Roof External Structural Reinforcement Strategy

For the Implementation of Multifunctional Roof Interventions on Post-War Typologies

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Abstract: The positive impact of green roofs for the users and the building performance has been demonstrated in research and practice throughout case studies from all over the world. Variations of these interventions have categorized the characteristics that will increase their performance under different climatic conditions. Not only for the building performance and aesthetics, but for the urban environment as well. For cities like Rotterdam, the increasing effect of urban environmental issues is a fact. Predictions show that they will become critical factors for the development and upgrade of urban areas in the coming years. Green roofs can play a significant role on this problematic, and their potential has been recognized by the Municipalities as well, where different initiatives and subsidies have been created to increase their rate of implementation. Nevertheless, there are still many factors restricting their implementation and causing the increase of costs of these interventions. An important one is the weight of these interventions, for which current structures are not prepared for and reinforcement strategies are required.

This research focusses on the exploration of roof reinforcement strategies for the implementation of multifunctional roofs: Interventions that combine green roofs with different functions to increase their performance for the building, their impact for the city and the benefits for the investor's interest. The city of Rotterdam is used as the context, where the vast flat-roof areas on post-war typologies create a great opportunity for the exploration of systemic solutions. Replicable strategies that will enable buildings for multifunctional interventions, increasing the roof's loadbearing capacity, and making these interventions more accessible. The research concludes with the proposal of a strategy and its evaluation on fulfilling the given objectives.

Key Words: Green Roofs, Blue-Green Roofs, Polder Roofs, Multifunctional Roofs, Roof reinforcement strategies, Rotterdam post-war typologies, Roof Renovation Strategies, Systematic renovation strategies, Computational workflows, Urban environmental mitigation.

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1. INTRODUCTION

According to the World Urbanization Prospects **[1]**, it is estimated that for the year 2050 68% of the world population will be living in cities. The incremental effects of climate change and the necessity of densification to accommodate the upgrowing population will increase the effects of Urban Environmental Problems (UEP) in cities. The Urban Heat Island effect (UHI), the air and noise pollution, flooding caused by rain showers and others, will become critical factors for the development and upgrade of urban areas. Addressing these problems will be crucial to sustain habitable urban spaces and prevent the permanent loss of biodiversity in cities.

For this, buildings will need to fulfill higher façade standards to perform better, not only for interior functions, but for the surrounding environment as well. Of course, addressing these problems through new construction will not be enough. The integration of mitigation strategies on renovation approaches for the existing building stock will be crucial to address the problem at the scale that it demands.

For this matter, literature on green roofs and multifunctional roofs was studied to understand the potential benefits they could bring for the urban environment and the constrains of their implementation on the vast amount of flat roof areas present in Dutch cities.

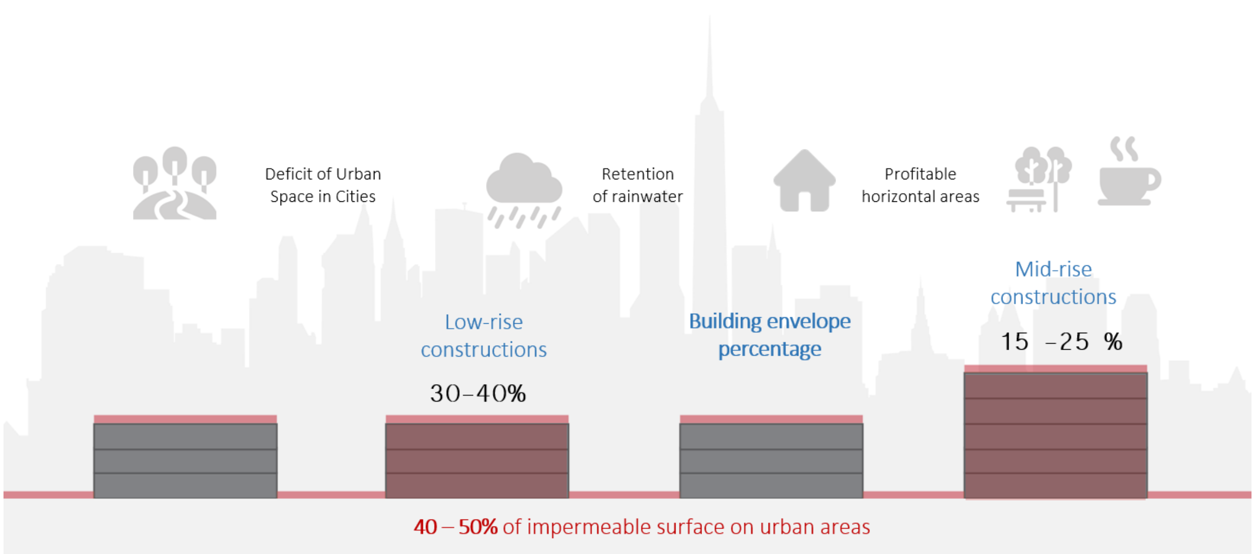


Figure 1 - Potential characteristics of roof interventions

1.1. POTENTIAL OF ROOF INTERVENTIONS

Roofs can cover 40 to 50% of the impermeable surface of urban areas **[2]**. As described in *figure 1*, these are the façades with highest radiation absorption roughout the year. They also represent a significant percentage of the total envelope area depending on the building height. For low-rise buildings, up to 30 and 40%. Due to the commonly applied materials, the thermal retention and lack of reflection can cause them to reach temperature levels above 50 °C and 60 °C and therefore, increasing indoor temperature and the external air temperature as well [3]. This has triggered the investigation on alternative materials and interventions, exploring traditional and modern options to reduce the heat absorption and storage of these surfaces and to increase their thermal and energy performance of the building. Green Roofs (GR), Cool Roofs, Blue Roofs, and Insulated Roofs [4][5][6][7][8] are the most discussed strategies applied all over the world.

Temperature accumulation, street flooding and unprofitable horizontal areas are the main problems associated to roofs, for which GR have demonstrated to be a great solution. Research and practice over the last 60 years has proven that the adequate use of green roof strategy and the proper selection of its components for the specific climatic conditions, will not only help to decrease the surface temperature and air temperature and reduce cooling and heating energy demands, but also contribute with additional valuable benefits that other roof interventions will not provide [9][10]:

- UHI mitigation: Reduction of surface temperature through evapotranspiration of plants and shading of soil surface to prevent overheating.
- Water retention and quality enhancement: Absorption and retention of rainwater to reduce the stream and prevent overflow of the sewage system during rain showers. Filtration of water to remove contaminants and reduce its temperature to prevent bacteria development.
- Increase biodiversity: Re-introduction of native vegetation species and increase of humidity levels to restore local fauna and flora biodiversity.
- Improve air quality: Reduction of air temperature, increase air humidity and absorption of dust particles and other contaminants produced by transportation and industrial pollution. Co_2 Absorption in case of implementation of medium shrubs and trees species.
- User physical and mental wellbeing: Visual and direct contact with nature to increase mental and physical health of users. It can also increase productivity and wellbeing in work environments as well.
- Additional Insulation: Increase insulation of roofs to avoid overheating in summer and temperature loss in winter.

The great potential of these interventions on the Dutch cities relies on the climatic and urban context, where consistent rains throughout the year are being retained by the vast amount of available flat roofs constructions that cause overheating of urban areas during summer. They represent a great potential for green infrastructure and additional functions in dense cities where the lack of horizontal space is already a problem. Nevertheless, their substantial increment of weight is the crucial aspect to be considered when thinking about renovation.

1.2. POTENTIAL OF ROOFS IN ROTTERDAM

The potential of roof interventions in the Netherlands for the implementation of functions and the mitigation of UEP has been recognized by Dutch authorities [11]. Due to the flat roof construction typologies developed during the Post-war period, extensive areas of flat surfaces for potential roof interventions is available today. 18.50 km^2 of flat rooftops exist in the city of Rotterdam (the highest one in the Netherlands), for which the municipality has started the Rotterdam Roofscape Development Program and similar initiatives in Amsterdam and other Dutch cities as well.

Figure 2 - Rotterdam Roofscape Development Program [11]

For Rotterdam, objectives for the year 2030 have been set to cover at least 1.00 km^2 of multifunctional rooftops (MR), contributing to the incremental use of rooftops to counteract the lack of available space in the city and improve the environmental quality for the building users and urban spaces. Today, 360 000 m^2 have already been covered, contributing to a water retention capacity of 9 million liters and a surface area of 168 000 m^2 of solar panels generating 24 GWh, enough for 7 700 households [11]. The municipality emphasizes on the potential of mixed functions for the benefit of users, investors, the city and urban environment.

1.3. PROBLEM STATEMENT

Green roof and multifunctional roof interventions are expensive additions, especially for renovation projects. They provide mainly long-term contributions that could counterbalance the implementation costs. Nevertheless, most of the substantial benefits they provide are of urban-interest more than user-interest, and therefore, less attractive for property owners and real estate investors. This is where the main drawbacks rely on.

Economic Investment: There are several factors causing the increased cost of roof interventions. For GR in particular, the factors discouraging building owners and investors to opt for these solutions are [9, 12]:

- Increased demand of maintenance.
- Risk of damage due to leakage and repairs.
- Uncertainty regarding the financial aspects and return of investment.
- Economic and trusted alternatives (with lesser or non-urban/user benefit).
- Structural capacity of the buildings.

Consultations with specialists from institutions and companies related to the field were carried out. Amsterdam Rainproof [13], Waternet [14], RESILIO [15] MetroPolder [16] and DakDokters [17]. It was pointed out that there will always be an increased investment to be financed by the investor or throughout subsidy sources like municipalities and other institutions. The only way to counterbalance the costs with the urban benefits that these systems can provide will be throughout the implementation of regulations and normative to enforce or/and reward their integration.

A SCBA (Social Cost-Benefit Analysis) tool was developed for the program "Life @ Urban Rooftops"[18], for which an overview of cost of roof interventions is given. It is possible to see a difference between interventions with and without structural reinforcement of 200 - 300 €/m^2. This aspect was discussed with the company of MetroPolder [16], emphasizing on the potential benefits that a more economic and reliable reinforcement system could bring to increase the rate of implementation of these strategies on the existing building stock.

Structural Capacity: Most of the roofs are designed to withstand the load of the roof finish layers and the eventual load of rain, snow, wind and access for maintenance or repairs. In the great majority of cases, the incremented weight of GR and MR can normally be withstood by the vertical structure and foundations. The problem relies on the roof horizontal structure, where the incremented weight will require its reinforcement.

Heavier variations of GR will substantially increase the benefits they can bring for the urban environment, especially for the denser urban areas in cities. Moreover, the implementation of MR interventions provides a great opportunity for areas where horizontal space is scarce already, but this will imply higher load demands as well.

This causes an additional subsequent problem, where the increased costs of reinforcement systems for such heavier solutions causes investors to opt for other economic and generic solutions that won't require investments on the structure. Although some of these options include lighter GR systems, these solutions won't take advantage of the full potential that heavier interventions could bring for the urban environment, specially in the most critical areas of urban centers. This is a situations identified as non-regret solutions [12]. Disabling the potential of highly economically and environmentally profitable areas due to insufficient investment capacity.

Approach: On this manner, the focus was set on structural solutions that could enable the potential of these highly profitable areas through more accessible and reliable interventions.

First, understanding the requirements and variables of GR and MR interventions. Their categorization, requirements, and their potential benefit of all end beneficiaries. Secondly, as stated by the municipality, focusing on the great opportunity unveiled for the large groups of Post-War Typologies [11]. Systemic constructions that created a vast amount of flat roof surfaces present today in the largest cities of the Netherlands like Rotterdam. Understanding the characteristics, requirements, and target capacities of this buildings to find feasible and accessible reinforcement alternatives.

2. RESEARCH FRAMEWORK

To follow on the given problem statement and considerations, the development of alternative reinforcement solutions will require the understanding of two main topics, which were set as the structure of this research.

- **The intervention requirements:** Understanding the variety of GR interventions and their integration with compatible functions for the creation of sustainable MR. Understanding how the different components influence on the overall weight and performance of the interventions, and what additional compatible uses and functions could lead to more beneficial interventions.
- **The building requirements:** Identifying the characteristics of the building and its structure that will determine the possibilities and limits of an intervention. First, the selection of a relevant construction typology that could allow to increase the reach of the proposal. Secondly, understanding of the structure and building characteristics that could restrict the design approaches to reinforce its horizontal loadbearing capacity. Thirdly, Understanding the factors increasing the costs of current reinforcement systems.

These will result in the considerations, the limits, and the opportunities to guide the exploration on alternative reinforcement systems, to then finalize with a design proposal.

2.1. RESEARCH QUESTIONS

For this matter, the following research question and sub-questions are stated:

How to enable and potentiate the implementation of Multifunctional Roof Systems on post-war typologies with reduced loadbearing capacities?

- *What are the main parameters to obtain a satisfying performance for the user, the building, and the urban level?*
- *Are there factors that could be optimized to reduce the structural demand of the system without losing performance?*
- *What are the building parameters to determine the limits of the intervention?*
- *What are the main factors increasing the costs and difficultness of current reinforcement methods?*
- *What alternative systems could be applied to reinforce the roof structure?*

2.2. RESEARCH OBJECTIVES

As stated before, the research will be structured in the 3 following chapters:

The System Scale:

- Analyzing the components of a MR to determine the factors influencing its structural demand and performance.
- Investigate how these factors effect on the desired benefits at an urban, building and user level.
- Overview of projects and products to determine the loads that can be expected.
- Analyzing possible solutions that could reduce the weight of the intervention.

The Building Scale:

- Selecting a representative sample of Rotterdam's Post-War typologies to potentiate the reach of application of the outcome.
- Understanding the building loadbearing performance according to its design and the norms that were used to determine their minimum capacity requirements.
- Overview of current reinforcement systems to determine the factors increasing the cost of implementation.
- Identify the building parameters to be considered for the development of alternative reinforcement strategies.

Design Exploration:

- Elaborate on possible strategies that could increase the roof loadbearing capacity.
- Proposing strategies and tools to create an adaptable and replicable solution for the buildings of the selected sample group.
- Elaborate on the selected strategy.
- Discussion of outcome and results.

2.3. RESEARCH STRUCTURE AND METHODOLOGY

The research structure, objectives and research questions are structured in the three previously described chapters. An evaluation of the findings and outcomes of every chapter will be given after every chapter, summarizing the conclusions and aspects to consider for the design phase and answering the research sub-questions as well.

- The System Scale: Green roofs (GR), Blue roofs (BR), and Multifunctional roofs (MR). Components, weight, and performance.

Research methodology: Research through papers and publications on GR, BR and MR interventions was the main source of information to understand the performance of these interventions for the different beneficiaries: Users, Building Owners and Urban Scale. Information from providers and information obtained by the consulted companies and selected case studies were the source of information for the understanding of the system requirements and component characteristics.

- The Building Scale: Selected building typologies, structural systems, construction considerations, roof structural capacity, building structural limit.

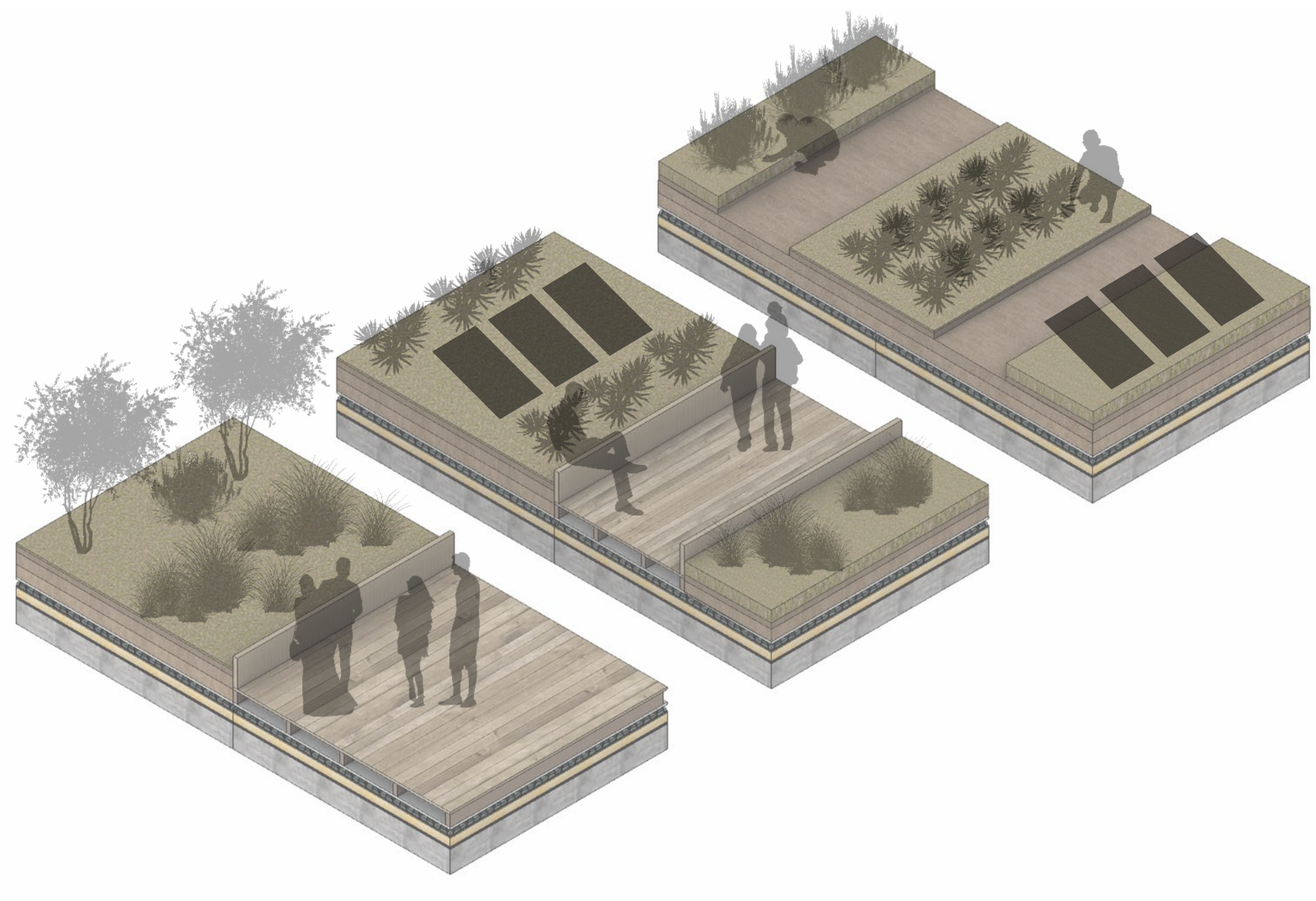
Research methodology: For this chapter, documentation on post-war construction was researched. Drawings from the selected case studies were consulted at the Municipality Archive in Rotterdam. Through the information obtained on interviews and publications of case studies, information on roof reinforcement strategies was gathered. Normative documents were also consulted, to understand the current norms for roof capacities. Additionally, papers and publications on comparative analysis between current and past construction norms were found, to evaluate the effect that changes could bring for current post-war structures.

