

VENTILATED SUSTAINABLE FLOOR ELEMENT WITH HEATING SYSTEM FOR MODULAR BUILDINGS

LAB University of Applied Sciences
Bachelor of Civil Engineering
Double Degree in Civil and Construction Engineering
2021
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Abstract

Author(s) Sergey Boev	Publication type Bachelor's thesis	Completion year 2021
	Number of pages 41 pages, 2 appendices	
Title of the thesis Ventilated sustainable floor element with heating system for modular buildings		
Degree Bachelor of Civil Engineering		
Name, title and organisation of the client Toni Sjöman, FM-Haus Oy, Jokioinen		
Abstract <p>The scope of this work is to design, test and compare different floor structures for modular buildings. The requirements for the element are following: it should contain floor heating system (and the layer for pipes, that would not crack and it should be able to spread the heat evenly at the same time), efficient heat insulation; all the elements should have as little carbon impact as possible, and be easy to produce.</p> <p>This thesis contains two parts: theoretical knowledge about prefabrication and radiant floor heating and practical implementation (structural design of modules, manufacturing, sustainability calculations).</p> <p>Two different structures were designed and tested in production. The first one is based on thin steel profiles with XPS/EPS insulation between them and concrete screed with embedded pipes on top of it. The second structure is based on LVL-beams covered by LVL-plate and plywood sheets.</p> <p>Both structures have trade-offs. The concrete and steel structure causes a lot of extra load to the slab, but at the same time, it provides an even heat distribution. The wooden structure is very thin and light, but it has poor heat performance. But both solutions can be enhanced for further use.</p>		
Keywords Modular buildings, Timber construction, Floor element, Structural design, Manufacturing, Sustainability, Heating system		

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Appendices

Appendix 1. Results of radiant floor heating calculation (provided by Warmia Oy)

Appendix 2. Results of carbon dioxide calculations

List of terms

Cavitation – formation of vapour bubbles within a liquid at low-pressure regions that occur in places where the liquid has been accelerated to high velocities (Britanica 2018)

Thermosiphoning – a phenomenon when a coolant is circulated by convection caused by a difference in density between the hot and cold portions of the liquid (Collins English Dictionary 2014)

Expanded polystyrene (EPS) – a rigid and tough, closed-cell foam. Polystyrene foams are good thermal insulators and are therefore often used as building insulation materials, such as in insulating concrete forms and structural insulated panel building systems (Thermal Engineering 2019).

Extruded polystyrene (XPS) – a thermoplastic polymer. Extruded polystyrene has a closed cell structure and is often stronger, with a higher mechanical performance and is, in principle, often more expensive than EPS. Its density range is about 28–45 kg/m³ (Thermal Engineering 2019).

Polyisocyanurate (PIR) – a thermoset plastic typically produced as a foam and used as rigid thermal insulation (Wikipedia 2021).

Laminated veneer lumber (LVL) – a type of high-strength engineered timber that can be used as an alternative to solid timber, concrete, and steel for structural applications. It is manufactured by bonding rotary peeled or wood veneers that have been sliced thinly under heat and pressure (Designing Buildings Wiki 2020).

Estimated service life (ESL) – service life that a building or parts of a building would be expected to have in a set of specific in-use conditions, calculated by adjusting the reference in-use conditions in terms of materials, design, environment, use and maintenance (ISO 15686).

Reference service life (RSL) – service life that a building or parts of a building would expect (or is predicted to have) in a certain set (reference set) of in-use conditions (ISO 15686).

1 Introduction

This thesis work is written for the Design department, FM-Haus. FM-Haus is a company that designs, produces, and installs prefabricated elements and modules made from wood.

The company has experience in implementing radiant floor heating. Two variations were tried earlier: thin concrete screed with embedded pipes on top of the standard structure and pipes with metal plates under a plywood floor. But both had their disadvantages. The concrete screed cracked during hardening, and the piping work in the second case was time-consuming, which slowed down the production process. Thus, FM-Haus was looking for a new structure.

The thesis aims to create a durable, sustainable solution for wooden floor elements for modular building, that will carry out well on every phase of its lifecycle (production, transportation, lifting, maintenance, relocating). During the thesis work, two test modules with different floor structures will be designed, produced, and tested to find out the best solution in terms of uniform heat distribution, manufacturing time and cost, carbon footprint, flexibility, and the possibility of scaling to the bigger modules.

The floor element should follow further requirements: it should contain a floor heating system (and the layer for pipes, that would not crack and it should be able to spread the heat evenly at the same time), efficient heat insulation; all the elements and the finish covering, in particular, should have as little carbon impact as possible; production should be easy and efficient with a high level of prefabrication.

This thesis includes 5 chapters. Chapters 2 and 3 provide a theoretical background of prefabrication, modular construction, and radiant floor heating. Chapter 4 and 5 represents a practical implementation of this knowledge and describes test modules, that were built to check the production process and monitor operational characteristics. The last chapter is devoted to comparing modules.

There are two appendices in the thesis. The first shows the results of radiant floor heating calculation (layout, system parameters), and the second one contains the results of carbon dioxide calculations according to SYKE (The Finnish Environment Institute) method.

I want to thank FM-Haus and LAB University of Applied Sciences for giving me an opportunity to research and to make better structures; especially Toni Sjöman, the manager of the project, and Timo Lehtoviita, my lecturer and thesis instructor, for help and support.

2 Wooden modular buildings

2.1 Wood as a material

Wood is a remarkable material for sustainable construction (Figure 2.1). It is renewable, and it has important characteristics for structures: high strength-to-weight ratio, ease of processing, high durability, shock absorption, chemical resistance, and so on. And since wood has the lowest carbon footprint due to the low amount of energy for manufacturing, increasing the proportion of wooden construction will lead us to a climate-neutral society (Swedish wood)



Figure 2.1. Glulam roof structure in Algard Church (photo: archdaily)

But aside from all positive characteristics, timber is very sensitive to environmental conditions, because of shrinkage and swelling.

Finland has a solution of how to decrease the effect of that issue. Prefabrication is quite common there because of difficult weather conditions and high labour cost.

2.2 Timber and prefabrication in Finland

Prefabrication culture was started in Finland by Alvar Aalto after the Winter war. It was based on North America's platform system of building timber single-family houses. Pre-sawed wood members should be delivered to the construction site and then assembled to elements. But due to different climate, it was not successful (Pekka Korvenmaa 1990)

In the late 60s, modernistic movements were popular, and concrete became a primary material. But in the 90s Finland started to put effort to come back to wooden timber as a sustainable construction material. Many programs were established to promote wood, such as the Wood in Construction Technology Programme 1995–1998, the Year of Wood 1996, the Time of Wood 1997–2000, Wood Finland 1998–2005, and so on (Melta 2012). But because the level of collaboration between engineers and product manufacturing companies was poor, the process was stagnating.

Another momentum was generated by changes in Finnish Firesafety Eurocode in 2011. The new document made legitimate high-rise timber frame building (up to eight floors) and wooden cladding for facades. This step widened the field of implementation of wood. It opened an opportunity to use this material in multistorey residential and office buildings. (Melta 2012). It also was a green light for timber product manufacturers to develop in this market segment. And unlike it was in the 90s, this time manufacturers provided technical support to engineers.

All these factors created favorable conditions for wooden construction development and prefabrication. In fact, the production of wooden constructions has increased more than twice since 2000 (Melta 2012). Prefabrication building systems have been developed either as a response to the Finnish climate.

2.3 Modular buildings

2.3.1 Definition

A module is the volumetric unit of a modular building. The modules are produced indoor and then delivered to the site. This method of construction leads to a faster erection, reduced material usage, and improved quality due to constant line-up of designers, assembles, and supervisors.

2.3.2 Idea of module

The aim of the module is to assemble the building from large parts in a very short period, striving for the highest level of prefabrication; in other words, maximization of off-site and minimization of on-site works. The philosophy of the module is to create buildings, that can be changed or moved, when it is needed. For example, if a shop is not relevant anymore in a certain area, it can be relocated to another place, because the modular buildings basically consist of individual transportable parts.

This kind of construction also can change their functionality and adapt to new needs. Additional modules can be embedded in the existing building. In this way, a nursery school can be transformed into a secondary school by changing the configuration of the building.

This flexibility in functionality and location allows decreasing the number of abandoned buildings, which leads to sustainable construction.

2.3.3 Limitations of modulus

In terms of structure, the module is basically a boxlike section without sidewalls. So, it requires at least two walls to bear the roof. In some situations, there should not be any walls within one module. Then that certain areas are made with individual elements.



Figure 2.2. The module of the nursery school has arrived in Lappeenranta

As the modules should be moved through the roads (Figure 2.2), there are some transportation limitations. In Finland the maximum length of cargo space on a truck is 21.41m, the weight is 60 tons (Logistiikan Maailma), the width is 2.6m, but modules are usually 4-5.5m

width, so the truck must get special authorization. There are also height limitations because the truck should go under bridges safely. In the Helsinki area, this limit is 4.8m. To fulfil these transportation requirements different modules divisions can be applied.

2.3.4 Production

The modules are produced in closed facilities with controlled environmental conditions inside (Figure 2.3). The temperature and humidity are kept almost constant for precise assembling. However, some operation requires special conditions. In this case, it can be adjusted. For instance, gluing should be executed in a higher temperature environment, so it can be raised in a certain production hall.



Figure 2.3. The production hall (photo: Euro Focus Oy)

To create one module all its parts should be assembled from prefabricated elements: the floor, exterior and interior walls, and roof structure. Also, water supply, sewerage, heating, ventilation systems and electricity facilities are installed in the factory. All structure elements are prefabricated and then put together inside different closed halls.

