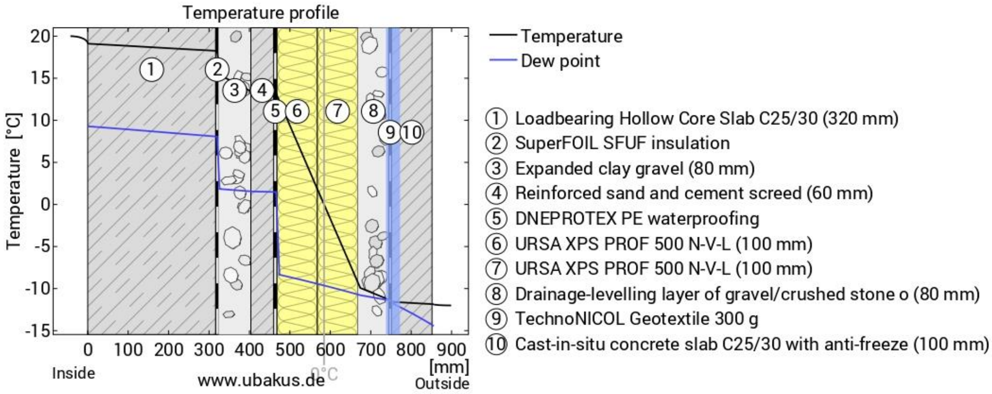
Appendix 7. Ubakus-calculation for inverted rooftop parking

ubakus

All statements without guarantee

3-Group 3: rooftop parking N, U=0,11 W/(m²K)

Temperature profile



Temperature and dew-point temperature in the component. The dew-point indicates the temperature, at which water vapour condensates. As long as the temperature of the component is everywhere above the dew-point temperature, no condensation occurs. If the curves have contact, condensation occurs at the corresponding position.

Layers (from inside to outside)

#		Material	λ [W/mK]	R [m²K/W]	Temperatur [°C] min	max	Weight [kg/m²]
		Thermal contact resistance*		0,100	19,1	20,0	
1	32 cm	Loadbearing Hollow Core Slab C25/30	1,310	0,244	18,2	19,1	736,0
2	0,6 cm	SuperFOIL SFUF insulation	0,008	0,800	15,4	18,2	6,6
3	8 cm	Expanded clay gravel	0,140	0,571	13,4	15,4	176,0
4	6 cm	Reinforced sand and cement screed	1,200	0,050	13,2	13,4	120,0
5	0,81 cm	DNEPROTEX PE waterproofing	0,030	0,270	12,2	13,2	8,9
6	10 cm	URSA XPS PROF 500 N-V-L	0,032	3,125	1,2	12,2	3,0
7	10 cm	URSA XPS PROF 500 N-V-L	0,032	3,125	-9,9	1,2	3,0
8	8 cm	Drainage-levelling layer of gravel/crushed stone o	0,180	0,444	-11,5	-9,9	176,0
9	0,2 cm	TechnoNICOL Geotextile 300 g	0,080	0,025	-11,6	-11,5	0,3
10	10 cm	Cast-in-situ concrete slab C25/30 with anti-freeze	1,300	0,077	-11,9	-11,6	240,0
		Thermal contact resistance*		0,040	-12,0	-11,9	
	85,61 cm	Whole component		8,872			1.469,8

*Thermal contact resistances according to DIN 6946 for the U-value calculation. Rsi=0,25 and Rse=0,04 according to DIN 4108-3 were used for moisture proofing and temperature profile.

Surface temperature inside (min / average / max):	19,1°C	19,1°C	19,1°C
Surface temperature outside (min / average / max):	-11,9°C	-11,9°C	-11,9°C

Appendix 7. Ubakus-calculation for inverted rooftop parking

ubakus

All statements without guarantee

3-Group 3: rooftop parking N, U=0,11 W/(m²K)

Moisture proofing

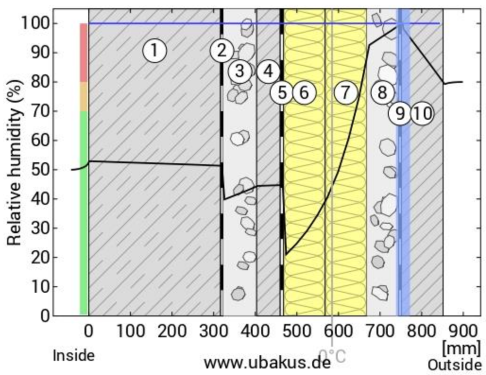
For the calculation of the amount of condensation water, the component was exposed to the following constant climate for 90 days: inside: 20°C und 50% Humidity; outside: -12°C und 80% Humidity (Climate according to user input).

This component is free of condensate under the given climate conditions.

#		Material	sd-value [m]	Condensate [kg/m²]	[Gew.-%]	Weight [kg/m²]
1	32 cm	Loadbearing Hollow Core Slab C25/30	25,60	-		736,0
2	0,6 cm	SuperFOIL SFUF insulation	104,00	-		6,6
3	8 cm	Expanded clay gravel	4,00	-		176,0
4	6 cm	Reinforced sand and cement screed	0,90	-		120,0
5	0,81 cm	DNEPROTEX PE waterproofing	104,00	-		8,9
6	10 cm	URSA XPS PROF 500 N-V-L	8,00	-		3,0
7	10 cm	URSA XPS PROF 500 N-V-L	8,00	-		3,0
8	8 cm	Drainage-levelling layer of gravel/crushed stone o	4,00	~0		176,0
9	0,2 cm	TechnoNICOL Geotextile 300 g	1,80	~0		0,3
10	10 cm	Cast-in-situ concrete slab C25/30 with anti-freeze	13,00	-		240,0
	85,61 cm	Whole component	273,30	~0		1.469,8

Humidity

The temperature of the inside surface is 19,1 °C leading to a relative humidity on the surface of 53%.Mould formation is not expected under these conditions.
The following figure shows the relative humidity inside the component.



— Relative humidity (%)
— saturation point

1. Loadbearing Hollow Core Slab C25/30 (320 mm)
2. SuperFOIL SFUF insulation
3. Expanded clay gravel (80 mm)
4. Reinforced sand and cement screed (60 mm)
5. DNEPROTEX PE waterproofing
6. URSA XPS PROF 500 N-V-L (100 mm)
7. URSA XPS PROF 500 N-V-L (100 mm)
8. Drainage-levelling layer of gravel/crushed stone o (80 mm)
9. TechnoNICOL Geotextile 300 g
10. Cast-in-situ concrete slab C25/30 with anti-freeze (100 mm)

Notes: Calculation using the Ubakus 2D-FE method. Convection and the capillarity of the building materials were not considered. The drying time may take longer under unfavorable conditions (shading, damp / cool summers) than calculated here.