- Design Exploration: Implementation of the obtained information for the determination of possible design strategies. Evaluation and elaboration of a final design approach. Finalizing with a discussion of the findings, conclusions, and possible aspects to consider for future research and further steps.

Methodology: Databases of information were consulted to obtain the relevant material properties and values for the testing and design process. Information of relevant products available in the market was consulted as well. The software for 3d modeling and parametric modeling of Rhinoceros, Grasshopper will be used. Karamba 3-D, FEA software will be used for the structural calculations in connection with Rhinoceros and Grasshopper.

3. SYSTEM SCALE

On this chapter the different categories of Green Roofs (GR), Blue-Green Roofs (BGR) and Multifunctional Roofs (MR) will be analyzed. The objective is to define the benefits of most interest for the different end users and relate those benefits to the components or layers of most influence on their performance. Doing so, understand which components and layers should be prioritized and the possible combinations that can be achieved. Moreover, by analyzing products from different providers and design examples, identify possible strategies that could allow to reduce the structural demand of these interventions without reducing their performance.



3.1. GREEN ROOFS

Green roofs are characterized by the vegetated layer that covers the surface, protecting It from the sun, allowing to cool down the surface and the air and serving as an additional insulation barrier for the roof. These systems have been used for thousands of years in vernacular architecture as insulation barriers and to protect roofs from climatic conditions. Overtime, this strategy has been updated for its use in modern buildings and has been studied for the past 60 years due to its potential as a UHI mitigation strategy, reduction of energy consumption and improver of the urban environmental quality of cities.

Germany, as the oldest and main research contributor on Green Roof building and urban environmental benefits, also has the largest application rate of this strategy, covering 10% of the roof building stock and increasing 13.5 million m2 per year **[9]**. Their benefits have been demonstrated through practice and research, which have triggered its application on multiple countries around the globe. For some countries like the USA, Canada, Germany and Japan, the use of green roofs is mandatory for new building above a certain surface area of rooftop, public infrastructure, and other conditions. In other countries, like the Netherlands, China and South Korea, its implementation is encouraged by governments through subsidies or tax and levies relief **[9]**.

	Extensive Green Roof	Semi Intensive Green Roof	Intensive Green Roof
Maintenance	Low	Periodically	High
Irrigation	No	Periodically	Regularly
Plant communities	Moss-Sedum-Herbs and Grasses	Grass-Herbs and Shrubs	Lawn or Perennials, Shrubs and Trees
System build-up height	60 - 200 mm	120 - 250 mm	150 - 400 mm on underground garages > 1000 mm
Weight	60 - 150 kg/m^2	120 - 200 kg/m^2	180 - 500 kg/m^2
Costs	Low	Middle	High
Use	Ecological protection layer	Designed Green Roof	Park like garden

Figure 3 - The impact of greening systems on building energy performance: A literature review. Raji, B., Tenpierik, M., & Dobbelsteen, A.V. (2015). Renewable & Sustainable Energy Reviews. 45*. 610-623.*

Green roofs are generally categorized into 3 different groups. The parameters for its categorization can variate in different research papers and different providers of these systems. The two components responsible for the main variations between categories are:

- **Vegetative layer:** Selected vegetation species for the targeted urban benefits
- **Substrate Layer:** Required depth of soil for the selected plant species.

Figure 4 - Extensive, Semi-Intensive and Intensive Green Roofs

Extensive systems range between 50 and 100 mm of soil depth. This allows only certain types of vegetation to grow. The most common species groups are sedum, mosses and lichens. These surfaces are usually only accessible for maintenance and inspection. The maintenance level of these systems is the lowest of all three. Their weight can range between 90 to 120 kg/m2.

Semi-Intensive systems range between 100 to 250 mm of soil depth. In this case, additional groups of vegetation are also available. Mixed varieties of low and mid perennials, grasses, bulbs and annuals, wildflowers and dared sub-shrubs. These systems are mostly non accessible as well, but because of the vegetation they demand more maintenance and irrigation. Their weight can range between 150 to 200 kg/m2.

Intensive Systems are green roofs above 250 mm of soil depth. They can reach depths of 1000 mm and more, depending on the plant species to be implemented. The vegetation types are widely variated. Small tree species are also available. These systems are meant to be used as gardens and parks in case of public rooftops. Moreover, the amount of water absorption of the soils will substantially increase the weight of the system. These interventions are above 200 kg/m2 and can go above 600 kg/m2 as well.

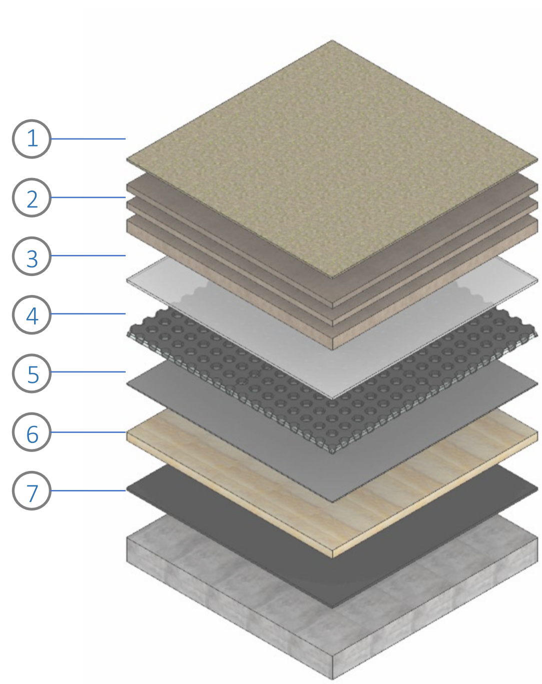
3.2. GREEN ROOF COMPONENTS

Fig 4 shows the standard configuration of a green roof. The components will variate depending on the type of vegetation and substrate type and thickness to be used.

The layers will be described from bottom to top according to *fig 5*, giving an overview of the main considerations and weight of all components.

Waterproofing Layer

The waterproofing layer is the most important layer to increase the lifespan of the roof intervention. It is present in all roof interventions to prevent any leakages to the main structure. Above this layer, an additional root barrier protection layer is installed to avoid any piercing that the vegetation layer could cause, especially for intensive interventions with long and strong root species. The most common options for the impermeabilization are the bitumen sheets (as the example shown in *fig 5*, liquid applied membranes, polymer cement and thermoplastic membranes.



1 Vegetation Layer **2** Substrate Layer **3** Filtration Layer **4** Drainage Layer **5** Root Barrier **6** Insulation Layer **7** Waterproof Barrier

Figure 5 - Green Roof system: Standard configuration of layers

This is also the less sustainable layer of a green roof intervention, for which its protection and proper installation is crucial to avoid replacement and make it as durable as possible.

Insulation Layer

Part of the benefits of a green roof is the increase of insulation to prevent thermal gains through high surface temperatures in summer and to prevent thermal loss through the roof in winter. Many variables acting on this property has made its effect unquantifiable until today. Although the effect is there, it will not add an additional R value to the roof performance for design approval of the building thermal performance. This has led to add an additional layer of insulation on roofs, which is mostly combined with the waterproof barrier and the root barrier to act as an additional protection of the waterproof barrier.

To avoid any leakage due to condensation of air moisture on the insulation layer, a vapor barrier is normally installed as well to prevent ant water content to access the building. An example of waterproof layering recommended for green roofs is show by the company Radmat (*fig 5*). In this case, The PIR (Polyisocyanurate) blocks are installed on top of a primer coating and the aluminum vapor barrier film.

Drainage Layer

The purpose of the drainage layer is to allow the waterflow underneath the substrate layer to drain the water and avoid any weight accumulation that could represent a risk for the structure or excess of humidity for the above plant species. This layer is also used to further protect the waterproof barrier. There are two types of drainage systems, shown in *fig 6*:

Granular Materials, like gravels, expanded clay aggregates, crushed bricks and others, which create porous spaces to ensure the waterflow.

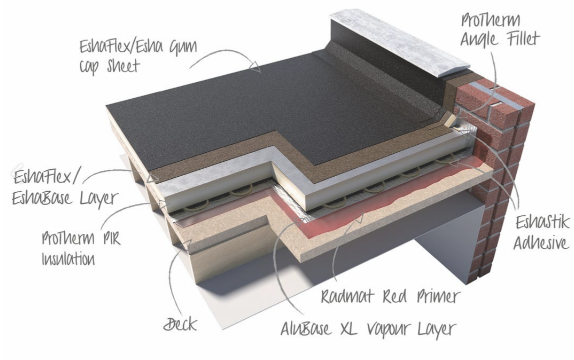


Figure 6 - Radmat - Detailing of roof insulation + waterproof solution. Source: https://radmat.com/products/permaquik/

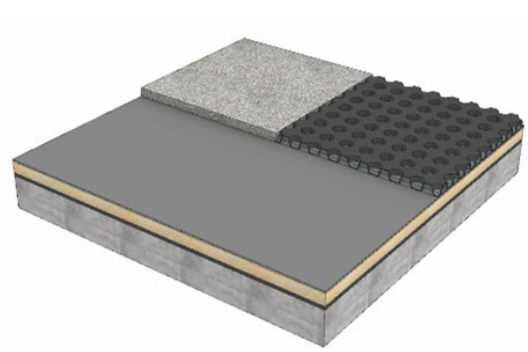


Figure 7 - Drainage Layers, modular buffer units or gravel layer

Figure 8 - Permavoid - Box Buffer system. Source: http://www.permavoid.co.uk/products/

Modular Panels from plastics, that create hollow box spaces easier to control/calculate and permit the waterflow with the desired height.

The cost and disposal of these elements are two factors to consider. Although providers of these box systems like Permaviod (*Figure 8*) show that the boxes are made from 100% recycled material and recyclable material after use, it adds cost and non-desirable materials to the intervention.

The additional temporary water content that these components can cause needs to be considered as well.

Filtration Layer

The task of the filtration layer, shown in figure 9, is to prevent the particulate matter of the soil and plant debris to clogging the system. Geotextiles are the commonly used layers for this component, which provides a textile strength against piercing and high permeability to fulfill this function without the need of replacement. Again, this is an additional layer that contribute as part of the root barrier to protect the waterproof system.

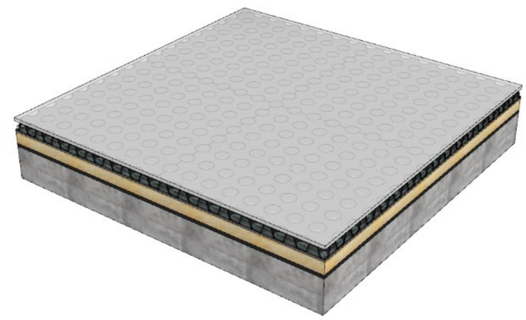


Figure 9 - Filtration Layer - Base Layer configuration for all interventions

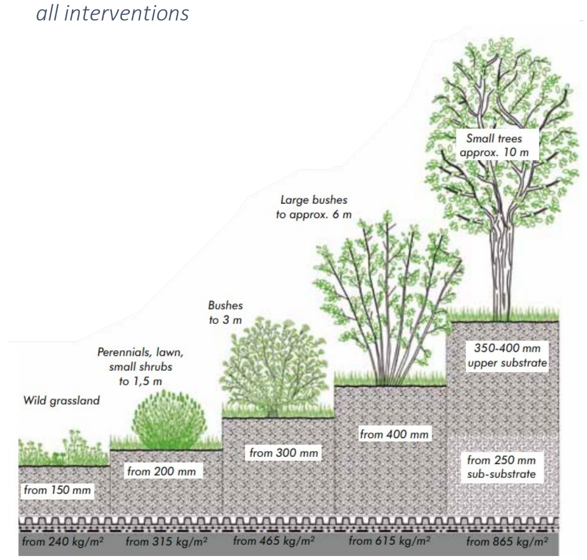


Figure 10 - Drainage, Filtration, Substrate and Vegetative layers

Substrate Layer

The substrate layer is the most important layer for the optimal performance of the vegetation layer. It provides the greatest number of benefits of a green roof intervention, as it takes part in the insulation, water retention, water quality and quantity and evaporation process. This layer is composed by organic and inorganic materials. The proportion between both is crucial to reduce the required amount of maintenance and elongate the health and lifespan of the plants. A presence of 80% of inorganic material is recommended. Specifically, 4 to 8% of organic for extensive systems and 6 to 12% for intensive systems.

As mentioned before, one of the main parameters is the water storage capacity of the soil, which will be dictated by the substrate thickness and density. Additional use of additives like biochar is also common to enlarge the water retention and purification process.

Reaching all the ideal properties of the substrate layer is a very hard but significant balance that will influence on the performance and cost of the intervention. Ideally, locally available compositions to support local and native plant species. A high-water retention capacity, aeration and flow properties and stability under wet and dry conditions. For Intensive Green Roof Systems, there are two layers of substrate. The Base layer and the surface layer.

Vegetative Layer

The vegetation layer is the main actor for the heat transfer coefficient to reduce the surface temperature and therefore the air temperature. The main vegetation characteristics for these effects are:

- Leaf Area Index (LAI): Shadow index of the surface based on the size of the leaves and the density of the foliage.
- Plant Height: Height of the foliage layer. This, in relation with the LAI coefficient, will dictate the fractional coverage of the surface.
- Fractional Coverage: Shadow coefficient of the roof surface and total % coverage based on the intervention dimensions.
- Albedo coefficient: Reflectivity coefficient of the plant leaves to reduce radiation absorption.
- Stomata resistance > Rate of evapotranspiration: Based on the size and internal structure of the leaves, the temperature and radiation conditions at which the process of evapotranspiration starts.

Moreover, this layer is very influential on the water run-off quantity and quality and the only layer responsible for the air quality improvement. This is also the main layer responsible for the increment of biodiversity on the system. The use of variated native species is crucial for this. The more similar to the existing ecosystem, the better the overall performance and health of the system. The better the plants health, the better their performance and the less the maintenance costs of the GR intervention. For this, the appropriate plant selection is required by considering the following aspects:

- Geographical Location – Climatic conditions: Humidity, Wind, Radiation.
- Solar Exposure (Considering urban context)
- Rain Intensity – Water availability (Natural and Artificial).

Waterproof and Insulation Layers	
Component	Weight loading (kg/m^2)
Base coating	0.05
Vapor Barrier	0.05
Insulation – 30 to 150 mm	2.00 – 5.00
Root Barrier	4.00 - 5.00
Waterproofing Layer	4.00 - 5.00
Drainage Layer	
Component	Weight loading (kg/m2)
No Retention / 10 to 30 mm	0.75 - 2.50
Water Content X 10 mm	10.00
Filtration Layer	
Component	Weight loading (kg/m2)
Filter	0.10
Protective Layer and Filter	0.30 + 2.00 to 1.20 + 7.00 (Water)
Vapor-Open Filtration	0.12
Filter and Capillary	0.50 + 4.00 (Water)
Saturated Substrate Layer	
Substrate X 1 cm	Weight loading (kg/m2)
Light	12.60
Heavy	17.00
Under Substrate	Weight loading (kg/m2)
Light	12.50
Heavy	18.00
Vegetation Layer	
Green roof vegetation type	Weight loading (kg/m2)
Extensive	5.00 - 12.00
Semi – Intensive	5.00 – 30.00
Intensive	5.00 – 150.00

Table 1- Weight overview of Green Roof Components

3.3. BLUE-GREEN ROOFS

Blue-Green roof systems (BGR) are the combination of vegetated roofs, either extensive or intensive systems, with the additional function of water retention. As mentioned before, extensive and intensive GR also contributes as a water retention mechanism by the absorption of water through the plants and the growing medium, but BGR interventions have an additional water storage layer that increments the storage capacity. This quality will be favorable for the city as a rainwater micromanagement system that, if applied at a large scale, can have a huge impact on reducing and improving the rainwater flux to the sewage system to prevent saturation during heavy rains.