The base of the module is the floor element. The load-bearing part of it is usually made from LVL beams with an insulation layer between them. The beams are covered with LVL panels to enhance the stiffness and avoid lateral torsional buckling. From beneath, there are boards, that nailed to the beams. They make the structure more rigid, and also spread loads from the beams to the foundation, bear insulation, and anti-rodent layers. On top of the structure, there are guide boards for precise wall installation. In some cases, there can be a floor heating system in the structure.

The structure of the walls is made from engineered wood. It is a row of studs, that is united with upper and lower plates. The thermal insulation layer is located between the studs. In

cases when the higher energy class is needed, there is one extra layer of insulation above the studs. It helps to avoid thermal bridges. For stiffness and fire protection sake gypsum boards are nailed from both sides to the stud frame. The water vapour barrier is always installed on the inner surface of the frame to make the building air-tight and avoid moistening of the insulation. It is common to embed flexible pipes for electrical wire housing and install electrical facilities in the wall. If there is more than one wall in the row, an additional board above the elements connects them into one stiff piece.

The bearing part of the roof can vary. It can be made with trusses or with LVL beams, mostly depending on the architectural idea. Several beams or trusses are united in one block with a width of one module. There are stiffening beams between structural elements to make this block geometrically stable. The water protection layer may represent metal sheeting or bitumen-based roll materials. An HVAC system is common to be installed between the webs of the trusses.

2.3.5 Transportation

When the modules are assembled in the main production hall, preparation for the transportation begins. The module itself, if there are not any stiffening walls inside, is a geometrically unstable system, so temporary bracing ropes should be installed. And to protect the module from unfavourable weather conditions, it is wrapped with plastic foil. Then several hydraulic jacks from both sides of the module lift it and load it to the truck.

2.3.6 On-site installation

The truck with the module comes next to the place of installation. Then the mobile crane with an X-shape traverse puts it in the design position. The modules are supported by steel beams during the lifting process, so the structure is not stressed.

3 Radiant floor heating

3.1 Basics of thermal radiation and hydronic radiant panel

In general, radiant heating systems use thermal radiation as the main mechanism of heat transfer. It means that the energy goes from the warmer surface to the cooler one through electromagnetic waves.

Thermal radiation is emitted from any surface that has a temperature greater than absolute zero (S. Blundell 2006, 247), so it is constantly emitted from the human body to any cooler surface around us. The rate of thermal radiation depends on the difference in temperatures of the surfaces, the distance between surfaces, the angle between them, and the emissivity of the surfaces.

Thermal radiation includes both the visible and infrared portions of the electromagnetic spectrum. Surfaces at a temperature lower than 480°C (750K) emit infrared light, thus it is not visible for human eyes (Siegenthaler 2012, 436).

The thermal radiation is emitted by a low-temperature hydronic radiant panel. According to Siegenthaler (2012, 423), the hydronic radiant panel is any object warmed by passing heated water through tubing embedded in or attached to it, and which releases at least 50% of that heat to its surroundings as thermal radiation, and has a controlled surface temperature under 149°C .

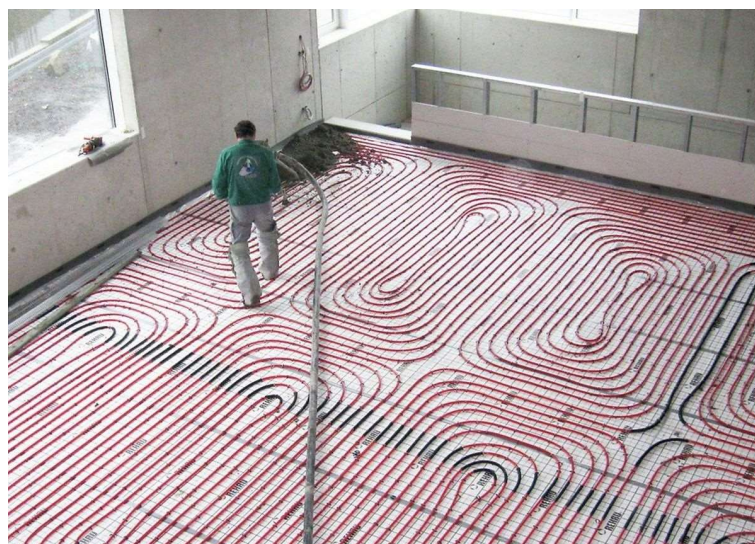


Figure 3.1. Piping system of radiant floor heating (photo: Rehau)

The radiant panels can be embedded into walls, ceilings, and floors. This thesis is focused on water-based floor systems (Figure 3.1).

3.2 Radiant floor heating and human body

The human body loses heat through four mechanisms: evaporation, convection, conduction, and radiation. Radiation has the greatest contribution to heat loss accounting for roughly 60% of the whole (Koop 2020). That is why when people are rescued, they are coated with aluminium foil blankets, that reflect electromagnetic radiation. And because the rate of thermal radiation is the higher, the more significant the difference in temperature of the body surface and surrounding surfaces, it is crucial to warm up the inner surfaces of the room evenly.

Radiant floor panels can achieve this goal because they are spread throughout the whole floor area. So, the temperature difference is not great, and heat losses caused by thermal radiation from the body to cold walls or floors are decreased.

Another important factor for human comfort is an air temperature profile. When the body loses more energy, than it produces, the blood flow to limbs (hands and feet) is reduced, and the heat is concentrated in the core of the body (torso) to maintain the temperature of critical organs (Siegenthaler 2012, 426). Besides, feet are in a taught contact to the cooler surface of the floor, which causes heat losses through the conduction mechanism. It means that the temperature in the lower zone of a room should be a little higher to avoid significant heat losses from feet. At the same time, the head is usually well supplied by blood and also it is insulated by hair. It allows the head to feel comfortable with slightly lower air temperature.

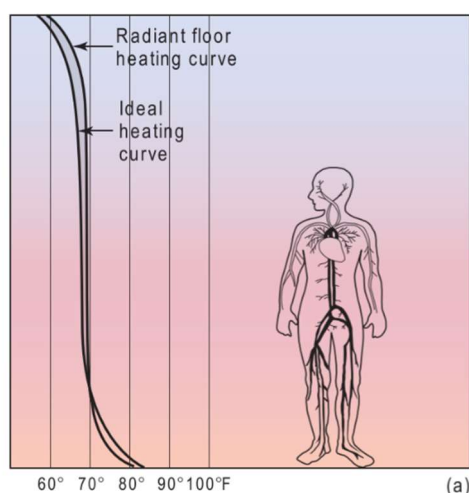


Figure 3.2. Comparison of ideal temperature profile and radiant floor heating profile, where 60°F = 16°C, 70°F = 21°C, 80°F = 27°C, 90°F = 32°C (Siegenthaler 2012)

Figure 3.2 shows that the radiant floor heating profile is close to the ideal one: the temperature near the lower limbs is slightly higher than the average temperature, and the temperature in a head zone is a bit lower.

3.3 Benefits of radiant floor heating

According to Siegenthaler (2012, 425) radiant floor heating has a long list of benefits:

- It provides superior comfort for humans in comparison to other methods of heating because its temperature profile is close to the ideal one, the inner surfaces are uniformly heated and there is no significant temperature stratification.
- It is an inconspicuous heating system, so it does not occupy space and interfere with furniture.
- It is a durable system. It is protected from physical damage because it is embedded into the structure.
- It operates in silence. A properly designed radiant panel system does not produce any noticeable noise.
- It does not contribute to dust movements and drafts as hydronic baseboard convectors or air-forced registers do. Radiant panel heating creates very gentle air motion within individual rooms rather than the building as a whole.
- It uses low-temperature heat sources. That opens up an opportunity to utilize rock-heating and solar collectors to supply heat.
- It can quickly dry floors. This is critical in wet areas such as bathrooms, entry foyers, and garages, where vehicles with snow or water on tires can come in.
- It has thermal storage. Some hydronic radiant panels, such as a heated concrete floor slab have high thermal mass. Such panels can store large quantities of heat, allowing them to deliver a “surge” of heat in situations where large doors are open and cold outside air pours in.
- It is capable of a fast response. Not all hydronic radiant panels have high thermal mass. Some are specifically designed for low thermal mass, allowing them to quickly “turn on” and “turn off.”
- It provides room-by-room zoning. Sleeping areas can be maintained cool while bathrooms are maintained warm.
- It reduces energy usage because of the ability to provide comfort at low interior temperatures, lower operating water temperatures, reduced air temperature stratification, reduced air leakage, and the ability to provide room-by-room zoning.

3.4 Disadvantages of radiant floor heating

Another side of floor heating is cost, time of installation and height issue (Warmup 2018).

The start-up cost of heated floors is higher than traditional heating radiators solution. This is mainly due to the installation of additional equipment, the use of extra materials, and a more complicated installation process. Radiant floor heating causes decreasing in height of the room because it requires additional layers on top of the floor structure for equal heat distribution. It may be crucial in renovation projects.

3.5 Types of radiant floor heating

There are three main types of radiant floor heat: air-heated, electric, and hydronic. Cost and energy efficiency of each type was estimated by U.S. Department of Energy:

- A forced air-heated system uses circulating hot air to distribute energy. Pipes of the system are usually 100mm diameter and require thick concrete screed for efficient use (The Legalett way). Air cannot keep large amounts of heat. This kind of systems not cost-efficient in residential buildings, so they are seldom used (U.S. Department of Energy)
- Electric systems can be made of separate cables, cables mounted on a plastic net, or electric radiant plastic film. These kinds of systems are efficient when there is a layer with high thermal mass (for example, thick concrete screed) in the floor structure, because of the relatively high cost of electricity. The high thermal mass allows to use heating during the day peak-hours and turn it off at night. It will stay warm.
- Hydronic systems are the most cost-efficient in regions with long heating seasons. These systems pump heated water from a boiler through the tubes embedded in the floor structure. The water circulates to the system. That allows using a small amount of energy to sustain the water temperature and comfortable indoor climate.