An example is the city of Rotterdam, where the combination of 360 000 m^2 of Green and Blue-Green roofs are capable of absorbing 9 million liters of rainwater **[11]**. Moreover, the retained water can be used by the plants to reduce irrigation requirements. The addition of cylindrical fiber membrane cones on the storage systems allows the soil to absorb the water through capillarity again whenever required to feed the plants (*figure 12*). The plants will also eliminate the water through evapotranspiration instead of draining it, increasing air humidity, and absorbing heat by doing so which is substantially beneficial in summer conditions. By maintaining the plants and growing medium humid, the system provides a more natural ecosystem, favorable to the increase of biodiversity, especially whenever applied with an intensive system **[19]**.

Multiple systems have been developed for this application. This system has been implemented not only on roof structures, but also in different infrastructure like parks, roads, and many other examples that allow to retain the rainwater momentarily to prevent street flooding due to sewage saturation under heavy rains.

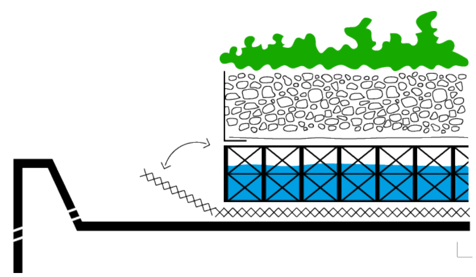


Figure 11 - Polder Roof System - DakDokters [16]

Polder Roofs System

A State-of-the-art solution on Blue-Green roof systems are the Polder Roofs. Working with the same concept of water retention, the implementation of a digital system improves the performance of this strategy. The roof is responding to the climate forecast to know when to drain water in case the capacity has been reached and when to retain the water to prevent saturation of the drainage system during heavy rains (*figure 11*). Moreover, being able to maintain a constant water storage for the vegetation on top. Two of the main companies working with the system are MetroPolder and DakDokters [16, 17].

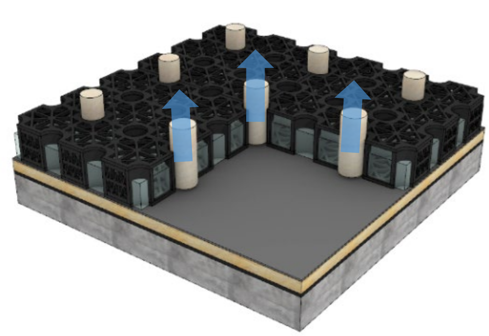


Figure 12 - Box system with Capillary cones for passive irrigation

3.4. MULTIFUNCTIONAL ROOFS

According to the Municipality of Rotterdam and the Program for multifunctional rooftops **[11]**, the combination of a blue and green function is already categorized as a multifunctional roof. Nevertheless, these combinations can be even more fruitful for roof interventions if further layers are considered.

Making a roof accessible will substantially increase the weight of the system, but it creates additional usable space that is highly valuable especially in urban areas where the lack of horizontal spaces is already an issue. The occupancy of these roof spaces is show in *figure 13*, categorized in 3 conditions:

No occupancy: In case the building is not capable of carrying the additional weight of functions, and the maximization of functional characteristics will be the objective.

Low Occupancy: In case the rooftop will be available for the private use of the neighbors. Functions like small terraces, spaces for urban farming, gardening viewport balconies and transit areas.

High Occupancy: In case the rooftop will be used for **private functions**, living spaces, terraces and playgrounds for the users in addition to the previously mentioned functions could be possible. In case the rooftop will be used for **public functions**, cafes and restaurants would also be possible and beneficial for buildings that can withstand the added weight of such an intervention.

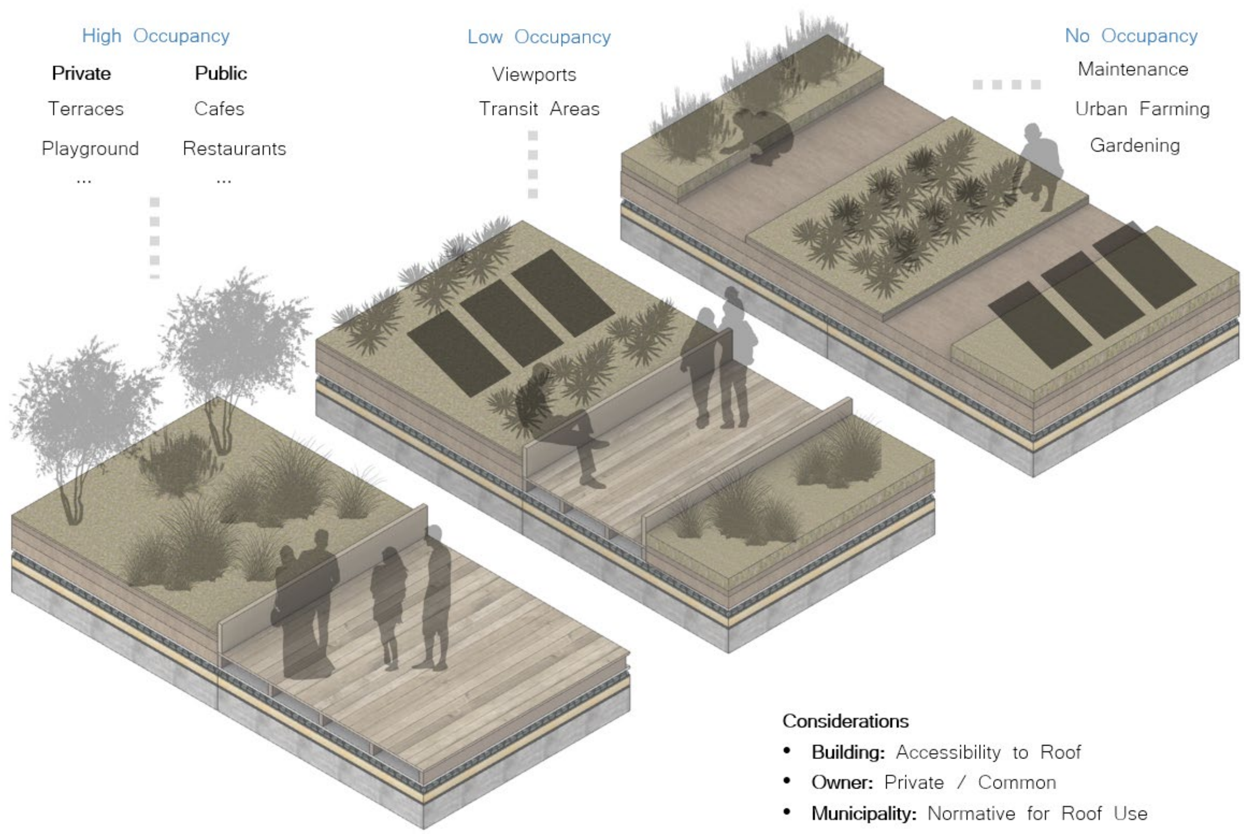


Figure 13 - Multifunctional roofs - Design scenarios of accessible rooftops

Company	Optigroen									
Name	Economic Roof	Lightweight Roof	Natural Roof	Meander FKM 30	Meander FKM 60	Drossel Extensive	Drossel Intensive	Garden Roof	Roof Park	Solar Green Roof
Category	Extensive	Extensive	Extensive	Extensive	Extensive	Semi-Intensive	Intensive	Intensive	Intensive	Semi-Intensive
Blue Integration	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Accessible / Functional	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	-	-	-	-	-	Low	High	High	High	Low
Vegetation Type	Pre-Cultivated Sedum-Moss	Pre-Cultivated Sedum-Moss	Herbs - Grasses - Sedum	Sedum	Sedum - Herbs - Grasses	Sedum - Herbs - Grasses	Perennials - Shrubs - Lawn	Perennial - Shrubs - Trees - Lawn	Perennials - Shrubs - Trees	Sedum
Depth (mm)	80	50	100 - 280	90	120	140	300 - 350	≥ 260	420 - 1000	≥ 140
Substrate Layer (mm)	60	30	60 - 250	60	60	60	≥ 200	230-400	250 - 400	≥ 60
Drainage Layer (mm)	25	25	40	30	60	80	85 - 150	60	60	85 - 150
Retention Capacity (L/m2)	25	18	30 - 80	30 (+ ≤ 20)	32 (+ ≤ 50)	75 (+ ≤ 70)	80 (+ ≤ 140)	100 - 160	180 - 320	95-150 (+ ≤ 140)
Dry Weight (Kg/m2)	45	27.5	≥ 54	54	66	60	186	192	≥ 360	72
Saturated Weight (Kg/m2)	90	55	≥ 90	90	110	100	310	320	≥ 600	≥ 120
Saturated Weight + Retention (Kg/m2)	90	55	≥ 90	110	160	170	450	350	≥ 650	360

Table 4 - Product overview – Optigroen: https://www.optigruen.nl/

Company	ZinCo							
Name	Rockery Type Plants	Irrigated Extensive Green Roof	Urban Climate Roof	Sedum Carpet	Urban Rofftop Farming	Heather with Lavander	Roof Garden +	Roof Garden
Category	Extensive	Extensive	Extensive	Extensive	Intensive	Semi - Intensive	Intensive	Intensive
Blue Integration	No	No	No	Yes	Yes	Yes	Yes	No
Accessible / Functional	No	No	No	No	No	Yes	Yes	Yes
	-	-	-	-	High	Low	High	High
Vegetation Type	Sedum, Herbs	Sedum, Herbs	Sedum, Herbs	Sedum	Fruits - Vegetables	Perenials - Grasses - Low Shrubs	Lawn - Perenial - Shrubs - Small Trees	Lawn - Perenial - Shrubs - Small Trees
Depth (mm)	100	≥120	≥140	150	≥250	≥140	150	≥270
Substrate Layer (mm)	≥80	≥80	≥100	≥60	200 - 400	≥100	100 - 150	≥200
Drainage Layer (mm)	10	40	40	30 + 60	60	40	50	≥70
Retention Capacity (L/m2)	36	42	51	80	100	60	60	136
Dry Weight (Kg/m2)	55	100	100	72	200	100 - 153	120 - 144	≥230
Saturated Weight (Kg/m2)	110	130	155	90	300	150 - 225	210	≥330
Saturated Weight + Retention (Kg/m2)	≥100	130	155	152	300	236	235	≥370

Table 3 - Product overview – ZinCo: https://zinco.nl/

Company	DakDokters				
Name	Basic Green Roof	Biodiverse Roof	Shade Roof	Landscape Roof	Roof Garden
Category	Extensive	Extensive	Extensive	Semi - Intensive	Intensive
Blue Integration	Yes	Yes	Yes	Yes	Yes
Accessible / Functional	No	No	No	No	Yes
	-	-	-	-	High
Vegetation Type	Sedum	Sedum - Herbs - Grasses	Shade Plants - Herbs	Sedum - Grasses - Flowers - Herbs - Small Shrubs	Lawn - Perenial - Shrubs - Small Trees
Depth (mm)	90 - 200	120 - 240	120 - 240	200 - 280	≥ 300
Substrate Layer (mm)	≥ 50	≥80	≥80	≥130	≥ 250
Drainage Layer (mm)	50 - 150	50 - 150	50 - 150	50 - 150	50 - 150
Retention Capacity (L/m2)	32 - 150	40 - 150	40 - 150	70 - 150	≥ 70
Dry Weight (Kg/m2)	≥ 50	≥ 50	≥ 50	≥ 50	≥ 50
Saturated Weight (Kg/m2)	60 - 90	120	120	200	≥ 200
Saturated Weight + Retention (Kg/m2)	120 - 240	160 - 280	160 - 280	270 - 350	≥ 250

Table 2 - Product overview – DakDokters: https://dakdokters.nl/en/

3.5. PROVIDERS SAMPLES

As seen in tables 2, 3 and 4, different systems from different providers in the market were analyzed to have an estimate of their average weights. The samples were collected from two of the biggest companies specialized on GR systems in the Netherlands, Optigroen and ZinCo, and one of the main developers of the Polder Roof System for BGR, DakDokters.

The products of all three companies are categorized in Extensive, Semi–Intensive and Intensive systems. They were compared by the configuration of their components and their weight. The weight was differentiated between normal weight and saturated weight of the systems and the weight of the retention system (if available) was specified separately as well.

Detail compatibility

It was possible to see that, although the names and characteristics of the products variate between providers, the configuration and the function of every system is in practice the same. This situation is noticeable on the drainage and retention layers, where the different designs variate substantially in size, compressive strength, weight, capacity, and flow. They all fulfill the same function: Creating an empty space between the substrate layer and the drainage system to accumulate water.

The layering and components of the system is a very established construction that has proof to function optimally in the many existing design examples. Any reinforcement strategy to be implemented should allow replicating the detailing or modify it only if components can be removed or obviated. Creating specific custom components would imply making the system incompatible with all the existing products, which is not ideal when the objective is to upscale their implementation.

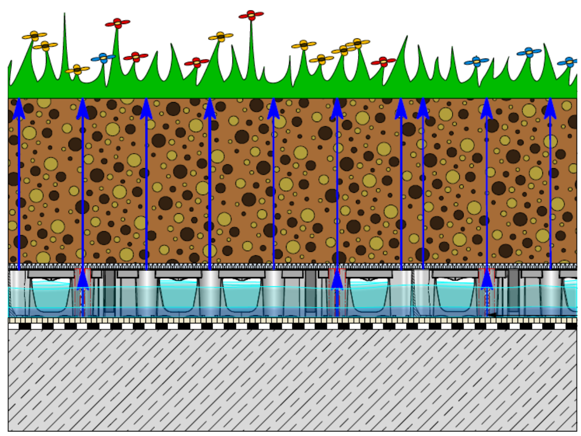


Figure 14 - Optigroen, Intensive system detail. Source: https://www.optigruen.com/system-solutions/landscape-roof/system-build-up/

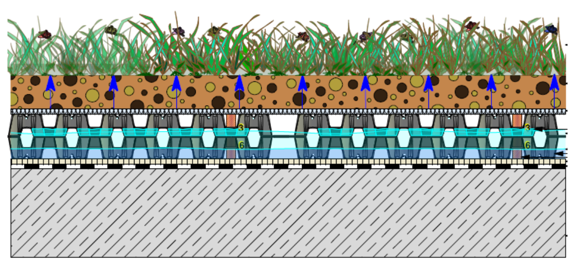


Figure 15 - Optigroen - Extensive system detail. Source: https://www.optigruen.com/system-solutions/lightweight-roof/system-build-up/

Combination of functions

For Intensive roofs, the category of garden roofs, park roofs or landscape roofs is categorized as the heaviest intervention. These are the closest options to natural parks.

Although these options are viable and very valuable for the users, the combinations of loads need to be considered. Not only the weight of the roof and the water content will be accounted for, but the weight of a public and open function on top as well. This will not only increase the load of the intervention, but also create the areas of the highest maintenance demand to preserve the green areas. In the case of Optrigrun, it is shown that the weight of the Landscape roof can reach up to 600 kg/m^2 (Figure 16). ZinCo shows the option for “Urban Rooftop Farming” as well, in which an estimate of 300 kg/m^2 is given.

In most of the interventions it is possible to see that accessible areas and vegetated areas are separated to avoid accumulation of loads and to decrease the maintenance requirements that accessible grass areas will imply. Maintenance is one of the main discouraging factors of GR interventions, making this logic valid. Satisfying the load requirements might be possible, but these approaches would be more feasible for structures that are designed for this capacity from start and integrated to public areas to exploit their public use, like the Dak Park in Rotterdam (figure 18).

Figure 16 - Optigrun - LVM MÜNSTER Project. Source: https://www.optigruen.com/references/landscape-roof/project-lr-1/

Figure 17 - Dakpark Rotterdam. Image from Google maps. Source: https://www.dakparkrotterdam.nl/

Figure 18 - Urban Farming – DakAkker Rotterdam. Source: https://dakakker.nl/site/

3.6. DETAILS AND CASE STUDIES

A set of standard detail drawings for the Polder-Roof System were provided by the company MetroPolder (figure 19). These details were used to determine the compatibility requirements and surface characteristics that any reinforcement strategy would need to provide for these strategies. Full details will be added in (Annex A).

Maximum Deflection: The drainage system and the slope of the roof should be capable of draining the whole water storage volume, considering the content that might remain due to the surface deflection.

Installation of Horizontal Partitions and Supports for accessible Areas: Providing a continuous leveled surface with available connections for the correspondent contention structures of the vegetated areas and supports for the transit surfaces of functional areas.

Accessibility to the Waterproof Barrier: All layers above the Waterproof barrier should provide removable components to facilitate inspections and repairs that may be needed. Ideally, no fixed components that could hinder the process.

Ballast on edges due to wind uplift forces: Any lose or light component near or inside areas of high uplift forces should have ballast loads to prevent any damages. For example, Box drainage systems.

Drainage system clearance: Either if the drainage system is in the middle of the slab or on the edges (Most common case), there should be clearance to allow an uninterrupted flow of the water drained by the system in case the maximum capacity is reached or during heavy rainstorms.

Irrigation through Capillarity: The distance between the Substrate layer and the water buffer layer should be as short as possible to allow the maximum absorption of water.