3.6 Hydronic radiant floor heating system

3.6.1 Basic components of the system

Basic components are described in Siegenthaler (2012, 13).

A radiant floor heating system is a collection of different components, that can vary depending on the complexity and the heating area. In general, the system consists of four subsystems: a heat source, distribution system, heat emitters, and control system (Figure 3.3).

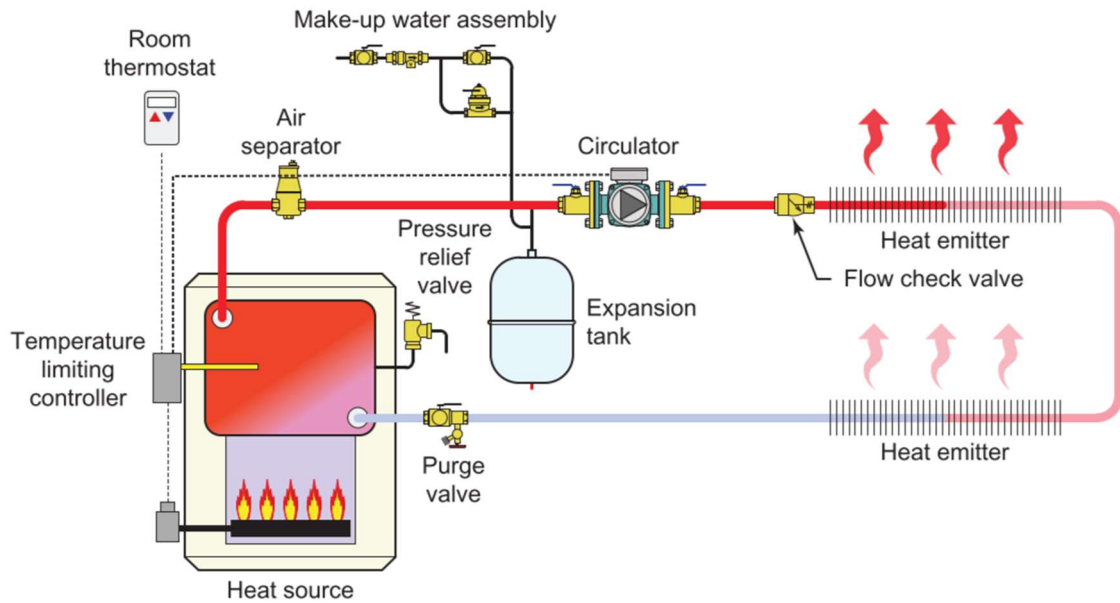


Figure 3.3. Basic components of heating system (Siegenthaler 2012, 17)

Basically, the system aims to produce energy with the rate of heat loss from the building. To find out what amount of energy is needed, the room thermostat is installed in a heating area. Once the air temperature is below the thermostat's setpoint, the boiler starts to heat the water in the system. The boiler is equipped with a temperature limiting controller, that stops the heating process when the temperature reaches its maximum value. If the controller fails, the boiler continues to heat the water. The pressure in the system rises and it may damage the components. For this reason, a pressure-relief valve is installed to the heat source to protect the system from extremely high pressure.

As water is heated, it expands. To neutralize this phenomenon during normal operation the expansion tank is added to the system. It usually uses a flexible diaphragm with air in the sealed cell (Figure 3.4) to let the water volume increase without damaging the system. The expansion tank is recommended to install vertically with a water intake valve at the top due to corrosion and mechanical issues (Siegenthaler 2012, 595).

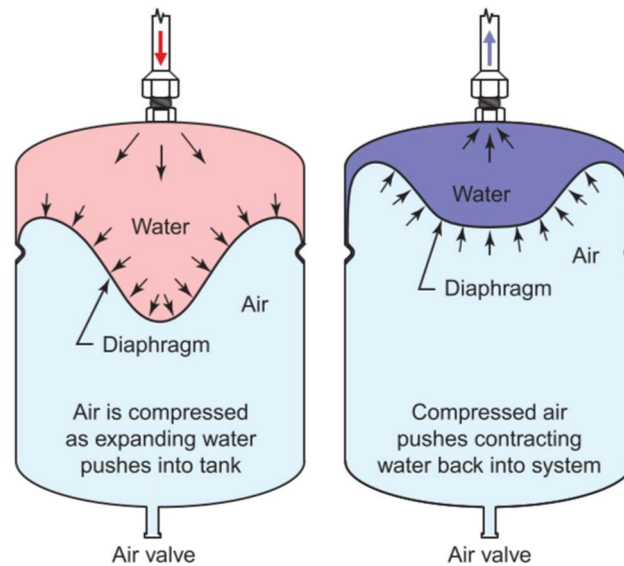


Figure 3.4. Diaphragm-type expansion tank (Siegenthaler 2012, 591)

Minor water losses occur in closed-loop hydronic systems due to evaporation, pump seals, and so on. These losses must be replenished with water from an outer cold water source through the make-up water assembly, which includes a pressure-reducing valve, backflow preventer, pressure gauge, and shutoff valves.

New water brings air to the system. It may cause multiple problems such as flow noise, accelerated corrosion, poor heat transfer, unstable flow, and so on. An air separator creates regions of reduced pressure and expels bubbles with air from the system. This process goes better the higher the water temperature, thus the separator is placed right after the heat source.

A circulator makes the water flow happen in the system. The circulator has a rotating impeller to add mechanical energy to the fluid. This mechanism is also called a centrifugal pump (Figure 3.5). The circulator is recommended to be installed right after the expansion tank to reduce the chance of cavitation due to high-pressure situations.

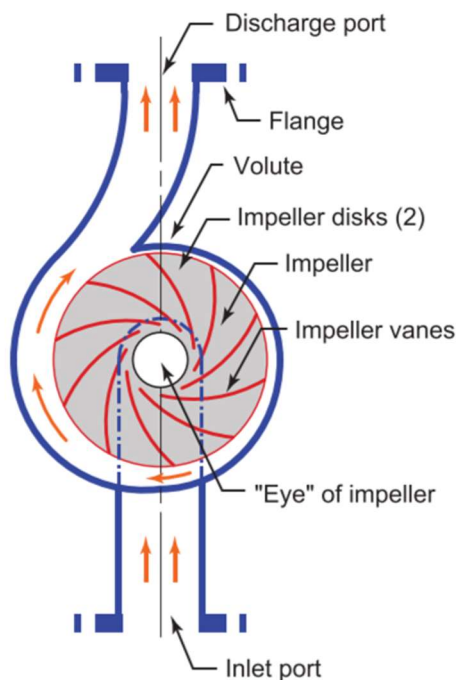


Figure 3.5. Simplified cross-section of a centrifugal pump (Siegenthaler 2012, 234)

A flow-check valve prevents the system from thermosiphoning when the heated water goes backward in the boiler when the circulator is off. This process may cause uncontrolled heat leaks. A purge valve is installed to eject major portions of the air from the system.

Heat can be obtained from several heat sources such as conventional gas- and oil-fired boilers, electric heaters, hydronic thermal pumps, solar thermal heat sources, and rock heating systems. The most widely used types of heat sources are gas- and oil-fired boilers due to efficient operational cost and relatively reasonably priced installation (Siegenthaler 2012, 52).

The heat distribution system is represented by loops of pipes with a circulating heat carrier. The division of pipes, its material, depth of installation will be discussed in the following chapters.

As a heat emitter, the metal plates or concrete screed may act. In the floor systems with dry installation, aluminium plates are installed above the tubes to provide an even distribution of heat to the flooring material. When tubes are installed into the concrete screed, the layer itself is used as a heat emitter, spreading energy from the heat carrier to the area around the tubes.

3.6.2 Types of floor installations

Two main types of installation can be identified: wet and dry (U.S. Department of Energy)

The «Wet» method involves the installation of the tubes into a layer of concrete, gypsum, or other materials cast on top of a subfloor. The systems with thick concrete layers can store a lot of energy. It allows using heat sources with fluctuational income, such as solar heating panels. But at the same time, it is almost impossible to change the temperature instantly in these systems.

In the «dry» installation systems the tubes are set between two solid materials of a subfloor or installed under the floor. These systems are more agile in terms of changing indoor air temperature. However, they require a higher temperature of a heat carrier and as a rule heat emitters installation (for instance, thin aluminium plates).

3.6.3 Types of tubes

There are many types of tubes that can be used in radiant floor heating. The main types are described by Siegenthaler (2012, 151).

PEX and composite PEX-AL-PEX are the most widely used types of tubes for radiant floor heating due to their flexibility and durability. PEX tubes are made of elastic cross-linked polyethylene, which allows them to withstand stress caused by heating and cooling cycles, being embedded in a solid material. PEX tubes are resistant to kinking during installation. And even if a kink occurs, it can be fixed by heating the kinked area to 135°C.

Composite PEX-AL-PEX tubes consist of two PEX layers and one aluminium layer between them. These tubes can withstand higher temperature and pressure rates, than PEX tubes. The aluminium layer also reduces the thermal expansion of the tubes. However, composite tubes cannot be repaired by heating, as PEX tubes do. They can be fixed only by mechanical cutting of the kinked area and reconnecting with fitting.

The structure of PEX tubes is such that oxygen may diffuse through the tube walls and be absorbed by the fluid. This oxygen can accelerate the corrosion process of all metal parts of the system, such as fittings, valves, and so on. That is why it is important to use PEX tubes with oxygen diffusion barrier to avoid oxygen diffusion. These tubes can be identified by the EVOH mark (ethylene vinyl alcohol). Composite PEX-AL-PEX tubes do not need any additional layers, because aluminium itself is a good oxygen barrier.