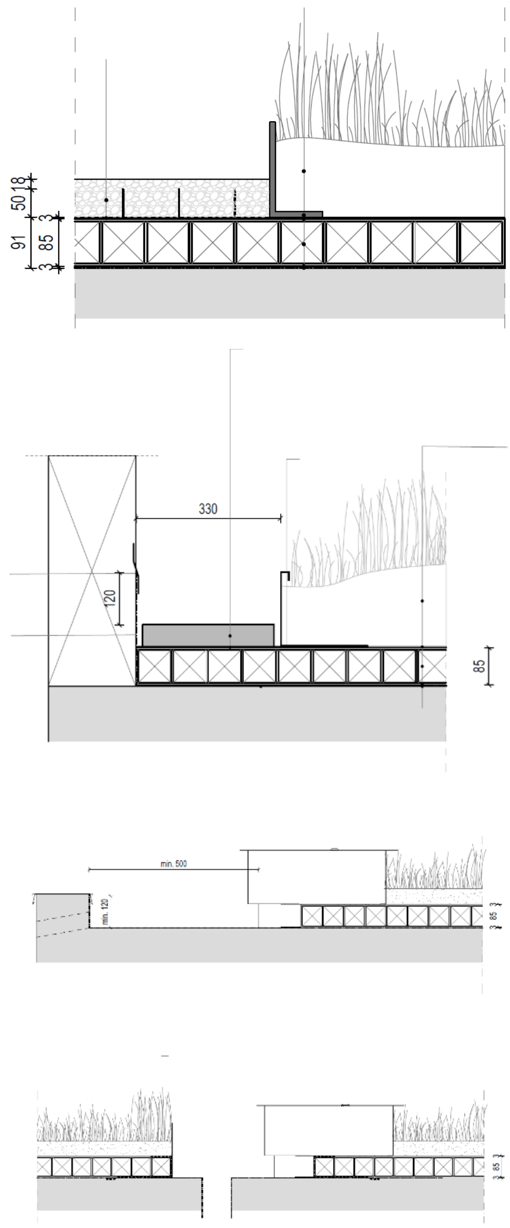


Figure 19 - Basic Polder Roof Details - Provided by MetroPolder [17]

These are two examples of the most relevant projects in which this system was implemented. The examples are two semi-intensive interventions. Both projects have the Polder-Roof System installed and one is accessible for the users of the building. The data of the projects and images were taken from MetroPolder Website.

Roof Garden Alphatoren

Client: Vesteda
Location: Leiden
Surface water collection: 400m^2
Water: 30 000 liters
Dynamically controlled: yes

The intervention consists of a Semi-Intensive System for an apartment complex building that does not require an irrigation system. All the water for the vegetation species is obtained from the water buffer layer provided by the polder roof system.

Figure 20 - Roof Garden Alphatoren - MetroPolder. Source: https://metropolder.com/projecten/roof-garden-alphatoren/

Smartroof 2.0

Client: Waternet
Location: Marineterrein, Amsterdam
Surface water collection: 350 m2
Water storage: 25,000 liters
Dynamically controlled: yes

The project was developed as a lab to conduct research on the evaporative effect of blue-green roofs on biodiversity and surface cooling under the effect of different substrate thickness and water buffering configurations. The air conditioning units were not required during the summer in which the project was installed.

Figure 21 - Smartroof 2.0 - MetroPolder. Source: https://metropolder.com/projecten/smartroof-2-0-2/

3.7. GREEN ROOF BENEFITS

Surface Temperature Cooling – UHI Mitigation

Green roofs can reduce the temperature of roofs by shading it with vegetation, transforming this energy in vapor and cooling themselves by convection. This is called Evapotranspiration, a natural process in which plants use energy to evaporate droplets through the leaves during photosynthesis [20]. This condition depends on many factors. The stomata resistance of the plant species (transpiration rate), the Leaf Area Index (LAI) of the plant, the height of the plant and the amount of constant exposure to radiation (overshading can substantially reduce the plant performance) [21]. The substrate layer can also contribute to the process by evaporating water content on the soil through radiation. This means that the more water available for plants and substrate, the better the performance will be [9].

Moreover, the albedo coefficient of plants (Reflective coefficient of irradiation to bounce back energy to prevent accumulation, where 1 is the maximum and 0 the minimum) is higher than most used roof materials. Investigation regarding the reduction of surface temperature by the comparison of results between Green Roofs and Cool Roofs [21] showed that the performance of green roofs will be closely effective to cool paints of average potential (r=0.66) but lower than cool paints of high performance (r=0.8). Other research points that typical vegetation for roof intervention ranges between 07 and 0.85, higher than other solutions. Moreover, the refraction of energy is diffuse reflection that will not cause affection to the surrounding buildings [9]. The influence of the type of vegetation will also influence on the accumulation of hot air on top of the roof, as the plants can influence the sky view factor of the roof at a lower scale, creating a partial increase of thermal retention in comparison to sedum-based plants [7].

Green roofs can reduce surface temperatures by 30 to 60 °C [9]. Research showed Their effect on heat fluxes released to the microclimate resulted in a reduction of 42 to 75% depending on the climatic context [3]. A 20-year survey of a green roof in the University of Applied Sciences of Neubrandenburg, showed an increase of the average temperature of 1.5 K on the area due to UHI, where temperature of the green roof did not follow the trend and remained 1.5 K cooler than surrounding roofs of gravel solutions [6]. Moreover, research showed that a probabilistic approach of increasing 10% of green areas in the UK could prevent 4 K overheat in the next 80 years [21].

Water Retention

The use of green roofs and Blue-Green roofs has demonstrated to be the best water management practice at a building scale [2]. Especially for climatic conditions of constant rains during the year, green roofs have demonstrated to be the best contributors to mitigate the reduction of permeable surface in cities [21]. The water retention capacity will mainly depend on the composition and thickness of the substrate in the system. The Bio/Synthetic composition, density, porosity, and saturation capacity [21]. The vegetation layer will have a smaller influence. Mainly in the retention capacity and evapotranspiration rate to release water as well [22].

Data provided by STOWA [23] shows that the behaviour of green roofs is ideal for medium showers, but not as effective for heavy showers, where the saturation capacity is filled and the release of water towards the sewage system is the same as in a normal roof. Nevertheless, this condition can be avoided by increasing the retention capacity of the Blue addition, where an ideal 80 mm of retention would be ideal for the climatic conditions of the Netherlands [14].

This potential is of great benefit for the city, as water retention of roofs will prevent the collapse of sewage systems and street flooding by retaining a percentage of the rainwater during heavy rains and slowly draining it afterwards. This water accumulated on the storage system and growing medium will be accessible for plants and therefore enlarge the potential surface temperature reduction, cost of maintenance, and increase plant health for biodiversity [12].

Gravel systems can delay 25% of the flux, where extensive roofs can reach up to 50%. Extensive roofs can retain up to 60% of the total year rainfall average, where intensive roofs can reach up to 100%. Comparisons between Vegetated and Non-Vegetated roofs showed almost no difference on the retention capacity, proving that the soil and storage capacity are the only contributors [21]. Nevertheless, plant species will play a big role on the surface runoff volume (the lesser, the better), showing a short and long grass vegetation (Semi-Intensive species) performing better than sedum species (Extensive species).

The Municipality of Rotterdam stated that the already existing 360 000 m2 has the capacity to hold 9 000 000 L of water [11]. Studies showed that an increment of 25% in the district of Oud-Matenesse could reduce the flooding of the area by 19.5% [2].

Water Quality Enhancement

Green roofs have demonstrated to be the best intervention at a building level to improve water quality [12]. They are capable of absorbing rainwater pollutants, accumulation of contaminants (specially on flat roofs) including a percentage of heavy metals and reducing the surface water temperature to prevent microbial development [22].

The quality improvement depends on several factors. The bigger the runoff volume caused by plants will reduce its filtration effect. Organic concentration on soil and plant fertilizers may degrade water quality [24]. The age of the green roof may cause underperformance. Local water pollution will create different conditions and behaviors [12].

Research done on the water improvement capacity of green roofs has shown they can reduce 3 times the amount of lea, 1.5 times zinc content, 3 times cooper content and 2.5 times cadmium content. Moreover, by reduction of surface water temperature, prevent the spread of bacteria of contaminants that usually accumulate on roof surfaces [2].

Energy Savings (Insulation)

The effect of green roofs on the thermal comfort of buildings has been the object of substantial research. Until now no average value of resistance has been established to account for it as part of the overall U value of roof thermal performance. Nevertheless, its effect on reducing temperature gains in summer and decrease the thermal losses during winter has been measured in different climatic scenarios, showing the complexity of its understanding.

For summer, the surface temperature reduction plays a significant role, depending on the plant species (Albedo Coefficient, Stomata resistance and LAI), the climatic conditions (Rain flux and radiation) and the irrigation system (water availability) [6].

Reduction of heat gains in summer

The thermal properties of the system depend on the substrate layer and vegetation layer **[21, 22]**.

The Soil composition will dictate the mass of inertia. A higher thermal capacity will cause thermal lag and therefore a lower dynamic thermal transmittance.

The vegetation Foliage will provide shading to the roof and loss temperature through convection. 20 – 30 % of energy will be lost through reflection (Albedo coefficient), 60 % absorbed tough photosynthesis (Stomata resistance and LAI) and 20 % transmitted to the growing medium.

Reduction of heat losses in winter

The characteristics that will influence on the loss of temperature in winter are mainly dictated by the sol composition **[22]**:

- Substrate composition and thickness, saturation, additional.
- Additional insulation layer. The better the existing insulation on the building, the lesser the contribution of the green roof system **[21].**
- Climatic conditions (Radiation on roof, temperature outside and presence of snow).

This condition will be especially valuable for old buildings with bad insulation. New constructions have a required RC value of 6.0 m^2/kW, which is high enough already.

Increasing the substrate layer will provide benefits for both summer and winter, as it will increase the thermal insulation and increase the water content for the plants and the evapotranspiration process.

Green roofs have shown the highest impact on hot and dry climatic conditions to reduce the temperature gains in summer **[3].** Nevertheless, its effects have proven to be substantial in all climatic conditions. Studies in Japan (hot humid climate) shown a surface temperature reduction of up to 30 to 60 °C. Studies in China (hot humid climate) with sedum roofs, has proven savings of 3.83% in the annual cooling energy demand. In Shanghai, 20.9% of daytime and 15.3% of nighttime energy cooling demand in Summer, an average of 16% in Summer and 5% in winter. It has also proven to be useful in cold predominant climates. Daily temperature variations in Canada reduced to 6 °C from 45 °C with typical roofs and a heat flow reduction of 70 to 90% in summer conditions and 10 to 30% in winter conditions [21].

Energy savings (Solar Panels)

An additional benefit of Green Roof interventions is their compatibility with Photovoltaic Panels (PV Panels). The reduction of temperature where panels are installed has proven to increase the efficiency of energy production of these components.

Temperature of gravel roofs and bituminous roofs can range between 50 to 70 °C, where green roofs can maintain a temperature of 35 °C and lesser. An additional 0.25 to 0.5 % of extra yield per 1 °C above 25 °C of the ambient temperature **[22]**.

Sound Insulation

Green roofs have also been attributed the benefit to reduce the sound pollution and sound reverberation for indoor and outdoor spaces [21]. It is stated that they provide a high coefficient of absorption to reduce the urban noise levels [12].

Its performance depends on the substrate thickness, the substrate saturation and the vegetation type (Height and density). The transmission loss will increase and become more consistent with a ticker substrate layer [21].

It has shown to reduce 10 to 20 dB of street noise levels in comparison to non-vegetated roofs [12]. A transmission loss of 5 to 13 dB for low frequencies and 2 to 8 dB for high frequencies[21].

Air Quality Improvement

Green roofs are beneficial for the cities for alleviating air from dust and particle pollutants like NO_x, SO_2, O_3 and PM10 [21]. An indirect effect of green roof intervention in general, is the reduction of Co_2 emissions of cooling and heating demand by their insulation effect [21]. Although every plant practices photosynthesis, not all of them can absorb enough Co_2 to make a quantifiable contribution for a city scale. Only tree species have a high capacity of carbon storage that make them ideal to reduce co_2 concentration in urban areas. Trees are the most influential vegetation type for air pollution reduction. Deciduous shrubs have the maximum capacity for Semi-Intensive and Intensive systems, while herbs have the minimum capacity [12].

Its Performance depends on the vegetation species and the saturation of soil and water storage available.

Research shows that 109 Ha of green roofs can absorb 7.87 metric tons of air pollution per year [21] (72 kg/Ha). 1000 m2 of green roofs can capture 160 to 220 kg of pollutants per year. It has also been pointed out that they can reduce dust drops in urban areas by 100 mg/m [22]. A study in Zhengzhou – China on pollutant absorption of vegetation species has shown that trees account 87%, Shrubs 11.3% and Lawns 1.7% of the total absorption [12].

The increased area and density of vegetation will influence the overall performance [21], for which extending this strategy as much as possible will play an important role in cities. Another notation on the importance of increasing the use of Semi-Intensive and Intensive systems in cities when the building capacity allows it.

Biodiversity

Green roofs can play a significant role in the ecological preservation in urban areas. As for Air Quality Improvement, a larger surface area coverage, especially with intensive systems, will increase the effect and impact of these interventions [21]. Further study is required to measure their impact, for which the lack of large scale interventions in urban areas are needed plays against [22, 25].

Its performance depends on the similarity to local ecosystems that the selected vegetation, soil, and the air moisture can create. Improvement of air quality will also play in favor by providing a larger availability and variety of plant species [22].

Economic Benefits

Additional benefits come from economic aspects as well. The selection of the proper system will have the biggest impact on the Cost-Benefit analysis of such an intervention, where the main factors are: Structural capacity, investment capacity and regulations and subsidies [12].

The only benefits that can be economically quantified for the cost-benefit balance are: Energy savings due to insulation improvement, the use of solar panels and the increase of the roof longevity.

Rainwater retention properties are of significant interest and impact, especially for northern European countries with heavy and constant rain throughout the year [12]. A special subsidy is applied in many countries like the Netherlands per m3 of water retention [18]. The same needs to happen with the other urban environmental contributions like air quality improvement and biodiversity, to make them more profitable and attractive.

The use of green roofs will increment the property value in the long term by two factors.

- The waterproof barrier will be protected from extreme changes in temperature and wear damage thanks to the GR components, enlarging its lifespan.
- Additional accessible areas for users and increased aesthetics of the roof [12] will increase the value of the property in the long term. The Net Present Value (NPV) per unit area of roofs show that Intensive green roofs have a high net return on the long term that is double higher than the ones of extensive roofs, only due to the quantification of additional functional area for the users. Moreover, additional credits for LEED and BREEAM certifications that will increase the value of the building [22].

The private return of these interventions is negative, but the public return is positive [22]. The balance of both, depending on the area of intervention, will show an overall positive balance of cost (Specially for dense urban areas with lack of space). The additional costs must account for the contribution to the urban grid as contributors to safe, sustainable, and resilient cities [12].

Life Cycle benefits

As mentioned before, the lifespan of the roof will be increased by the implementation of green roof systems by reducing the thermal stress of the roof cover [22]. With a proper installation, an extensive roof can increase from 15-20 years (of a bituminous roof) to 30-50 years. This effect will reduce the price of the intervention in the long term, but also reduce the environmental footprint.

An analysis over 843 m2 for a period of 45 years showed that extensive roofs over-performed gravel ballast roofs, white reflective roofs and intensive green roofs. The main environmental impact factor was the drainage layer and the water retention/storage system. The most impactful materials were Polystyrene, Polyethylene, Rockwool and expanded clays. For the Intensive Green Roof system, Rebar Concrete (for reinforcement) and Perlite showed to be the most impactful components [26].

In terms of life cycle aspects, extensive roofs have proven to be less expensive and impactful than Intensive roofs because of the reduced maintenance costs [27]. But by considering the effects they can bring on the long term, both result in optimal interventions, as a bigger variety of plants and large water storage capacity will increase benefits to compensate for its impact.

Social Benefits

Green Roofs will not only affect the performance of the building and the urban environment, but also the life quality of the user. The improvement of environmental aspects like improved air quality, reduced noise pollution, increased biodiversity, increased humidity and thermal comfort is part of it. But psychological effects of being in direct and indirect (only visual) contact with nature has proven to be of substantial benefit for users [22].

According to DackDockters [17], The Additional use of garden space is the main leading reason for private investors to opt for green roof interventions, for which Intensive roofs are the preferred option [22]. Extensive roofs will contribute mainly to visual appeal and sense of environmentally friendly spaces that also affect the user's state of mind.

Bringing the opportunity for functions that can create social cohesion between neighbors, like gardening urban farming and recreation areas. An example of these is the project of Schieblock in Rotterdam [28], where the urban farming surfaces created for the common use of neighbors are maintained by residents and provide food and education for school visitors.

According to M. Hop [19], Intensive green roofs are the Large-Scale Ecosystem service that can provide the highest level of Ecosystem Services (ESS – Aspects of Ecosystems utilized, Actively or Passively, to produce human well-being).

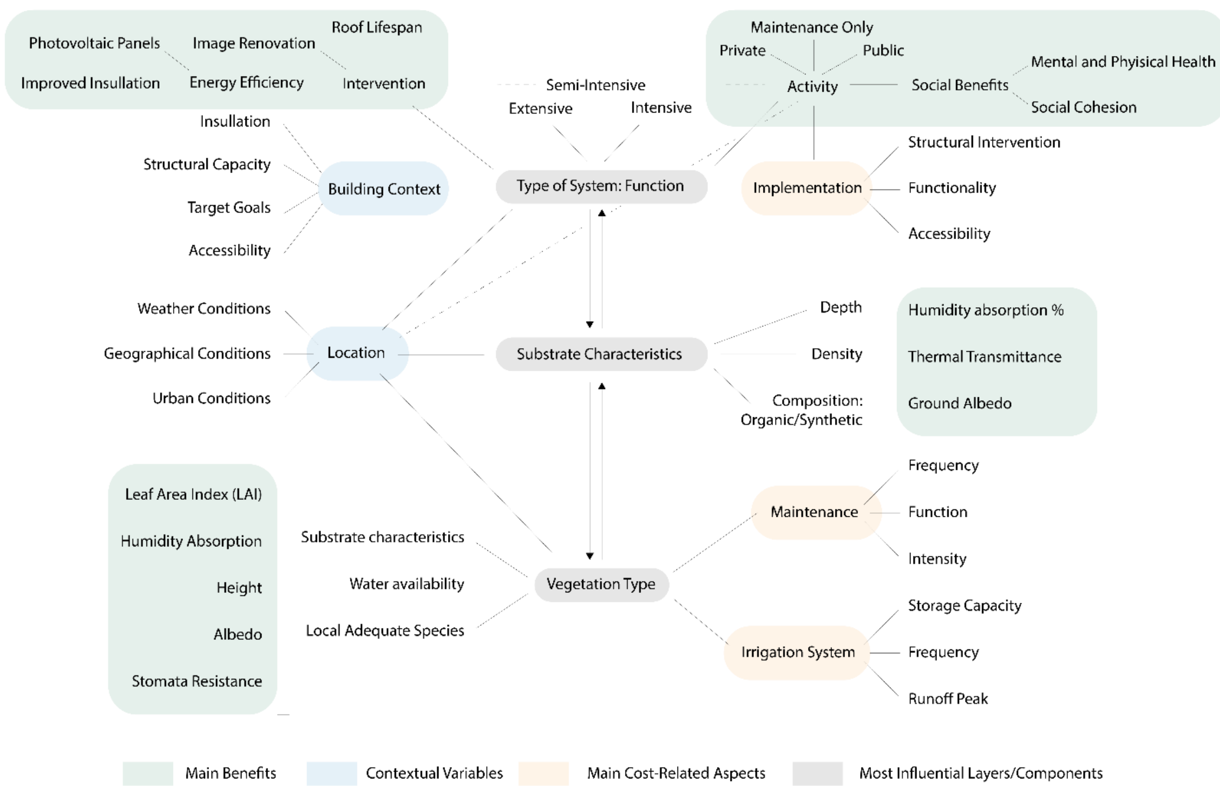


Figure 22 - Benefits, contextual variables, cost related factors and main influential layers

3.8. BENEFIT WITH INCREMENTED WEIGHT

As part of the described problematic, the roof structural capacity and costs are leading investors to opt for extensive roofs only, as these are lighter, less maintenance demanding and therefore more economic. After analyzing the benefits of green roof interventions, and their influence in costs and lifecycle aspects, is possible to point out the main aspects that being disregarded when the buildings load bearing capacity could allow heavier and better performing options (*Table 6*).

Increased Water Retention Capacity: Increasing the water capacity will increase the health conditions for plants, creating a more nature like environment for biodiversity, allowing a wider variety of species and allowing them to perform better. This will increase their cooling and their pollutant absorption capacity. Moreover, it will reduce the maintenance and irrigation costs.

Increased Substrate Thickness: Increasing the substrate thickness will increase the water retention capacity, increase the thermal lag for the insulative performance and will allow a larger variety of plant species to increase the urban performance of the subsequent benefits. Moreover, it will allow a higher quality of water filtration and nose pollution reduction.

Larger Variety of Plant Species: Allowing a larger variety of plants will increase the conditions for biodiversity development. It will allow the implementation of plant species that are better performing for air quality improvement and plants with higher water retention properties as well.

Roof Accessibility and Functionality: Providing access and functions to the roofs will increase the NPV per unit area of roofs, allowing to quantify the functional area to mitigate the costs of these interventions. Moreover, the physical and psychological wellbeing they can provide to the user in offices and at home must not be disregarded

Table 5 shows an estimation of the priority order of the contributions for the building owner, the building user and the urban environment. This table is based on the information and values provided by the Report of the “Life@Urban Rooftops”Program **[18]**. An SCBA tool developed to showcase the client/investor an estimation of the cost and benefit balance of an intervention, where characteristics like the type of green roof, area of solar panels, water retention capacity and more, can be varied to compare their effect on the cost-benefit balance for the investor. Additional values for the Lifecycle – Economic and Energy Savings (Insulation) benefit were added from the literature research as well. Although many of these quantification parameters are highly variable and quantified based on different criteria, they can provide an overview on the parameters that will be of most relevance for the different ends.

User A: Building Owner

User B: Building User

User C: Urban Environment

A	B	C	Benefit	Target	Qualitative	Quantitative
1	1	8	**Lifecycle – Economic**	Building Level	• Reduction of Bills • Substantial Economic Long-term Benefits on property value	• – 90 Year Lifespan: **€ 2.255/m2 per Year**
2	8	2	**Water Retention**	Urban Level	• Reduce Flooding at street level • Prevent general discomfort: circulation, smells, etc.	• Shadow costs of infrastructure damage and sewage quantity relieve • € 300-800/m3 • **Def. value 500€/m3**
3	3	9	**Energy Savings (PV Panels)**	Building Level	• Reduction of Bills	• **€/m2** • Increment of Yields on Green Roof: **0.25 – 0.5% X 1 °C above 25 °C**
4	4	5	**Energy Savings (Insulation)**	Building Level	• Temperature comfort • Reduction of Bills	• Variation on performance, not quantifiable yet: • Ranges depending on climate + system + Building conditions • 3.83 % – 20.9% (Daytime) + 15.3% (Nighttime) • **Energy savings € x Month**
5	2	6	**Social**	Urban + Building Level	• Mental wellbeing by nature presence • Physical wellbeing	• **Health care costs:** 0.835 fewer patients per 1000 inhabitants at 1% more green within a radius of 1 km around the building: **€ 868 per patient** • **Labor loss:** € 6,341 per patient per Year
6	9	3	**Biodiversity**	Urban Level	• Ecological preservation • Biodiversity	• € 8-20 X person (with a view of greenery) € 10 x User per Year Can be assumed
7	7	1	**UHI Mitigation**	Urban Level	• Reduce Surrounding Temperature • Reduce Heat Stress • Reduce Pollution	• Not estimation
8	5	4	**Air Quality**	Urban Level	• Improvement of air quality • Increment of air humidity	• Negligible effect
9	10	10	**Water Quality**	Urban Level	• Prevent bacteria spread on water • Prevent smell development of water and sewage system	• Negligible effect • € 0.03/m2 x year
10	6	7	**Sound Insulation**	Building Level	• Improve acoustic comfort	• Not estimation

Table 5 – Ranking of benefits priorities for the different beneficiaries. A: Building Owner – B: Building User – C: Urban Environment.

Benefit	Increase Water Retention Capacity	Increase Substrate Thickness	Larger Variety and Availability of Plant Species	Roof Accessibility and Functionality
Influential Variables	• Capacity of Drainage + Storage layers • Irrigation System + Capillarity Absorption • Substrate Saturation Capacity • Plant species: Absorption capacity	• Soil composition Organic/Synthetic • Soil density and Porosity • Additives and fertilizers	• Substrate conditions • Water availability • Geographical and Climatic Context	• Accessibility (Stairs/Elevator) • Building Function • Area of roof • Regulations for use designation
UHI Mitigation	• Larger quantity of water for Evapotranspiration process • More cooling capacity	• Incremented Thermal Capacity and Thermal Lag • Increase water availability for evapotranspiration process	• Plant Evapotranspiration process • Larger leave surfaces (LAI) + Lower Stomata Resistance • More water storage > More cooling capacity	
Water Retention + Water Quality	• Up to 100 % of rainwater retention • Reduce flooding risks in urban areas • Reduce infrastructure deterioration by water damage	• Larger availability of plant species with higher retention capacity • Increase water retention capacity • Increased thickness of substrate layer: Higher level of water filtration	• Species with higher retention properties • Local available species to reduce maintenance	
Energy Savings (Insulation)	• Irrigation supply + More evaporation = More cooling	• **Soil:** Mass of Inertia with higher thermal capacity > Thermal Lag> Lower Dynamic thermal Transmittance	• Vegetation Foliage: Shading of roof – Loss of temperature through convection + Absorbs energy through photosynthesis	
Energy Savings (PV Panels)				• Implementation of solar panels
Sound Insulation		• Increase Transmission Loss with thicker substrate > Effect is higher and more consistent		
Air Quality	• Increase of water availability for plants • Plant health > better performance > Less maintenance	• Increase thickness for better performing vegetation species (Semi Intensive – Intensive Category)	• Trees are the most influential vegetation type for air pollution reduction • Bigger and variety of plants > higher pollution dilutant rate over years	
Biodiversity	• Increase moisture and humidity levels • More natural conditions for local species	• The more similar to local ecosystems, the better the performance		
Lifecycle, Economic + Social	• More m3 of Water Retention > Reduce flooding and infrastructure damage			• Intensive roofs have high net returns on the long term that are double high the ones of extensive roofs

Table 6 - Overview of benefits with incremented weight and influential factors

A - The main factors of interest for the investor are:

- **Functional and accessible areas** to increase the value and the rentable areas of the building.
- **Increasing the lifespan of the building and** the lifespan **of the roof** will save renovation costs in the long term.
- **Maximize the water retention capacity** to increase the subsidy for the project and decrease the water expenses for the maintenance of the vegetated areas.
- **Implementation of solar panels** to reduce energy expenses for the maintenance of the building and user energy consumption.
- **Renovating the insulation layer** to increase energy efficiency of the building.

B - The main factors for the users are:

- **Accessible and functional** garden areas to increase mental and physical health.
- Implementation of **functions** that can bring **social cohesion** in neighborhoods or between residents in buildings.
- Increase **thermal comfort and energy efficiency** of the spaces and the building.

C - The main functions of interest for the city and the urban environment are:

- **Maximizing the vegetated areas** to reduce the surface temperature of roof surfaces, which will benefit other factors like air quality, biodiversity, energy efficiency and more.
- **Maximizing the water retention capacity** of the roof to prevent street flooding during rainstorms and to increase the performance of the vegetated areas.
- **Increase of biodiversity** in cities to restore the balance of the ecosystem by the integration of native plant species, soils and increasing the humidity and permeability of the roof surfaces.
- If applied on a large scale, **increasing the air quality of the city**. For this, the use of larger varieties of plants that enter the category of Intensive vegetation.

3.9. SYSTEM SCALE CONCLUSIONS

The research conducted on this chapter allowed to identify and relate the relevant contributions of GR, BGR and MR interventions, to the layers and components of most influence on their performance. It was possible to see that, for most of the urban related benefits, further research is required to quantify their effects and contribution. This will allow the development of incentives and regulations to economically quantify their contribution to counterbalance the costs of implementation. Part of the requirements for further research will be the development of more case studies and larger covered areas with GR, BGR and MR interventions for the collection of data at a larger scale.

Which are the main parameters to obtain a satisfying performance for the user and the urban level?

Throughout the literature review conducted for this chapter it was possible to see that the priority order of benefits changes for all 3 ends: Users, Building owner and Urban scale. Nevertheless, most of them coincide on the main factors that would be looked upon from all ends. These factors can be related to the components of the Blue-Green roof that should be prioritized and combined to create a valuable multifunctional intervention. Functions and uses might change according to the requirements of the specific building and context, but the components will be the same.

According to the research, the main variables to consider for all ends are:

- Accessibility to functional spaces.
- Maximizing water capitation.
- Facilitating the implementation of solar panels
- Increasing the use of intensive green roofs to increase the variety of plant species.
- Additional insulation for the roof, especially for non-renovated old buildings.

The components that will be relevant for these benefits are:

- **Substrate Layer:** Increasing its thickness and selecting the optimal composition to increase its saturation capacity. This will not only allow a larger list of available species to increase biodiversity and create more natural spaces, but also to improve the performance and health of the selected species.
- **Water Drainage + Retention Layer:** Increasing the water buffer and the use of irrigation through capillarity to reduce maintenance, increase humidity level of soil and plant health for their better performance. Moreover, helping to mitigate the overrun of sewage systems by retaining the rainwater.
- **Accessibility:** If the building conditions allow it (roofs that have accessibility by elevators or stairs), provide accessible spaces for the different public or private functions, whichever suit the building function the best. This will improve the life quality of the users, create more rentable spaces for the owner and more functional areas in neighborhoods with a shortage of horizontal space.

Are there factors that could be optimized to reduce the structural demand of the system without losing performance?

Defining the loads

An important factor that was observed in many of the interventions is the separation between the accessible functions and the vegetated areas. Making accessible green spaces will not increase the performance of the roof for any of the end benefactors. It will only increase the costs of maintenance and the loads for which the roof needs to be reinforced.

Creating a chart of the different combinations of functional areas and green roof variants is necessary, to estimate the maximum load for which the roof needs to be designed but avoiding the combination of functions that would lead to an excessive load that will not bring additional benefits.

Weight Distribution of the Intervention

The main factor that could be optimized on the design of a multifunctional roof is the weight distribution. This is a factor that was observed in many of the studied interventions. Different loading capacities will be possible in relation to the distance from the vertical supports. Heavier intensive vegetated areas can be applied near the loadbearing structure. Normally this is done by a thumb rule determining the distance limit at which the capacity will be higher.

A design tool could be developed in parallel to the reinforcement structure to work with this strategy from start. Creating a floor plan that provides an overview of the maximum loads that the roof can take in distinct areas.

The result of such a tool could result in a strategy that allows the design of the roof structure for a lower capacity to reduce its weight and cost but providing a percentage of areas for interventions of higher loads as well. For this approach it is necessary to consider which layers can form part of the weight distribution and which will always be constant throughout the roof.

3.10. OUTPUT OF SYSTEM SCALE: LOAD CHART COMBINATIONS

For the Definition of the load cases, it is required to differentiate the loads that will act as variable loads and the ones that will act as permanent loads. The vegetated areas will be calculated independently from the Accessible Functional Areas, as the loads of these will not be combined and only the governing one (depending on the combination) will be used.

The process of determination of the forces to be applied is explained in the following tables.

1- Defined Categories

2- Combination of Variables – Application of safety and reduction factors.

3- Selection of Governing Load for analysis.

Accessible Functional Areas

These areas are categorized in three groups:

- **High Occupancy Areas:** Spaces that will have constant transit and gathering of the residents living in the building or for public areas of other functions like cafes.
- **Low Occupancy Areas:** Spaces designated for functions that will not have as much traffic and users as a public space. Designated mostly for terraces, viewports and functions like urban farming and gardening.
- **Maintenance Access:** Spaces that will be accessible only for the maintenance of the vegetated roof and providing access to the maintenance units of the building facades.

Vegetated Areas

These areas will be categorized again into three groups, based on the main categorization of green roof interventions. The given values will be the **minimum requirements** for each category, but the increase or decrease of the thickness will depend on the selected vegetative species. In all cases, the weight of the saturated soil and full vegetation coverage needs to be considered.

- **Extensive Systems: 80 mm -** Mostly sedum, mosses and lichen species.
- **Semi-Intensive Systems 200 mm -** Mixed varieties of low and mid perennials, grasses, bulbs and annuals, wildflowers and dared sub-shrubs.
- **Intensive Systems 300 mm -** The vegetation types are widely variated. Small tree species are also available.
- **Maintenance:** The load for maintenance access in vegetated spaces will be considered in all cases.

Additional Loads:

The loads that will be present independently of the functions are:

- **Water storage and rain:** The presence of the water buffer layer and drainage system at the maximum capacity for the roof. As stated by the research, a maximum of 80 mm is ideal for the rainfall index of the Netherlands plus the weight of the retention system and the additional overflow quantity.
- **Snow:** The load of snow will be mostly governed by the other variable forces. For the vegetated areas for example, the access for maintenance will be the governing load, as no situation will lead to the accumulation of both. For accessible common spaces, the possibility of people accessing the roof deck during a snowfall might happen, for which it will be considered.
- **Wind Load:** Wind load will only be applied for the final design, as the affection area variates on the different areas of the roof, which will depend on the distribution logic and characteristics of the strategy.

The reference values for the components are based on the information obtained during the product research. These are summarized in the group of *Table 7*. These values will be used to configure the loads.