There is another type of tubes – PE-RT (polyethylene at raised temperature resistance). PE-RT consists of five layers: the first and the fifth layers are polyethylene, two layers of

polymer adhesive and EVOH oxygen barrier between them. The outer layer of polyethylene protects all other layers from damage, and the polymer adhesive acts as an adhesive layer between polyethylene and the oxygen barrier. These pipes are flexible, can operate with water with temperature from 5°C to 80°C, and can be recycled after the service life is finished.

3.6.4 Principles of layout design

It is critical to follow the basic rules of design to maximise efficiency of the system. Here is the list of main principles of layout design (Siegenthaler 2012, 475):

1. The warmest fluid should go along the exterior walls first. It allows compensating heat losses, where they are the greatest. That is why heat radiators are installed below the windows.
2. Tubing should be arranged so that to maximize straight runs and minimize return bends and corners. For example, if a room is long and narrow, the main runs should be along the long wall. In this situation, the number of bends is smaller than if the runs are placed along the short wall.
3. The length of individual circuits should be limited to the recommended rates, depending on the diameter of the tubes.
4. The circuits should be designed so that room-by-room temperature control is possible. For instance, it makes sense to use separate circuits for the bedroom and bathroom. The air temperature in the bedroom should be slightly lower for good sleeping, and the temperature in a bathroom should be higher to provide comfort and allow water to evaporate faster from the floor.
5. Manifold stations should be installed in central locations to minimize the distance between the manifold and the heated room.
6. Tubes should not cross over each other. In this case, it requires to use thicker concrete layer.
7. The placement of tubes should provide a minimal chance of fasteners penetration into the tubing. For example, tubes are recommended to cross the room under the doors, where most likely fasteners are not used.

3.6.5 Requirements for materials

The important characteristics of materials for the floor heating systems are following:

- uniform heat distribution
- dimensional stability

These characteristics are represented by the physical parameters:

- thermal conductivity coefficient λ and Specific heat capacity c . The higher λ -value, the better heat spreads through the material. The higher c -value, the higher the amount of energy, that the material can accumulate.
- coefficient of linear thermal expansion (CLTE). The lower CLTE-value, the lower the expansion of the materials as temperature changes

4 Test module №1

4.1 Concept

The first module was created to test the technology of wooden frame structure manufacturing with polymeric thermal insulation inside, as well as the “wet” method of flooring when tubes are embedded in a concrete layer.

The structural model (Figure 4.1) was created in hsbCAD software based on AuroCAD Architecture.

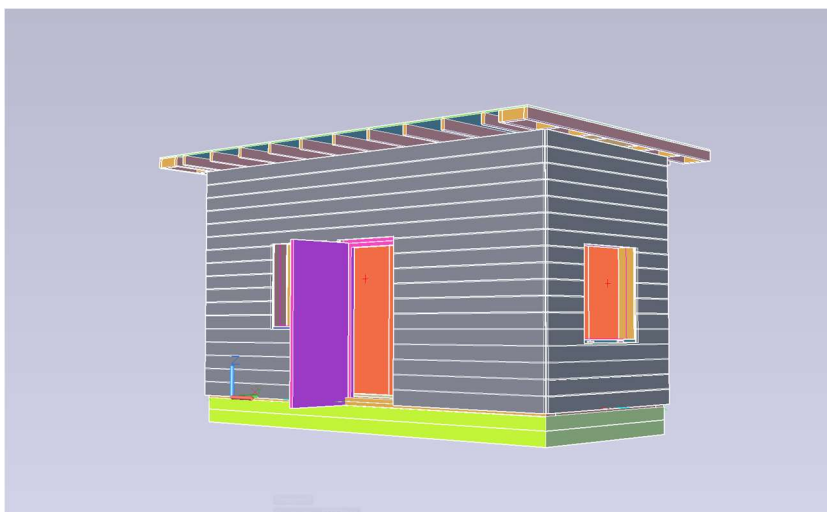


Figure 4.1. The structural model of the module

As a philosophy of a module is being there where and when it is needed, it was designed to be useful after the testing is done. The module can be used as a pandemic office, or it can be lent as a temporary building to some festivals or events. Figure 4.2 shows the example of a floor plan of the module used as a small office space.

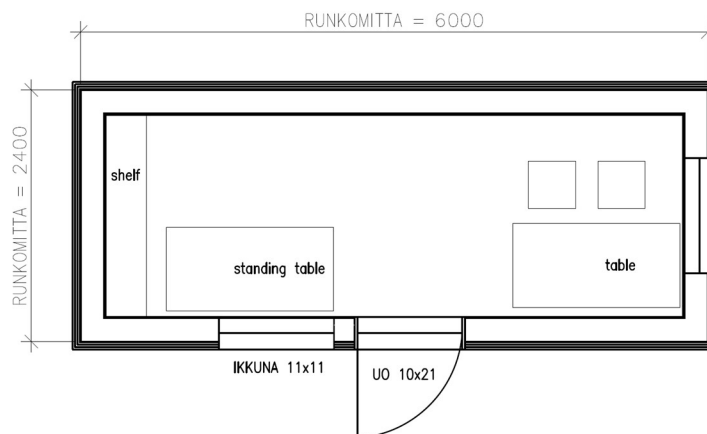


Figure 4.2. Architectural plan of the first module

4.2 Structure

The load-bearing capacity of the floor is provided by cold-rolled channels along the longest side and thin-metal insulation profiles along the shortest one (Figure 4.3). There are 180mm thermal insulation XPS boards between thermoprofiles and 100mm EPS profiled boards on top of them. The floor can be placed directly on the ground or can be supported by concrete blocks.

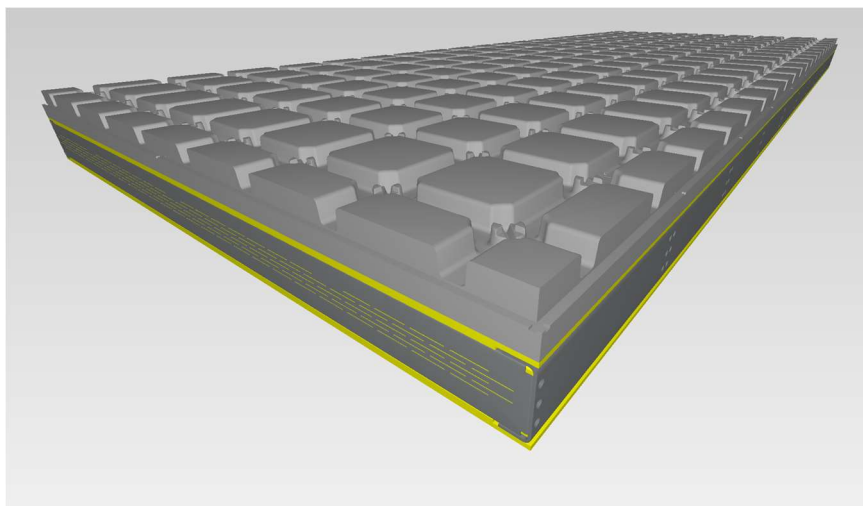


Figure 4.3. Load-bearing structure and insulation

A rebar mesh is installed into the cavities of profiled boards, and underfloor heating pipes are attached to the top of the insulation boards. The structure is covered by 50mm concrete screed.

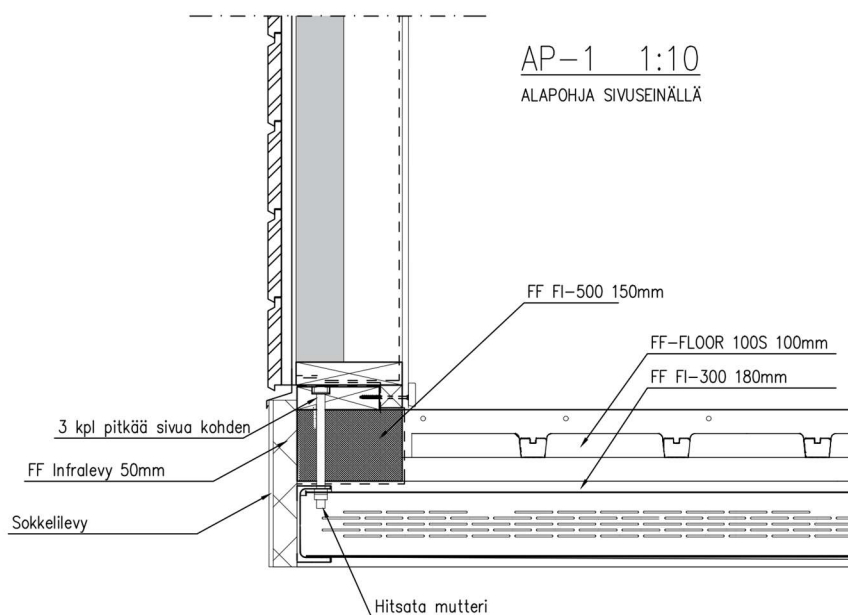


Figure 4.4. Wall to floor connection detail

According to Henri Nieminen, 3-dimensional structure allowed to increase the strength of the slab by 20% without extra reinforcement and decrease the amount of concrete by 30% comparing to traditional solutions (Nieminen 2020).

The walls are made of 48x223 mm wooden studs, that are covered with wind-barrier boards from outside and gypsum boards from inside (Figure 4.5). The long walls transfer the load from the roof to the foundation slab through the hard XPS foam (Figure 4.4).