Normative EC 1 - Floor Loading Categories	Function	Uniformly Distributed Load [kN/m²]	Load for Loading Cases [kN/m²]
H – Access For Maintenance	H - Maintenance	0.00 – 1.00	1.00
A – Areas for domestic and residential activities	A - Living Areas	1.50 – 2.00	2.00
	A – Circulation/Stairs	2.00 – 4.00	
	A – Balconies	2.50 – 4.00	
C – Areas where people my congregate	C1 – Areas in schools, cafes, restaurants, etc.	2.00 – 3.00	3.00

Function	Applicable to	Load for Loading Cases [kN/m²]
Maintenance	Maintenance	1.00
Private	Terrace - Viewports	2.00
	Urban Farming	
	Living Spaces	
Public	Public Terrace	3.00
	Cafe – Restaurant	

Function	Variable	Load for Loading Cases [kN/m²]	Total Load [kN/m²]
Extensive 10 cm	Substrate	1.15	1.20
	Vegetation	0.10	
Semi-Intensive 20 cm	Substrate	2.20	2.50
	Vegetation	0.30	
Intensive 30 cm	Substrate	3.10	3.80
	Vegetation	0.75	

Function	Load for Loading Cases [kN/m²]	Load for Loading Cases [kN/m²]
Dead Load Terrace	30.00 –80.00	0.58
Water buffer	85.00	0.83
Drainage	5.00	0.05
Waterproof Barrier	5.00	0.05

Function	Load for Loading Cases [kg/m²]	Load for Loading Cases [kN/m²]
PVP Tile	30.00 - 60.00	0.39
PVP Tile + Support	36.00	0.35
Snow load	60.00	0.58
Wind Load (Up)	-	1.20
Wind load (Down)	-	0.40

Table 7 - Material Properties and load overview for weight estimation process

Category	Accessible Functional Areas – Variable Loads			Vegetative Areas – Permanent Load		
Function	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive
Type	(Variable)			(Permanent)		
Load (kN/m^2)	1.00	2.00	3.00	1.20	2.50	3.80
Permanent Loads (kN/m^2)						
Dead Load – Terrace Finish	0.58	0.58	0.58	-	-	-
Water Buffer + WPB + Insulation	1.00	1.00	1.00	1.00	1.00	1.00
PVP Tile + Support	-	-	-	0.35	0.35	-
Variable Loads (kN/m^2)						
Maintenance	-	-	-	1.00	1.00	1.00
Snow	0.54	0.54	0.54	0.54	0.54	0.54
Wind Load (Down)	-1.20	-1.20	-1.20	-1.20	-1.20	-1.20
Totals (kN/m^2)						
Permanent	1.58	1.58	1.58	3.30	4.60	4.80
Variable	1.54	2.54	3.54	1.54	1.54	1.54

Table 8 - Combination of layers - Variable and Permanent loads

The different load components are added together based on the Load Equations (*Eq. 6.10a and 6.10b*) and the safety and reduction factors (*Table 9*) specified on the NEN – EN 1900 regulations. Different loads need to be configured for the Serviceability Limit State and for the Ultimate Limit State, to verify the compliance of the design to the minimum requirements of functionality and safety.

Load Equations –Serviceability Limit State (SLS) & Ultimate Limit State (ULS)

Eq. 6.10a:

$$\gamma Gj, sup\boldsymbol{G}kj, sup + \gamma Gj, inf\boldsymbol{G}kj, inf \; + \gamma Q, 1\Psi 0,1\boldsymbol{Q}k, 1 + \gamma \mathrm{Q,i}\, \Psi 0, i\boldsymbol{Q}k, i$$

Eq. 6.10b:

$$\xi\gamma Gj, sup\boldsymbol{G}kj, sup + \gamma Gj, inf\boldsymbol{G}kj, inf \; + \gamma Q, 1\; \boldsymbol{Q}k, 1 + \gamma \mathrm{Q,i}\, \Psi 0, i\boldsymbol{Q}k, i$$

Safety and Reduction Factors		SLS	ULS
Factor	Meaning	Value	Value
Gk	Dead Load	x (kN)	x (kN)
Qk	Live Load	x (kN)	x (kN)
γGj, sup	Unfavorable DL	1.00	1.35
γGj, inf	Favorable DL	1.00	1.00
γQ, 1	Main LL	1.00	1.50 (0 if fav.)
γQ, i	Other LL	1.00	1.50 (0 if fav.)
ξ	Load coefficient	1.00	0.85

Table 9 - Safety and reduction factors according to NEN-EN 1990 regulations.

Serviceabilitv Limit State Values - SLS

Vegetated Areas					
Configuration	Load	Load (kN/m2)	Reduction Factor Ψ_0	Equation 6.10 (A)	Equation 6.10 (B)
1	Extensive	1.20	1.00	3.66	3.54
2	Semi-Intensive	2.50	1.00	4.76	4.84
3	Intensive	3.80	1.00	5.52	5.79
	Water Buffer	1.00	1.00		
	PVP Tiles	0.35	1.00		
	Maintenance	1.00	0.70		
	Snow load	0.58	0.50		

Functional Areas					
Configuration	Load	Load (kN/m2)	Reduction Factor Ψ_0	Equation 6.10 (A)	Equation 6.10 (B)
1	Maintenance	1.00	0.70	2.72	2.57
2	Private	2.00	0.70	3.72	3.27
3	Public	3.00	0.70	4.72	3.97
	Snow Load	0.58	0.50		
	Dead Load Terrace	0.58	1.00		
	Water Buffer	1.00	1.00		

Ultimate Limit State - ULS

Vegetated Areas					
Configuration	Load	Load (kN/m2)	Reduction Factor Ψ_0	Equation 6.10 (A)	Equation 6.10 (B)
1	Extensive	1.20	1.00	5.13	4.93
2	Semi-Intensive	2.50	1.00	6.63	6.68
3	Intensive	3.80	1.00	7.64	7.96
	Water Buffer	1.00	1.00		
	PVP Tiles	0.35	1.00		
	Maintenance	1.00	0.70		
	Snow load	0.58	0.50		

Functional Areas					
Configuration	Load	Load (kN/m2)	Reduction Factor Ψ_0	Equation 6.10 (A)	Equation 6.10 (B)
1	Maintenance	1.00	0.70	3.86	3.62
2	Private	2.00	0.70	5.36	4.67
3	Public	3.00	0.70	6.86	5.72
	Snow Load	0.58	0.50		
	Dead Load Terrace	0.58	1.00		
	Water Buffer	1.00	1.00		

Table 10 - Resultant load combinations and governing loads.

As shown in *Table 10*, the load combinations for the functional areas and vegetated areas are calculated separately. The combination is calculated with both formulas, selecting the highest value for the comparison, giving us the resultant load for the 3 different functional areas and the 3 different GR interventions.

Combinations	Accessible Functional Areas – Variable Loads (kN/m^2)			Vegetative Areas – Permanent Load (kN/m^2)			With WB + PVP	
							Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)
A	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	3.66	5.13
	2.72	3.72	4.72	3.66	4.84	5.79		
B	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	4.84	6.68
	2.72	3.72	4.72	3.66	4.84	5.79		
C	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	5.79	7.96
	2.72	3.72	4.72	3.66	4.84	5.79		
D	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	3.72	5.36
	2.72	3.72	4.72	3.66	4.84	5.79		
E	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	4.84	6.68
	2.72	3.72	4.72	3.66	4.84	5.79		
F	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	5.79	7.96
	2.72	3.72	4.72	3.66	4.84	5.79		
G	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	4.72	6.86
	2.72	3.72	4.72	3.66	4.84	5.79		
H	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	4.84	6.86
	2.72	3.72	4.72	3.66	4.84	5.79		
I	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	5.79	7.96
	2.72	3.72	4.72	3.66	4.84	5.79		

Table 11 - Load cases - SLS and ULS governing loads

As seen in (*table 11*), all the possible combinations are shown from A to I. The different functional areas and the different vegetated areas that could be selected for any intervention. The highest load is selected as the governing load of the combination, to design the structure providing design freedom for any distribution.

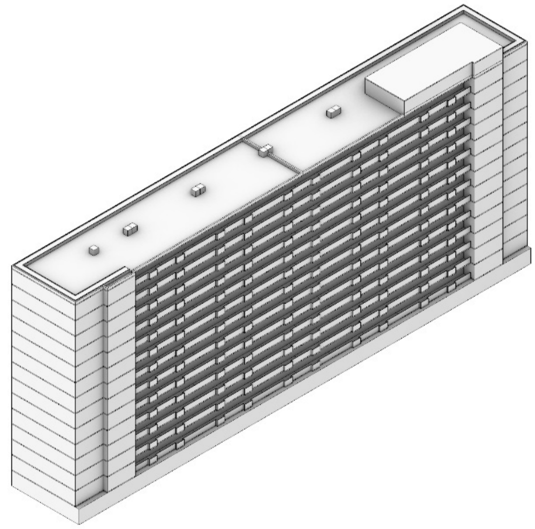
Option E for example, where the functional areas are designed for private functions and the vegetated areas for Semi-Intensive systems. The governing load for the design is set by the semi-intensive system.

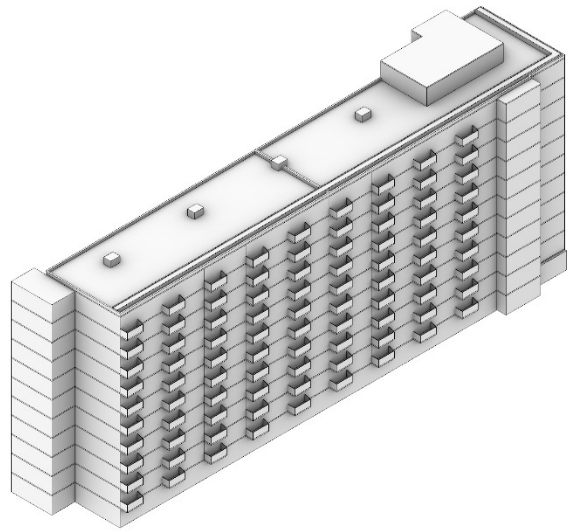
It's possible to see that, from the 9 combinations, only in 2 cases the functional areas are the governing force. Only when a function inside the private category is combined with an extensive system or when a public function category with an extensive.

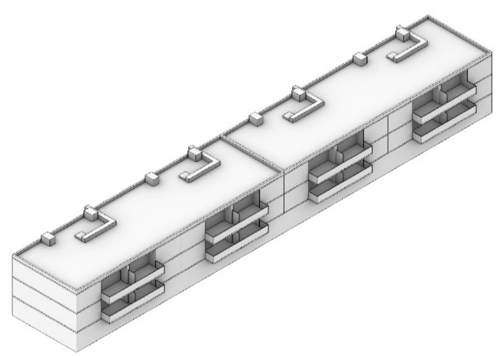
As stated before, it is possible to have in between options. These three categorizations for each group were selected as base values to ease the comparison process.

4. BUILDING SCALE

On this chapter, the selection and analysis of the relevant Post-War construction typologies was conducted, determining the main structural and constructive characteristics to be considered. The selection and analysis of design samples, and the analysis of the loadbearing capacity of the roof, walls, and foundations under the worst-case scenarios. Moreover, understanding current concrete reinforcement systems to identify possible cost relieving factors, and the potential roof residual capacity of existing roofs.







4.1. POST-WAR STRUCTURAL TYPOLOGIES

The “Program for multifunctional rooftops” from the Rotterdam municipality **[11]** states the potential of the flat roof typology that was developed on the Post-War period, especially on dense parts of the city center, where almost everything had to be rebuilt. The opportunity to intervein on these surfaces with strategies that will allow to maximize their function is of high interest in the current contexts, where available horizontal space is hardly found, and the city keeps growing.

Many of the flat roof typologies were developed in new districts of Rotterdam as well. These are typologies that were constructed all over the Netherlands to fight back the housing shortage. 90 000 Houses were required in the lapse of 10 years for the city of Rotterdam alone **[29]**. (Figure 23) shows the transition of 1940’s to 1960’s, where the affected area of the city after the bombing is marked in black and the city density in red.

After the war, as part of the “Basis Plan” strategy of demolish, reorganize, and rebuild, housing districts were developed in the new suburban areas of Rotterdam and giving more space for offices and commercial functions in the center **[29]**. To meet the housing demand, new construction systems were developed to save up on materials and make the construction process faster and efficient. These are known as the Systeem Constructie **[30]**.

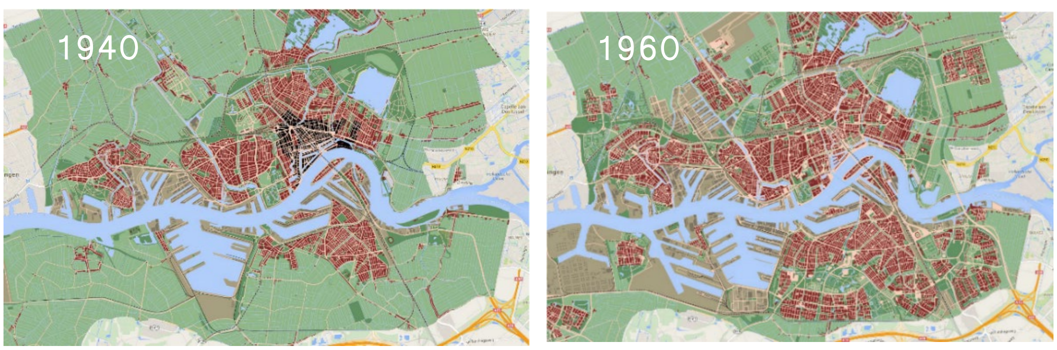


Figure 23 - Urban Growth - Rotterdam. [29]

4.2. CONTEXT

“Systeem Constructie” typologies were the result of the requirement on accelerating the construction process. As explained in the Research of C. Thijssen and C.l. Meijer **[31]**, from 1949 to 1965, 328 868 multifamily houses were built. in the period between 1956 to 1965, 1217 complexes of 100 houses or more were developed, which covers 2/3 of the constructed building stock. The “Documentatie Systeemwoningen 50-75” report by Bouwhulp Groep **[30]** shows that in the period of 1940 to 1975, 2.6 million houses were built in the Netherlands. From which, 25 % were built as social housing projects under these construction systems. A total of around 400 to 450 thousand houses.

The focus on these constructions was on efficiency, quality, and speed in construction rather than aesthetics. Mainly multifunctional projects of housing configurations were developed to make construction more compact, efficient, and economic, a tendency that was already present in the existing building stock but that was the basis for construction of these post-war typologies.

Continuous contracts were implemented between government and constructors to allow companies to innovate and improve the quality of construction, upscale production process of prefabricated products and increase the efficiency of construction sequences. These continuous contracts happened mainly in big cities like Amsterdam, Utrecht, and The Hague. Although, as explained in the document, this was not the case for Rotterdam, these construction systems were also vastly implemented.

The analyzed documents [31] showed that in many cases the Municipalities acted as client, architect, and commissioner of these projects. This led to the formation of many of the Rental Cooperatives existing today. Statistics of today show that 75 % of the housing configurations correspond to multifamily typologies, from which 45% belong to Rental cooperatives and 19% to private rent or others.

The Report on "Systeemwoningen" (figure 24) gives an overview of the main construction typologies that were developed in the Netherlands. A total of 23 were identified as the main samples developed mostly in big cities.

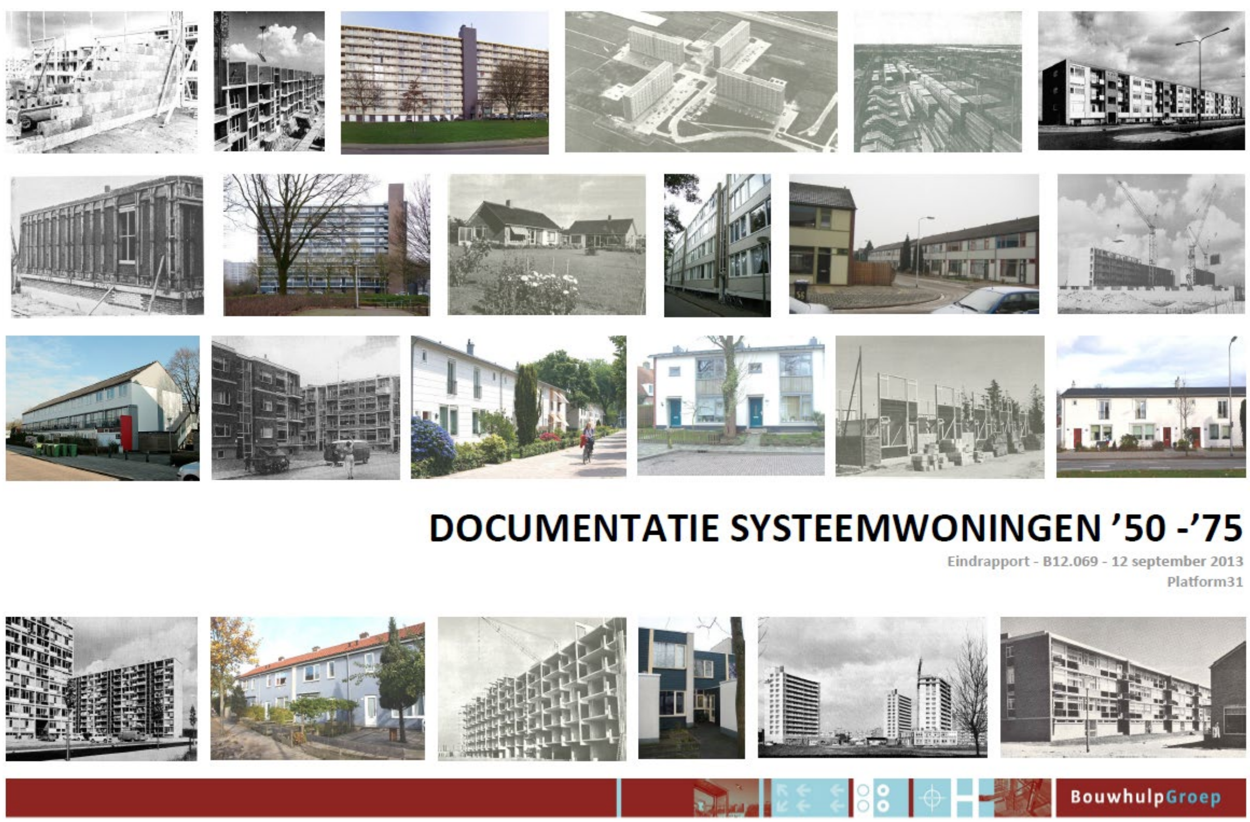


Figure 24 - Book cover - Systeemwoningen 50-75 [30].

4.3. SYSTEEMCONSTRUCTIE

The report of Thijssen and C.l. Meijer [31] was conducted with the objective of analyzing and quantifying the construction systems developed on this period to understand how they were constructed and identify which will be the most relevant considerations and problematics to be addressed in future renovations. It gives a insightful overview of the characteristics of the sample that is referred to the “Systeemwoningen”, defined by them as the “Non-Traditional” systems. Many relevant aspects can be concluded as a general description of the analyzed sample:

- Non-Traditional systems numbers were much higher than initially expected, as many of them were not registered in the Housing Act as part of the continuous contracts.
- The most common typology on Non-Traditional Building systems is the Gallery Building.
- Flat roofs on Non-Traditional construction systems are present in 88.9% of the sample.
- Flat Roofs on Non-Traditional: Concrete Systems (Prefab/Casted Slabs) is present on 96.4% of the sample.
- Flat Roofs were Poorly Insulated/Not insulated at all in 88.9% of the sample.
- No Vapor Barrier was found on insulation systems. They rely on ventilation to avoid weathering damage, which results in an almost neglectable insulation effect in winter conditions.
- The large sample of Non-Traditional Buildings with repetitive construction systems with systemic defects is higher than expected. Modular and systemic solutions will be a potential tool for the future renovation of these building

The “Documentatie Systeemwonngen 50’-70’” [30], includes a table where all the registered typologies in the Housing Act, organized by name of the construction system and city of implementation. From this document, it is possible to see all the developed systems in Rotterdam. 6 of these Systeemwoningen typologies cover 85.20% of the developed buildings under this category (table 12).

System Name	COIGNET	ROTTINGHUIS	PRONTO	MUWI	RBM I & II	ERA
Percentage [%]	18.9	10.7	13.0	7.1	25.9	9.6
Overall Percentage [%]	85.2					

Table 12 - Systeemwoningen in Rotterdam - Most implemented Systeemwoningen constructions [30].

RBM I & II	1945 – 1974
Building Typologies	Porch Flats Gallery Buildings
Locations	Amsterdam Rotterdam The Hague
Construction System	Stalked Construction Cast Construction
Structural System	1.25 Element System Casted walls

Description

The RMB construction system can be categorized in three different systems according to the period in which it was developed. Starting as a prefabricated stalking system and resulting in the end as a versatile casted construction system.

In the period of 1945-1954, it was based on a Prefab Stalking System. Based on a system of steel support prefabricated elements and prefabricated concrete slabs. This system was abandoned early due to the costs of the steel loadbearing structure.

From 1954 to 1965, RBM I system was redefined as a combination of Prefab Stalking System + Cast Construction system. It was characterized by the use of prefabricated wall panels every 1.25m. Joints were filled with concrete, creating a Loadbearing Wall (Shell Structure). External Walls made from brick cavity walls.
The possibilities of modulation made this system quite versatile for different configurations and therefore not as recognizable as other Stalking Systems like ERA or BMB. It was more a construction system than a Systeemconstructie.

From 1965 to 1974, RBM II started its implementation as a Cast Construction System. The access to machinery and cranes made it possible to transport the modular Steel formwork system to cast the loadbearing walls.
End walls and partitions were made of masonry systems, making the longitudinal direction no longer loadbearing. These buildings ranged between 4 to 12 stories high. The higher samples were built with the implementation of RMB I and II.

COIGNET	1959 - 1975
Building Typologies	Porch Flats Gallery Buildings
Locations	Amsterdam Rotterdam Eindhoven
Construction System	Large Elements
Structural System	Large Prefab segments

Description

This system is characterized by its high degree of standardization of construction elements which results in a standardization in design and layout as well and therefore a very recognizable typology. The most common typologies developed with the systems were 25% Porch Flats and 50% Gallery Buildings.

There were three variants of this system. Dura-Coignet and Indeco-Coignet for Mid-rise Buildings and Neduco-Coignet for Low-rise Buildings. These are all Stalked Construction Systems. A series of anchored prefabricated modules that configure the loadbearing walls. The concrete floors and roofs were made of prefabricated modules as well. External walls and internal divisions were made of prefabricated non-structural modules.
Between 1989 and 1990 Many were demolished after 20 to 30 years of use. The predominant prefab concrete elements lead to thermal bridges and the standardization of distribution made them unsuitable for renovation or improvement.

PRONTO	1955 - 1960
Building Typologies	Porch Flats Single Family Dwellings Gallery Buildings
Locations	Rotterdam Eindhoven Tilburg
Construction System	Stalked Construction
Structural System	Two Person Block + Concrete filling

Description

This system is an intermediate between a traditional construction system and a prefabricated staked system, as masonry loadbearing walls were used to support the prefabricated concrete slabs. This made this system available only for Low-Rise and Mid-Rise buildings. The Inner partitions between houses and Outer walls were composed of two layers of brick with a concrete core and an additional 3 cm of insulation. This construction system is characterized by having very bad thermal and acoustic properties and a very restrictive configuration for redistributing spaces for renovations.

MUWI	1951 - 1973
Building Typologies	Single Family Dwellings Porch Flats Gallery Buildings
Locations	Schiedam The Hague Leidschendam
Construction System	Stalked Construction
Structural System	One Person Block + Reinforced cavities

Description

The MUWI system is very similar to the PRONTO system. Characterized by Masonry Loadbearing walls of concrete blocks filled with gravel and prestressed concrete beams with filling blocks in between. A final layer of concrete is poured on top of the floor and roof system to make it work as a whole element. Front and back outer walls are made of non-loadbearing assembly frames.

ERA	1964 - 1972
Building Typologies	Gallery Buildings
Locations	Rotterdam Zoetermeer Zaandam
Construction System	Large Elements
Structural System	Tunnel Structure



Description

The ERA system is an example of the exploration process that was carried out to find new ways of industrializing the construction process to accelerate rates of production. In this case, the system is a Large Element Stalked System that consists of prefabricated concrete tunnels, developed in a factory, and transported to site to be mounted on top of each other by cranes, forming the main structure of the building. Because of the construction process it was possible to reach spans of 7.80, making the distribution of spaces very versatile and adaptable. This makes the building highly suitable for renovations, to maintain the structure and distribute the spaces for more suitable configurations.

ROTTINGHUIS	1949 – 1973
Building Typologies	Gallery Buildings
Locations	Rotterdam Zoetermeer Zaandam
Construction System	Large Elements
Structural System	Tunnel Structure



Description

The ROTTINGHUIS System is characterized to be an assembly building method for Mid-Rise buildings, based on prefabricated concrete walls and floors assembled by crane. The front and back facades are made of traditional brickwork.

4.5. STRUCTURAL CHARACTERISTICS

System Name	COIGNET	ROTTINGHUIS	PRONTO	MUWI	RBM I & II	ERA
Percentage [%]	18.9	10.7	13.0	7.1	25.9	9.6
Overall Percentage [%]	85.2					
Construction Typologies						
Porch Flats [%]	24.0	45.0 – 55.0	62.0	53.0	-	0.0
Gallery Flats [%]	55.0	55.0 – 45.0	4.0	46.0	-	100.0
Transversal Section [m]	10.95	9.65	10.53	11.90	11.40	11.80
Wall to Wall span [m]	4.35 – 4.50	2.70 – 4.70	3.99 – 2.91	4.31 – 3.21	3.60 – 4.30	7.30
Structural System						
System Type	Large Elements ---- ----	Large Elements ---- ----	---- Stalked Construction ----	---- Stalked Construction ----	---- Stalked Construction Cast Construction	Large Elements ---- ----
Vertical Structure	Large Prefab segments	Large Prefab segments	Two Person Block + Concrete filling	One Person Block + Reinforced cavities	1.25 element core system Casted walls	Tunnel Structure
	Load bearing walls					

Table 13 - Overview of system constructive and structural characteristics

After analyzing the most implemented construction system for Post-War Typologies in Rotterdam, it is possible to see that they fall into the three categories of Non-Traditional construction system described by Thijssen and C.l. Meijer **[31]**.

Stalked construction systems: Small Prefabricated elements, like the concrete bricks used for the reinforced loadbearing walls of the PRONTO and MUWI systems.

Large Element System: Large prefabricated construction elements like the prefabricated panels for walls and floors of the COIGNET and ROTINGHUIS systems and the tunnel structures on the ERA system.

Casted Construction Systems: Formwork used for On-Site Casted Elements like in the RBM II System.

One common configurator of all these systems is the use of loadbearing wall structures for the main structural grid, where internal partitions and outer front and back walls are almost always non-loadbearing. Spans between the loadbearing walls variate either, from the partition walls between dwellings (Almost all Gallery Buildings) or supported by internal loadbearing divisions as well (Mostly in Porch Flat Typologies). In general, the span to be covered variates between the 6 and 8 meters, split in two halves on the situations in which the additional partitions act as supports.

All systems use concrete for the floor and roof structures. Either prefabricated panels and prestressed beams, casted slabs, or a combination of both.

All these typologies enter the category of multifamily dwellings, in which they follow a modular configuration all the time. This results in one or two single variations of spans between the loadbearing walls that bring great potential to the idea of developing a modular and replicable solution for multiple buildings. Three considerations were deducted from this study and set as the main variables to account for the development of such a system.

Loadbearing Capacity of Foundations

Based on the construction system and the building height, an estimation of the structure weight could be estimated to understand the percentage of weight that would be added with the intended Green Roof configuration and estimate if the foundations could carry the additional weight.

Loadbearing Capacity of Wall

Determining the construction system that was implemented for the wall loadbearing system to determine the maximum weight they could carry before exceeding their capacity and causing deformations of failure by buckling. Determining the minimum amount of supports in which the total applied weight should be distributed.

Spans Between Walls

As mentioned before, considering the span between the loadbearing walls that needs to be covered with the new structure.

Insulation

As mentioned before, considering the span between the loadbearing walls that needs to be covered with the new structure.

Roof Slope

Based on the construction system and the building height, an estimation of the structure weight could be estimated to understand the percentage of weight that would be added with the intended Green Roof configuration and estimate if the foundations could carry the additional weight.

Roof Drainage Location

Based on the construction system and the building height, an estimation of the structure weight could be estimated to understand the percentage of weight that would be added with the intended.

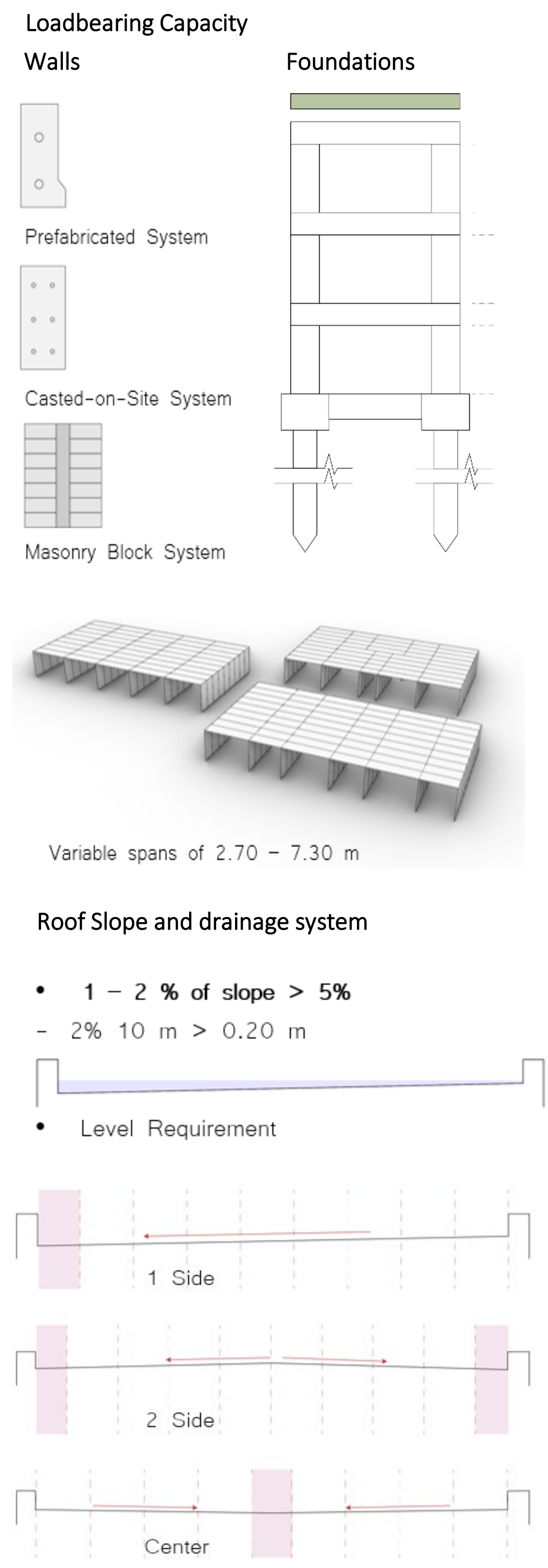


Figure 25 - Constructive and Structural Considerations

4.6. SYSTEEMCONSTRUCTIE IN ROTTERDAM

A Report by the author, C.C. Thijssen on the technical quality of post war typologies **[32]** gives an overview of the height average of construction of the new implemented system by year of construction between 1946 and 1989. It is possible to see that Mid-Rise buildings started Growth of the city from 40 to 60 and High-Rise buildings in from 1950 to 1974, where drawbacks on High-Rise constructions started to show its disadvantages on operative costs and uninterest on the market.

As shown in *figure 27*, it is possible to see that the period between 1950 and 1970 is when the construction rate reached its highest point. Between 1960 and 1970, the incremental scale of mid and high-rise typologies, as shown in *figure 26*. Precisely caused by the acceleration of systemic and industrial oriented construction systems in combination with the continuous contracts implemented by the municipalities. From this, in agreement with the statement by C.C. Thijssen **[32]**, the opportunity to develop systemic renovation strategies will be a great opportunity to improve and enlarge the life expectancy and quality of this vast amount of modular construction systems that can be found all over the Netherlands today.

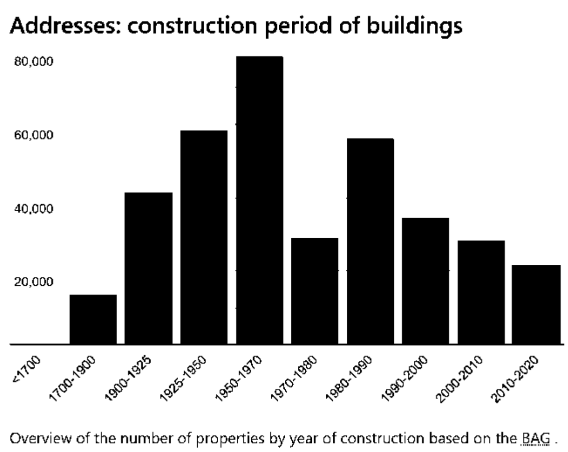


Figure 27 - Construction Period of Buildings in Rotterdam [29]

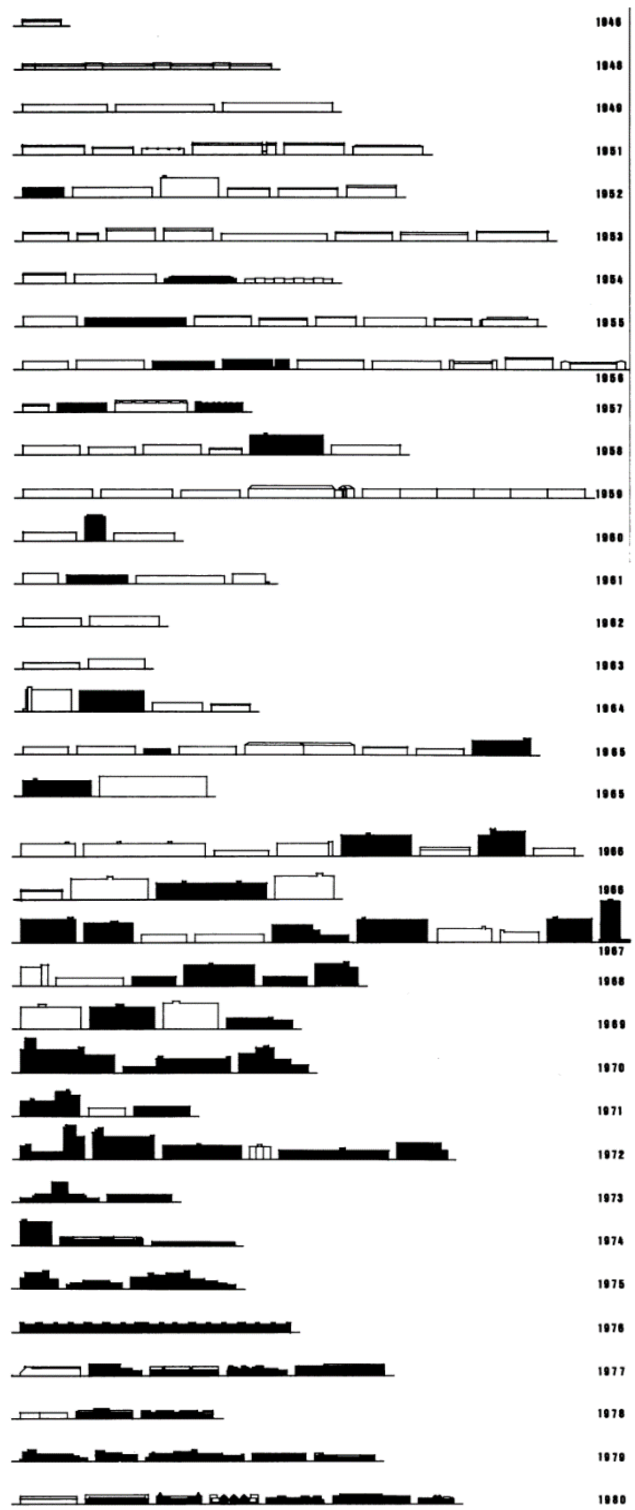


Figure 26 - Overview of building typologies and heights by year [32].