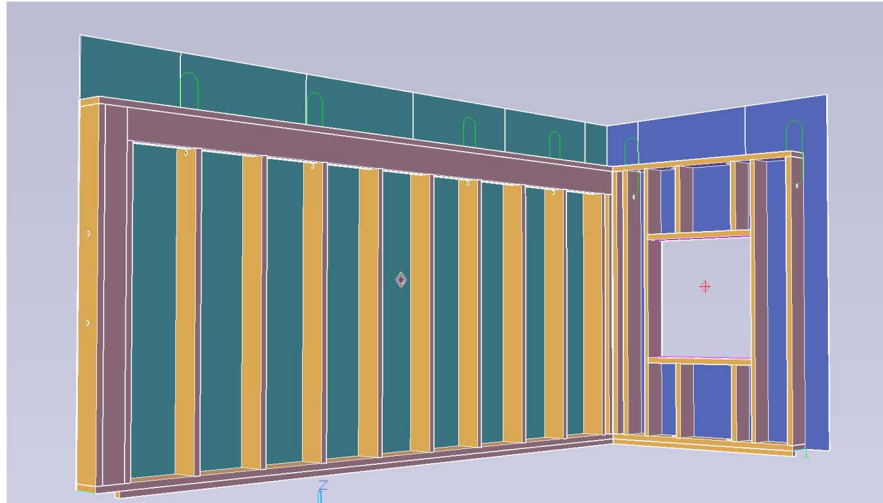


Figure 4.5. Structural model of the walls

The thermal insulation layer is represented by 100 mm PIR (polyisocyanurate) boards. They are installed between the studs and sealed with construction foam (Figure 4.6). The water vapour barrier was not installed to avoid condensation on it, as the PIR insulation has good water vapour resistance.



Figure 4.6. The long wall on the assembling table

The main structure of the roof consists of LVL beams that go along the short side. A snow load transfers to the main beams by 48x123 girders and OSB-4 sheets on top of them. The 210 mm EPS (expanded polystyrene) insulation layer is held by 48x148 beams and covered by a gypsum board on the bottom (Figure 4.7).

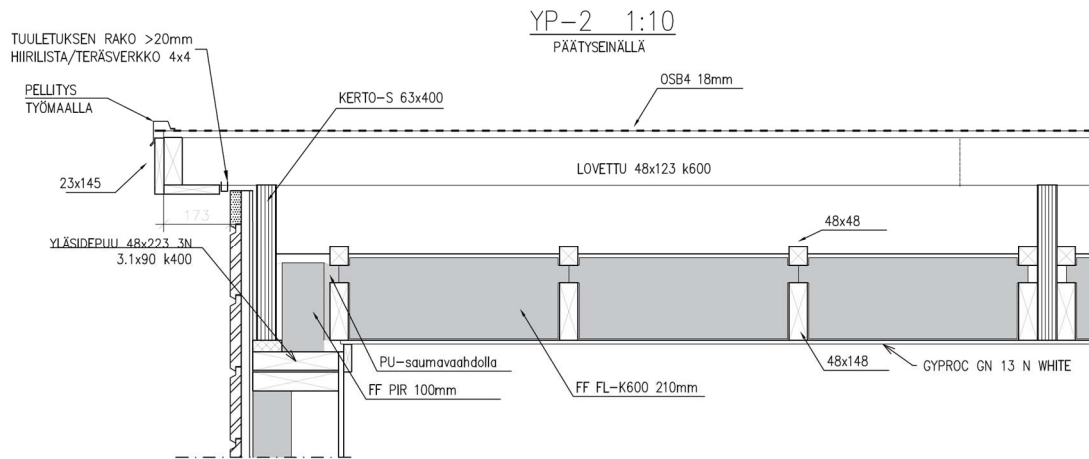


Figure 4.7. Section of the roof

Figure 4.8 shows the structural model of the roof.

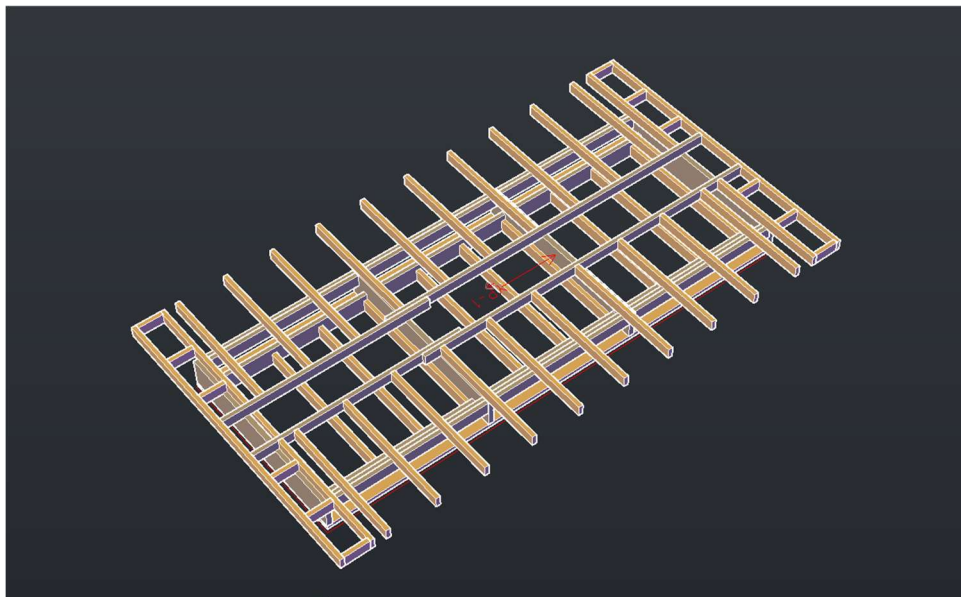


Figure 4.8. Structural model of the roof

Table 4.1 shows the list of used insulation products and their U-values.

Table 4.1. U-values of the structures

Structure	Insulation material	Thickness, mm	U-value, W/m ² K	Quantity, m ³
Floor	FinnFoam FI-300	180	0,12	2,6
	FinnFoam Floor 100S	100		1,4
Walls	FinnFoam PIR	100	0,22	3,8
Roof	FinnFoam FL-K600	210	0,17	3,3

U-values of the structures were calculated without taking thermal bridges into account, such as studs in the walls and beams in the roof. It was also assumed that the EPS-board on top of the slab (FinnFoam Floor 100S) has an even surface without cavities.

4.3 Floor assembling process

The load-bearing structure is assembled first. In the metal workshop, the main channel beams are cut to the required length and the holes for fixing thermal profile are made. After that thermal profiles and XPS insulation boards between them are connected to the main beams in sequence (Figure 4.9).



Figure 4.9. The floor structure on the assembling line

When the structure is ready, the mold for the concrete screed is placed on top of it. Hard foam is installed around the perimeter of the slab. It is needed to give a shape to the concrete as well as to transfer loads from the walls to the floor structure. Then the profiled plates are fixed to the main insulation by plastic anchors and the steel mesh is placed into the cavities of the plates. The bottom base plate is placed on top of the hard foam and connected to the main beams with long bolts (Figure 4.9). The wall elements are screwed to these bottom base plates. After wall installation, the roof is set to its place.



Figure 4.9. The floor structure with the base board for the wall fixing

Before concrete is cast, the piping system is tested with pressurized air. When the test is passed, self-levelling concrete is put on the profiled plates. The screed is cured in warm conditions for 3-5 days.

The assembling process was easy, as all the parts were prefabricated and match to each other. The structure was done by 2 workers for 4 hours. And it took one more hour to cast concrete.

4.4 Heating system

The «wet» method of pipe installation is applied in the first module. The concrete screed is 50mm thick. PE-RT 16mm tubes are fixed with plastic fasteners to XPS insulation plates (Figure 4.10). These fasteners allow tubes to move a bit without damages as the temperature changes. The distance between tube lines is 150mm.



Figure 4.10. Prepared structure for concrete pouring (picture: FinnFoam)

The area of the module is covered with a single circuit. The length of the circuit is 70 meters. A counterflow scheme was applied as it most likely will be used in the large modules. This scheme provides an equal heating distribution throughout the floor area. Heated water goes along the perimeter first to compensate heat losses and then it goes to the centre, alternating with the reverse flow.

4.5 Cost of materials

Preliminary cost estimation is based on construction materials prices in Finnish online stores. This estimation is mostly needed to compare the cost of 1 square meter of the different floor structures. The prices are relevant for 2021 year. Table 4.2 with approximate cost calculation is below.

Table 4.2. Preliminary cost estimation of the materials

Structure	Material	Price of 1 unit, euros	Quantity	Material cost, euros
Insulation	FinnFoam FI-300	12,7 per 1 sheet	10 pcs	127
	FinnFoam Floor 100S	8 per 1 sheet	20	160
	FinnFoam FI-500	19 per 1 sheet	8 pcs	152
	Cold rolled channels 6x50x146, 6000mm	107	2 pcs	214

Load-bearing parts	Aluminium profiles 2x50x146, 2600mm	65,7	18	1183
Total				1836

4.6 Carbon dioxide emission calculation

Calculation of greenhouse gas emissions for the floor structure is done with the SYNERGY Carbon Footprint tool of main structures developed by the Finnish Environment Institute (SYKE). This calculation considers greenhouse gas emissions as well as carbon dioxide storage in the materials. The amounts of emissions and storage used in calculation are taken from the calculator instruction and from certificates of materials from manufacturers.

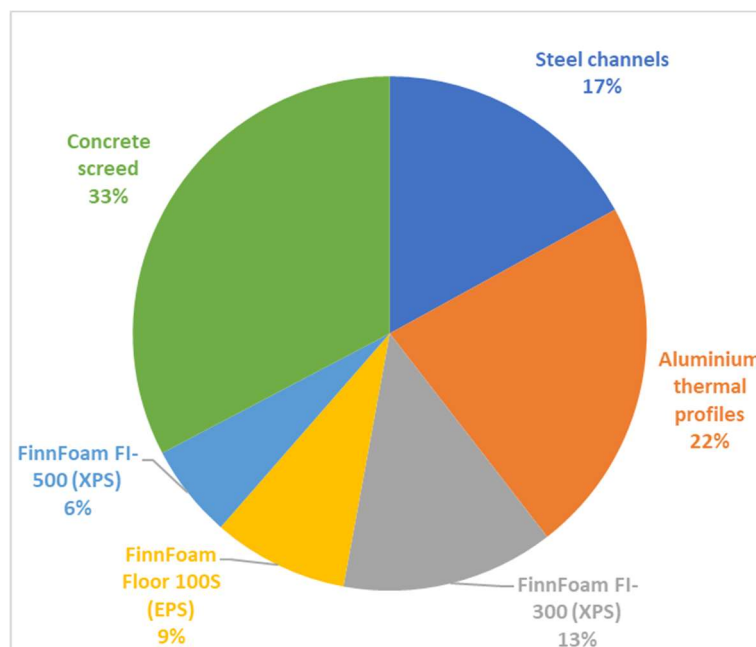


Figure 4.11. Proportions of carbon dioxide emissions from different parts of the structure

Carbon dioxide emissions of the whole floor structure are 926 kg CO₂-eq, or 64 kg CO₂-eq per square meter. The materials used in the first module do not store any CO₂. The greatest contribution of emissions is provided by the aluminium thermal profiles, steel channels and concrete screed. The table with calculation is in Appendix 2.

4.7 Service life

The calculation of service life of the structure is based on the method described in ISO 15686 and comments to it given in the scientific report by Hannu Viitanen (2014).

The method of service life evaluation is described in the equilibrium:

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G$$

The estimated service life (ESL) is the reference service life (RSL) multiplied by a variety of factors that take into consideration the quality of materials, actual design, construction, use condition, maintenance, and climate exposure of the structure. The names of factors and their values are given in table 4.3. The values of factors are taken from the scientific report (Hannu Viitanen, 2014).

The estimated service life of the load-bearing part (steel channels) is calculated below:

$$ESL_{steel} = 100 \times 1,0 \times 1,0 \times 1,3 \times 1,0 \times 0,8 \times 0,95 \times 1,0 = 99 \text{ years}$$

Reference service life of steel channels equals 100 years (NEPD-1905-832-EN 2019)

Table 4.3. The names of factors and their values

Factor	Name	Description	Value
A	Quality of components	Normal quality	1,0
B	Design level	Normal level	1,0
C	Work execution	Work done indoor	1,3
D	Indoor environment	Heating inside	1,0
E	Outdoor environment	Service class 2, wet climate	0,8
F	In-use conditions	Transportation	0,95
G	Maintenance level	Normal maintenance	1,0

As the XPS insulation is a part of the structure, that is exposed to the outdoor environment, it is good to calculate the estimated service life of it as well:

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G$$

$$ESL_{XPS} = 60 \times 1,0 \times 1,0 \times 1,3 \times 1,0 \times 0,8 \times 0,95 \times 1,0 = 59 \text{ years}$$

The reference service life is from the environmental product declaration of a similar XPS insulation board (NEPD-396-274-EN 2016).

The insulation is hard to replace, as it is embedded in the structure: one layer of it is between aluminium profiles and another layer is in contact with the concrete screed, so the load-

bearing structure should be disassembled during renovation. In residential buildings, it is barely possible. Thus, the ESL of the structure is determined by the weakest component and it is 59 years.

5 Test module №2

5.1 Concept

The second module was created to test the «dry» method of radiant heat floor installation. The code name of it during production was «puuversio», which means that it was totally made of materials based on wood.

The idea was to use the same structures that are usually applied in the regular modules, that is why the sections of the main structures are overkilling for the building that small.



Figure 5.1. Left to right: test module №1, test module №2, test module that was done earlier

The appearance is almost the same as the first module has (Figure 5.1), but the floor structure and insulation type are different. More detailed information is in the next sections.

5.2 Structure

The floor structure is LVL beams with a centre-to-centre distance of 400mm (Figure 5.2). They go along the longest side of the module as the supports and lifting beams will be placed along the shortest side.

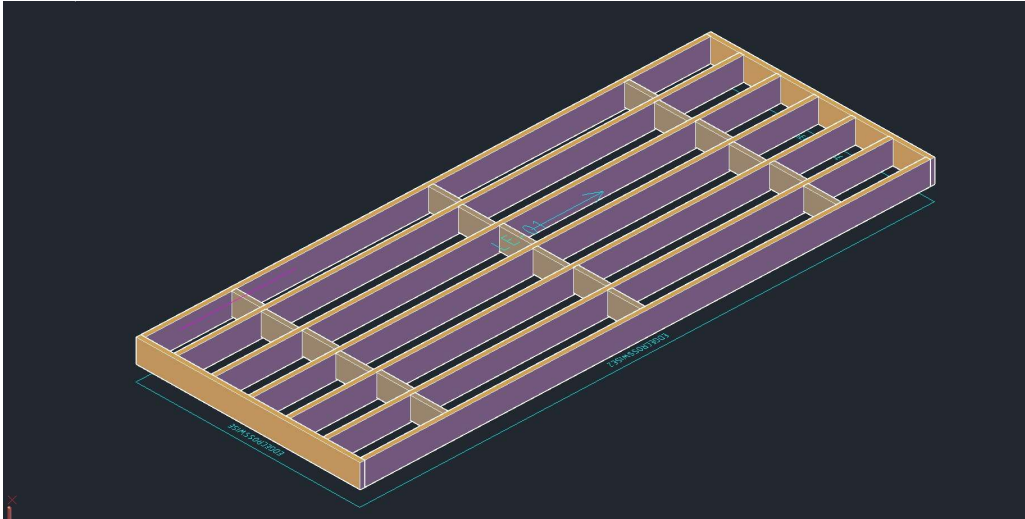


Figure 5.2. Structural model of the floor frame

Glass wool is placed between the beams. The insulation layer is protected by anti-rodent mesh, wind-barrier layers and supported by boards fixed to the bottom of the beams. LVL-plate is glued to the load-bearing beams. There are ditches in the plate for piping placement (Figure 5.3). The ditches are done on the CNC machine. On top of the LVL-plate 12 mm plywood is placed in a way that it is possible to easily take it off and change the configuration of the heating circuit.



Figure 5.3. LVL-plate with precut channels for piping

The wall structure is identical to the first module. The differences are in the insulation layer (glass wool) and in the availability of a water vapour barrier (Figure 5.4), that protects the wool from moisturizing.

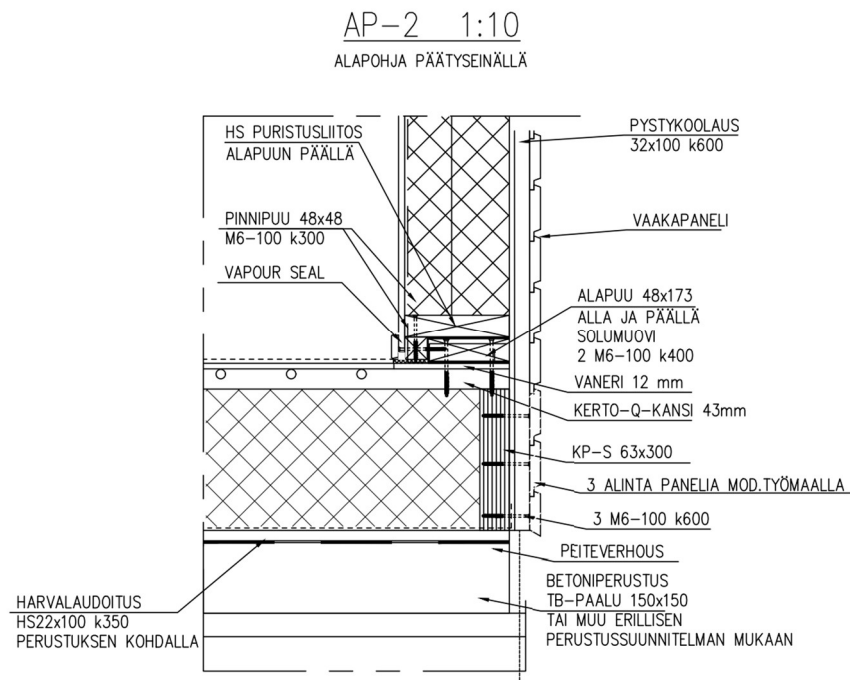


Figure 5.4. Wall to floor connection detail

The main structural parts of the roof are the same, but as the insulation layer (glass wool) is supported from the bottom side, the beams for XPS insulation support from the upper side are no more relevant, so they were deleted from the structure (Figure 5.5).

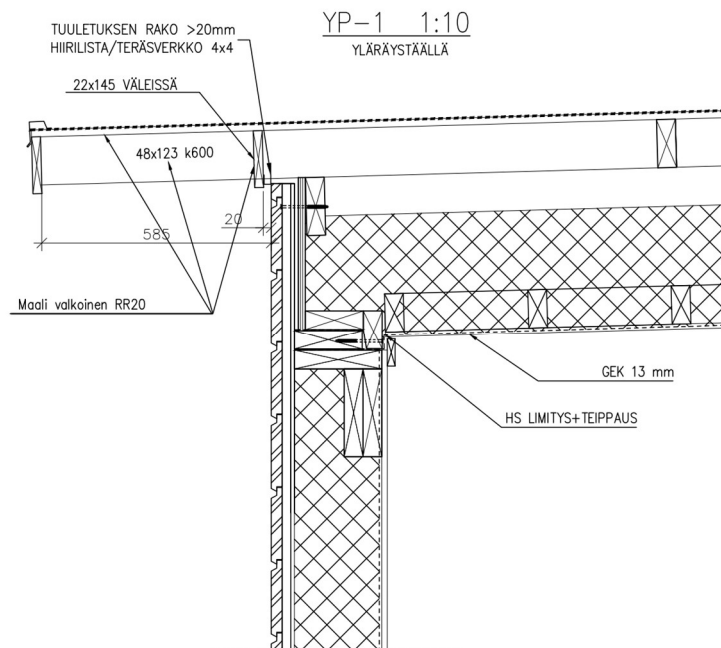


Figure 5.5. Wall to roof connection detail

Table 5.1 consists of characteristics of the insulation layers.

Table 5.1. U-values of the structures

Structure	Insulation material	Thickness, mm	U-value, W/m ² K	Quantity, m ³
Floor	Glass wool KL-37	240	0,15	3,5
Walls	Glass wool KL-33	225	0,15	8,2
Roof	Glass wool KL-33	300	0,11	4,3

U-values of the structures were calculated without taking thermal bridges into account, such as studs in the walls and beams in the floor and roof.

5.3 Floor assembling process

The assembling process is simple. The frame is assembled first. The beams of the frame are fixed to each other with screws. Anti-rodent mesh, wind-barrier layers and boards, that support insulation are fixed to the bottom of the frame. After the element is turned over, glass wool is put into the space between beams, and LVL plate is glued on top of the frame (Figure 5.6).



Figure 5.6. Process of glueing LVL-plate to the frame

5.4 Heating system

The «dry» method was tested in the second module. The tubes are placed in the precut ditches in the LVL plate and covered with plywood sheets. It was decided not to apply aluminium plates that are typical for this type of installation to decrease carbon dioxide emissions.

Basically, the same scheme and equipment were implemented as in the first module, but the water temperature is slightly lower, as the tubes are closer to the floor surface and the whole structure has a low thermal mass. The table with the scheme and calculated parameters can be found in Appendix 1.

5.5 Cost estimation

The preliminary cost estimation of materials is in table 5.2.

Table 5.2. Preliminary cost estimation of the materials

Structure	Material	Price of 1 unit, euros	Quantity	Material cost, euros
Insulation	Glass wool	29,6 euros per package	12	352
Load-bearing structure	LVL beams 45x260mm	85 euros per 6000mm beam	8	680
Heating layers	LVL-plate 43mm	25 euros per sq.m.	14,4	360
	Plywood 12mm	9,4 per sq.m	15	141
Total				1533

5.6 Carbon dioxide emissions

Carbon dioxide emissions of the floor structure are 234 kg CO₂-eq, or 16 kg CO₂-eq per square meter. The materials used in the second module do store CO₂. It means that the wood while growing extract from the atmosphere and accumulate some amount of carbon dioxide. If the carbon storage is subtracted from the carbon emissions, then the amount of

new CO₂ will be negative. In this case, the new amount of the gas is minus 837 kg CO₂-eq, or minus 58 kg CO₂-eq per square meter.

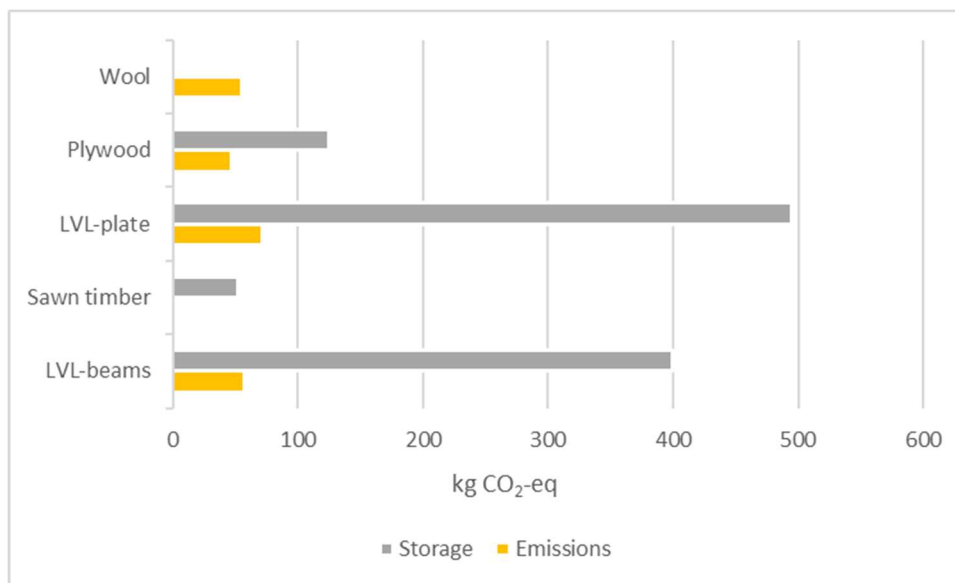


Figure 5.7. Amounts of carbon dioxide emissions from different parts of the structure

The greatest contribution of emissions is provided by the LVL beams and plate (Figure 5.7). The table with calculation is in Appendix 2.

5.7 Service life

The estimated service life of the structure is defined by the LVL beams. The insulation can be replaced before the end of the service life of the load-bearing parts. The names of factors and their values are given in table 5.3.

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G$$

$$ESL_{LVL} = 50 \times 1,0 \times 1,3 \times 1,3 \times 1,0 \times 0,8 \times 0,95 \times 1,0 = 64 \text{ years}$$

The reference service life of LVL beams is taken from European Technical Assessment (2018, ETA 17/0941, 2).

Table 5.3. The names of factors and their values

Factor	Name	Description	Value
A	Quality of components	Normal quality	1,0
B	Design level	Good quality (extensive experience of designing)	1,3

C	Work execution	Work done indoor	1,3
D	Indoor environment	Heating inside	1,0
E	Outdoor environment	Service class 2, wet climate	0,8
F	In-use conditions	Transportation	0,95
G	Maintenance level	Normal maintenance	1,0

6 Comparison of the floor solutions

The comparison of different floor structures is given in table 6.1.

Table 6.1. Comparison of different floor structures

Test module 1 («wet» flooring)	Test module 2 («dry» flooring)
Dimensions and weight	
<p>The total thickness of the concrete screed is 100mm: 50mm above the insulation plate and 50mm in the cavities of the profiled plate. The thickness of the plate itself is 100mm. Thus, the total thickness of the structure is 150mm.</p> <p>Additional load to the load-bearing structure is 1,52 kN/m²</p>	<p>The total thickness of additional layers is 55mm (12mm plywood and 43mm LVL-plate).</p> <p>Additional load to the load-bearing structure 0,26 kN/m². So, this structure is thinner and lighter.</p>
Structure requirements (deflections)	
<p>The concrete screed is sensible to deflections. The recommended deflection limit is 1/600 of the span (Siegenthaler 2012, 239). That is why steel was chosen as a material of primary beams. One of the previous test modules was done with concrete screed based on LVL-beams structure. But there were a lot of thin cracks on the screed, because it was calculated with less strict deflection requirements. This factor is especially critical as modules may be moved from place to place and have slight dynamic loads during lifting and transportation.</p>	<p>The plywood covering and LVL-plate are not sensible to deflections, and they do not have any special requirements to it. That makes the structure thinner and economically more efficient.</p>

Heat performance	
<p>Heat is spread evenly in the structure due to the high density of the material, high conduction rate and firm contact between the concrete and the heating pipes.</p> <p>The thermal mass of the structure is higher than in the structure of the second module. That decreases the response speed but increases the amount of heat that can be accumulated in the structure. Thus, it is not needed to sustain the water temperature of 30°C all the time.</p>	<p>The difference of temperature above the tubes and the other areas can be felt, as a lateral heat distribution is relatively low due to cavities in the LVL-plate (ditches are done throughout the whole area, so there are many air gaps in the zones between tubes). Thus, the installation of aluminium sheets, that spread the heat to the sides, is necessary, and channels should be only there where the pipes are supposed to be installed (to eliminate air gaps).</p> <p>The structure has a low thermal mass. So, the temperature response is rapid, but at the same time plywood and LVL-plate almost do not accumulate heat, as a specific heat capacity is decent and equals $c=1,8$ kJ/kg°C (Stora Enso), but the amount of material (thickness) is low.</p> <p>The structure allows operating with a lower temperature of water (about 24°C) due to low thermal resistance and the small distance between tubes and the floor surface.</p>
Manufacturing	
<p>The processing of steel parts consists of cutting, drilling, and welding. It requires special equipment.</p> <p>The assembling process took 4 hours for 2 people, plus 1 hour for concrete pouring. The assembling was that fast as all components were prefabricated.</p> <p>The main issue of manufacturing is the right work with concrete: suitable mixture, the</p>	<p>The assembling process took 4 hours for 1 person, plus glueing took 20 minutes for 2 persons.</p> <p>The structure requires special CNC processing of the LVL-plate, and warm conditions while glueing it to the load-bearing beams. Moreover, it is critical to make a precise markup on the plywood not to damage the tubes with screws.</p>

<p>right amount of water, height and speed of casting, vibration and so on. It requires several days for hardening, and during this period the conditions of +20°C temperature and high relative humidity should be sustained. It means that the module is kept in the production hall for several days, and it can decrease the speed of manufacturing.</p> <p>The configuration of tubes can be any, as plastic fasteners can be fixed to any place of the EPS plate.</p>	<p>The layout of tubes is limited by premade CNC-processed channels. It requires a detailed design of the piping layout.</p>
<p>Installation place and possibility of scaling</p>	
<p>The first module can be installed both on the concrete foundation lines and the prepared ground surface, as the water permeability of the EPS and XPS insulation is low, and the load-bearing structures are covered with this insulation.</p> <p>The structure can be scaled just by connecting the basic module to each other.</p>	<p>The second module can be installed on the foundation lines only, as the insulation (glass wall) is not covered by anything waterproof from below. Thus, it requires ventilation of the structure.</p> <p>As the heating layers are compact and light, and they share the same structure as the floors without a heating system (LVL beams), the structure can be scaled up to maximum transportation limits.</p>
<p>Carbon footprint and service life</p>	
<p>The carbon dioxide emission of the first module is significantly higher due to the vast usage of steel, aluminium and concrete (64 kg CO₂-eq per square meter).</p> <p>The service life is 59 years.</p>	<p>The emission is negative due to the usage of wood-based materials that accumulate CO₂ (minus 58 kg CO₂-eq per square meter).</p> <p>The service life is 64 years.</p>

A brief review of the structures with values and characteristics is given in table 6.2.

Table 6.2. A brief review of the structures

Attribute	Module 1 (steel and concrete)	Module 2 (wood)
Extra thickness	150 mm	55 mm
Extra load	1,52 kN/m ²	0,26 kN/m ²
Deflection limit	1/600 of the span	1/300 of the span
Thermal mass	High	Low
Water temperature	30°C	24°C
Thermal performance	Good	Poor
Service life	59 years	64 years
Carbon footprint	64 kg CO ₂ -eq per sq.m.	-58 kg CO ₂ -eq per sq.m.
Manufacturing time	4 hours (assembling), 3 days of curing	4 hours (assembling)

The structure with concrete screed gives a lot of extra load to the slab, has very strict limitations to deflections, requires several days of curing during the hardening process and has a high carbon dioxide emissions value, but at the same time, it provides a superior heat performance without significant difference in temperature throughout the surface. The all-wood structure can be applied virtually in every construction, as it is thin and light, it has a negative carbon footprint, operates with lower temperature, but the lateral heat distribution is poor, and it cools down rapidly when the circulation is off, as it does not accumulate much heat.

7 Conclusions

Two structures with very different materials were designed and manufactured during this thesis work. But both of them are not perfect.

The main issue with the first module is the concrete screed, which causes added weight, deflection limitation and slows down the production process. It can be replaced with poured gypsum layer. It is 20% lighter, more flexible, less prone to cracking, but sensible to water. It also requires several days of curing, but it can be walked on within 2 hours after pouring, so the other types of work can be done in the module during the hardening process.

The second structure should be modified to solve the main issue –heat performance. The channels for tubes should be done in the places where the tubes are installed to avoid air gaps, the metal sheets should be placed with tubes to provide lateral heat spreading. These plates have a slight footprint effect, as it has a tiny volume in the structure. The upper layer may be replaced by more thick material to increase the thermal mass in the zones, where it is needed (for example, near the entrance door of the shop, which often opens). These modifications do slightly compromise the advantages of the structure, but they should significantly increase the heat performance.

Uneven heat distribution is not critical in production halls, shops, or warehouses. Thereby the initial structure can be used in these types of constructions. But in the residential buildings, hospitals, nursery schools the structure with evenly spread heat is necessary.

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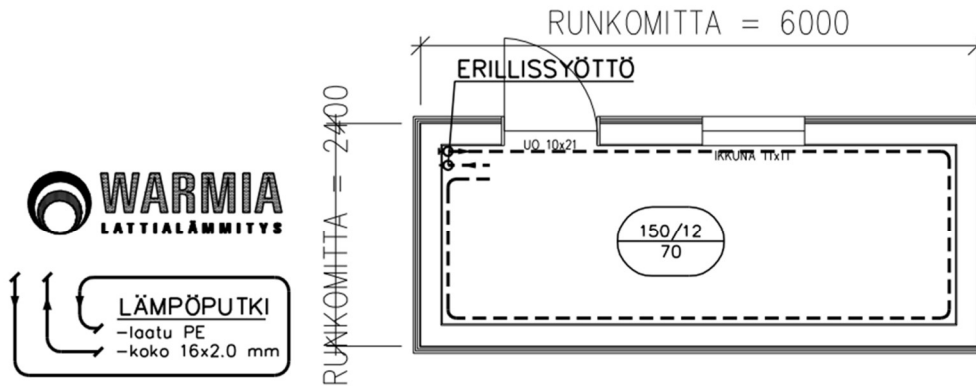
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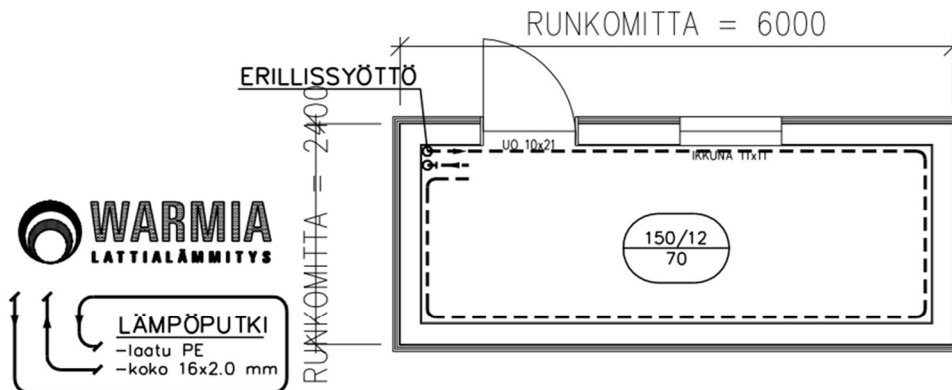
Appendix 1. Results of radiant floor heating calculation (provided by Warmia Oy)

Module №1



JT-2 Warmia WJT-1											
JT PAINEHÄVIÖ kPa	7.2										
JT VIRTAUS l/h	98										
LÄHTÖ	HUONE	kPa	l/h	ES	PUTKI	PITUUS	MENO	W/m ²	LATTIAPINTA °C	W	
1	BETONI	6.93	98	3	Warmia/16	70	39	67	30	710	

Module №2



JT-1 Warmia WJT-1											
JT PAINEHÄVIÖ kPa	9.5										
JT VIRTAUS l/h	116										
LÄHTÖ	HUONE	kPa	l/h	ES	PUTKI	PITUUS	MENO	W/m ²	LATTIAPINTA °C	W	
1	PUUPOHJA	9.23	116	3.5	Warmia/16	70	45	30	24	320	

Appendix 2. Results of carbon dioxide calculations

Module №1

SYKE Synergia building							APPENDIX 19.1	
Senaatti-Kiinteistöt								
MATERIAL EFFICIENCY AND CARBON FOOTPRINT								
Structure-specific calculations								
Type of structure:		Base floor /1						
Total area in the building:		1 m ²						
Default area (i.e. area for which the volume of each material is given):		1 m ²						
Volume of the structure, per default area (just for check, not used in calculations):		m ³						
Verbal description of the structure (give below):		check: 0 dm ³ (i.e. liters)						
In addition, attach a figure of the structural details, indicating main materials.								
Building materials and their carbon footprint								
Material <i>(Starting from outside) (See materials and their properties in Appendix 18.2. of the Instructions)</i>	Properties			Volume per default area	Weight is auto- matically calculated	Replacing If no replacing during 100 years, value is	Carbon footprint	
	Specific weight (weight per volume)	Green- house gas emissions	Carbon storage				emissions	storage
	kg/m ³	g CO ₂ -eq/kg	g CO ₂ -eq/kg	dm ³ (i.e. liters)	kg		kg CO ₂ -eq	
Steel channels	7850	1090		18,4	144,44	1	157,4396	0
Aluminium thermal profiles	2700	3640		21,2	57,24	1	208,3536	0
FinnFoam FI-300 (XPS)	19	2580		2528,9	48,0491	1	123,9667	0
FinnFoam Floor 100S (EPS)	20	3300		1198,4	23,968	1	79,0944	0
FinnFoam FI-500 (XPS)	33	2580		639	21,087	1	54,40446	0
Concrete screed	2400	140		901	2162,4	1	302,736	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
Introduce here the materials, that are easier to estimate by weight than by volume:					Weight			
Nails, fixing materials		500	0			1	0	0
						1	0	0
						1	0	0
						1	0	0
						1	0	0
					5306,9	2457,1841	925,9947	0
SUMMARY					check above			
Carbon footprint of the structure per square meter, kg CO ₂ -eq / m ²							926	0
Carbon footprint of the structure type in the building, kg CO ₂ -eq							926	0

Module №2

SYKE Synergia building							APPENDIX 19.1	
Senaatti-Kiinteistöt								
MATERIAL EFFICIENCY AND CARBON FOOTPRINT								
Structure-specific calculations								
Type of structure:		Base floor /2						
Total area in the building:		1 m ²						
Default area (i.e. area for which the volume of each material is given):		1 m ²						
Volume of the structure, per default area (just for check, not used in calculations):		m ³						
Verbal description of the structure (give below):		check: 0 dm ³ (i.e. liters)						
<i>In addition, attach a figure of the structural details, indicating main materials.</i>								
Building materials and their carbon footprint								
Material <i>(Starting from outside) (See materials and their properties in Appendix 18.2. of the Instructions)</i>	Properties			Volume per default area	Weight is auto- matically calculated	Replacing If no replacing during 100 years, value is	Carbon footprint	
	Specific weight (weight per volume)	Green- house gas emissions	Carbon storage				emissions	storage
	kg/m ³	g CO ₂ -eq/kg	g CO ₂ -eq/kg	dm ³ (i.e. liters)	kg		kg CO ₂ -eq	
LVL-beams	500	230	1600	499	249,5	1	57,385	399,2
Sawn timber	480	70	1600	68	32,64	1	2,2848	52,224
LVL-plate	500	230	1600	619	309,5	1	71,185	495,2
Plywood	450	600	1600	173	77,85	1	46,71	124,56
Wool	20	800		3456	69,12	1	55,296	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
					0	1	0	0
Introduce here the materials, that are easier to estimate by weight than by volume:					Weight			
Nails, fixing materials		500	0		3	1	1,5	0
						1	0	0
						1	0	0
						1	0	0
						1	0	0
					4815	741,61	234,3608	1071,184
SUMMARY								
Carbon footprint of the structure per square meter, kg CO ₂ -eq / m ²							234	1071
Carbon footprint of the structure type in the building, kg CO ₂ -eq							234	1071