	Totaal	Stads-centrum	Delfshaven	Overschie	Noord	Hillegersberg-Schiebroek	Kralingen-Crooswijk
Voor 1906	16.248	1.954	2.646	341	4.434	177	2.149
1906-30	48.039	680	13.454	794	8.728	4.009	5.386
1931-44	32.521	719	3.005	1.125	10.110	2.625	1.978
1945-59	36.120	2.997	2.836	3.867	1.082	4.938	3.016
1960-69	35.546	103	25	341	177	3.551	495
1970-79	21.148	580	114	100	699	737	1.629
1980-89	50.035	5.963	2.917	244	3.661	779	8.111
Na 1990	48.399	3.407	4.098	841	3.921	2.845	3.588
Totaal	**288.056**	**16.403**	**29.095**	**7.653**	**32.812**	**19.661**	**26.352**

	Feijenoord	IJsselmonde	Pernis	Prins Alexander	Charlois	Hoogvliet	Hoek van Holland	Bedrijven terreinen
Voor 1906	3.416	138	299	83	417	54	140	
1906-30	9.620	554	370	323	3.878	26	217	
1931-44	2.991	1.563	239	315	7.615	149	87	
1945-59	831	756	246	137	12.973	1.651	790	
1960-69	92	12.745	700	9.273	2.690	4.732	622	
1970-79	572	3.557	47	8.567	747	2.997	802	
1980-89	4.462	5.737	18	12.889	1.487	3.031	736	
Na 1990	7.523	3.159	228	9.996	4.297	3.709	787	
Totaal	**29.507**	**28.209**	**2.147**	**41.583**	**34.104**	**16.349**	**4.181**	**35**

Table 14 - Overview of roof surface area by year of construction and Sub-Municipalities of Rotterdam [29].

An overview of the Roof Surface area by year of construction and by Sub-Municipality is shown on *table 14*.

- **1945 – 1959:** The Sub-Municipalities of Centrum, Noord Karlingen Crooswijk, Delfshaven and Overschie.
- **1945 – 1969:** The Sub-Municipalities of Hillegersberg - Schiebroek and Charlois.
- **1960 – 1979:** The Sub-Municipalities of IJsselmonde, Prins Alexander and Hoogvliet.

The relation between roof surface area and construction rate is shown in figure 28, which gives and overview of the Sub-Municipalities with the highest index of construction during this time period.

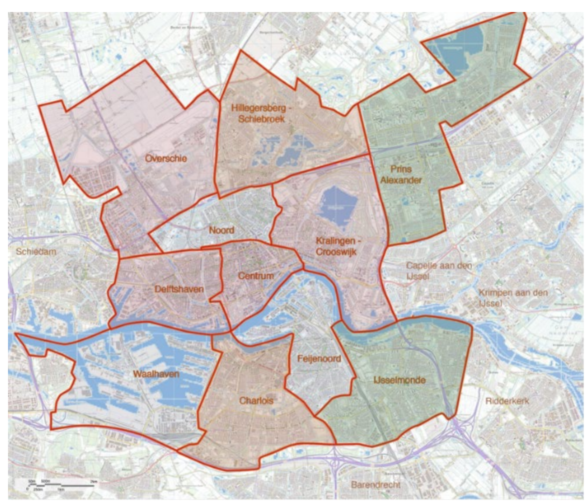


Figure 28 - Overview of municipalities and years of development.

Type dak	Totaal (m²)	Stads-centrum	Delfshaven	Overschie	Noord	Hillegersberg-Schiebroek	Kralingen-Crooswijk
Plat	10.451.333 65%	1.055.536 87%	877.353 70%	421.747 66%	817.534 74%	739.202 55%	995.038 76%
Niet-plat	5.698.543 35%	154.626 13%	369.571 30%	219.167 34%	285.724 26%	603.764 45%	317.953 24%
Totaal	**16.149.876**	**1.210.163**	**1.246.925**	**640.914**	**1.103.258**	**1.342.966**	**1.312.991**

Type dak	Feijenoord	IJsselmonde	Pernis	Prins Alexander	Charlois	Hoogvliet	Hoek van Holland	Bedrijven terreinen
Plat	908.604 63%	1.181.343 76%	64.548 46%	1.493.409 68%	1.012.357 67%	588.517 59%	296.145 21%	877.758 99%
Niet-plat	541.545 37%	367.603 24%	75.296 54%	719.485 32%	491.703 33%	406.343 41%	1.145.762 79%	9.709 1%
Totaal	**1.450.149**	**1.548.946**	**139.844**	**2.212.894**	**1.504.060**	**994.860**	**1.441.907**	**887.466**

Table 15 - Roof Surface area per Sub municipality to roof type [29].

Moreover, information about the flat roof surface area per Sub-Municipality also points out the ones with the highest potential horizontal surface of the analyzed construction systems. Table 15 shows that the 5 Sub-Municipalities with the highest rates (Figure 29).

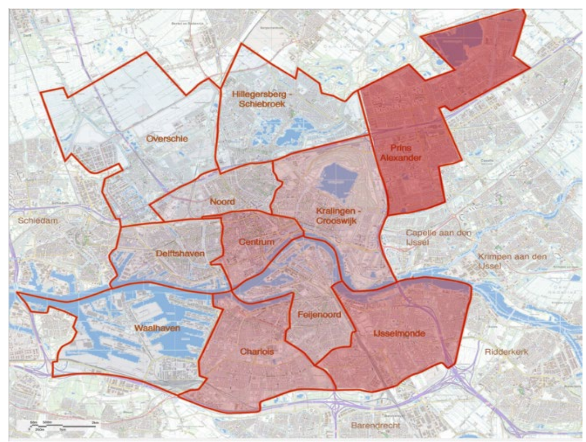


Figure 29 - Municipalities by flat roof potential areas

An open-source database of building year of construction is available online, which allows the user to visualize all the buildings registered in the municipality by year of construction. This data is updated to 2020 (figure 30).

By using this tool, it is possible to trace by color the buildings that belong to the time periods of the different Systeemwoningen.

This, combined with the information provided by the research, allowed to trace the neighborhoods of Rotterdam in which Gallery buildings and Porch Flat Typologies were developed in large scales. A few examples are shown in the following figures.

Figure 30 - Rotterdam building ages - Parallel. Source: https://parallel.co.uk/netherlands/#14.1/51.91214/4.44826/0/1

Figure 31 - Post-War typologies: Examples found through maps and databases

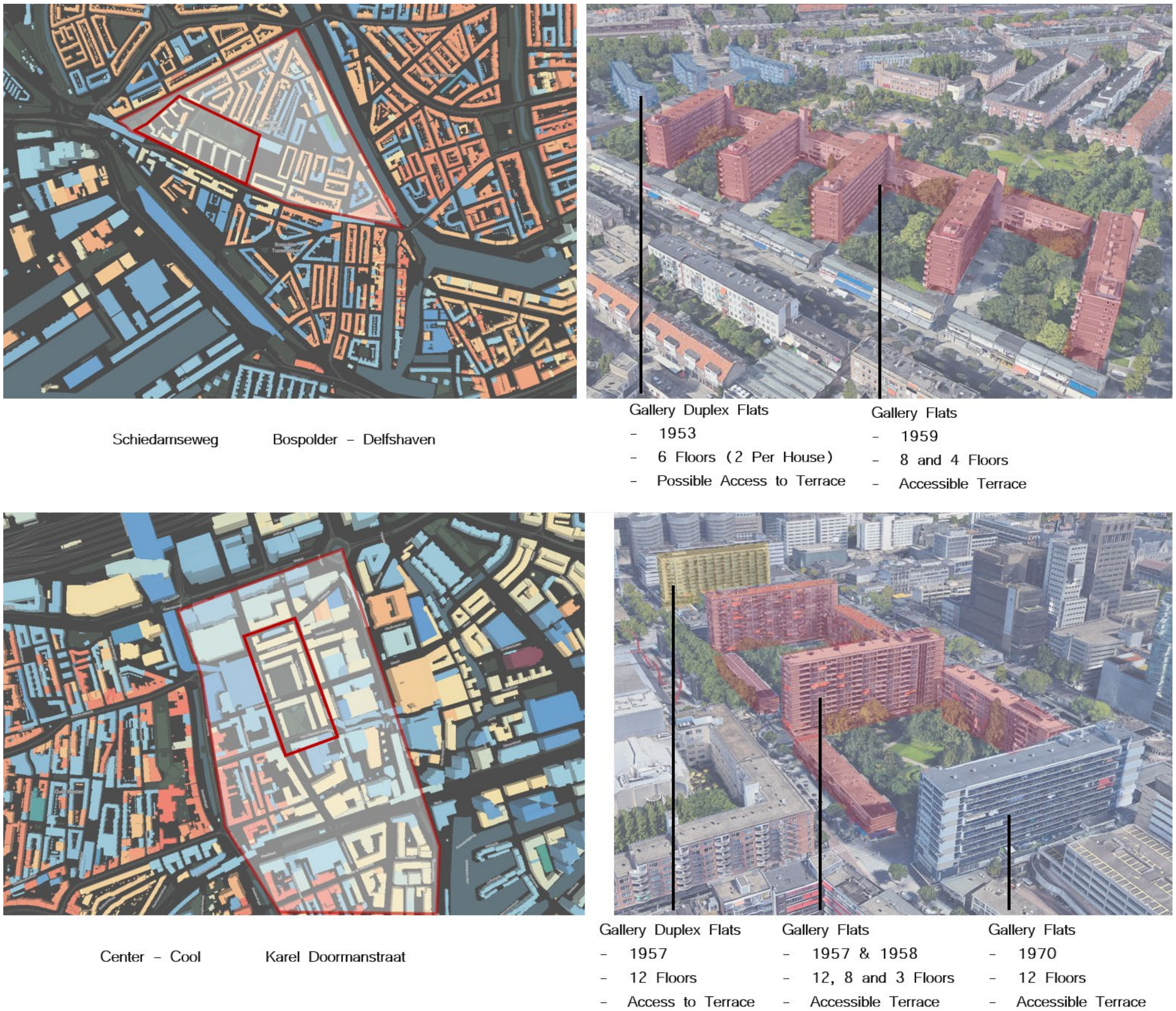


Figure 32 - Post-War typologies: Examples on Rotterdam city center

Green Roof Potential – Context

It is possible to see that the Sub-municipalities where these building typologies are concentrated are mostly Prins Alexander, Feijenoord, Charlois and IJsselmonde. Nevertheless, multiple examples of the gallery buildings can be found in all districts including Centrum, Cool and Delfshaven.

Through the research on the potential effect of multifunctional interventions and green roofs for the urban environment, three main variables were identified as the most relevant for the city:

- The reduction of Roof Surface Temperatures through vegetative surfaces.
- Water Retention for the prevention of street flooding.
- Implementation of functional roofs on highly dense areas with scarcity of space.

For this, maps showing the hotspots of recurrent flooding [34] and the Urban Heat Island map from the Hotterdam report [35] were consulted, the reason why more interest was given to the examples found in the Sub-Municipality Center.

UHI Stress maps of Rotterdam: figure 33 shoes the Sub-Municipalities that are most affected by the urban heat island effects. Information about the different factors adding to the problem can be found on the Hotterdam Report [35]. Surface permeability, albedo coefficient of surfaces, Vegetation coverage area are determinant factors for temperature accumulation, for which green roofs have proven to be of substantial benefit.

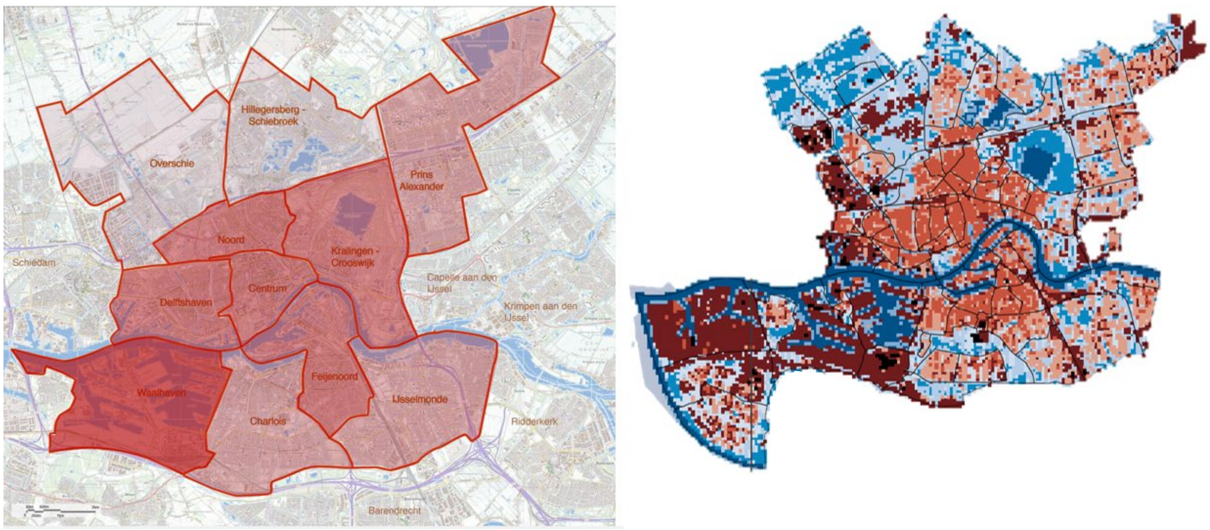


*Figure 33 - Rotterdam Heatmaps in relation to Sub-municipalities **[35]***

Flooding Risk Maps: Areas of the city that are mostly affected by flooding due to heavy rainstorms were consulted through the report on [34], which provides a map of the hotspots in the city with the most amount of flooding reports, combined with the surface ratio of imperviousness.

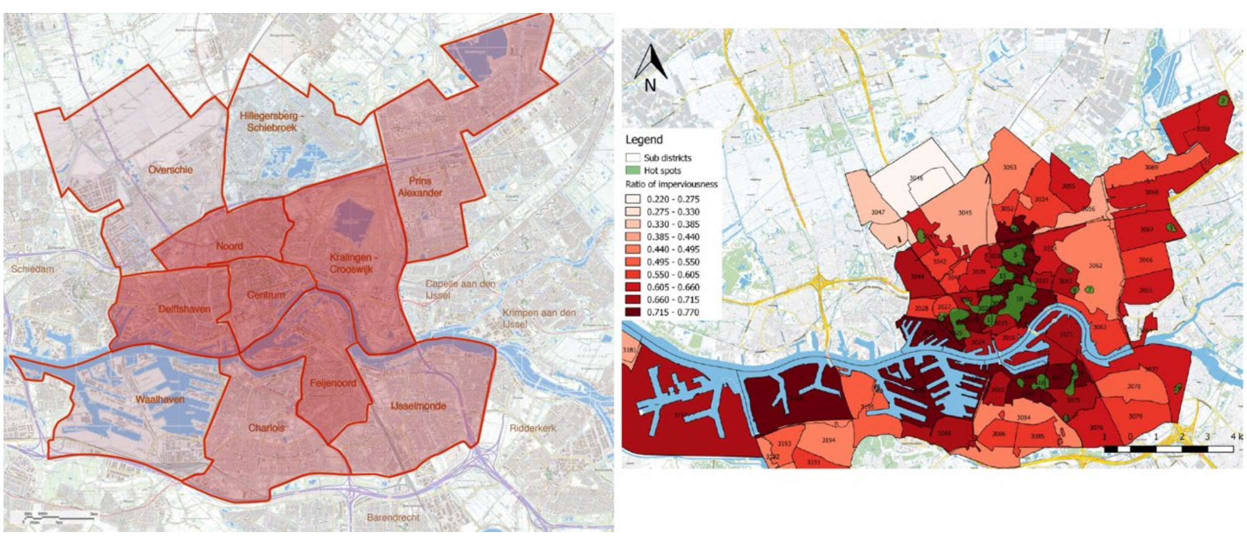


*Figure 34 – Rotterdam hotspots of recurrent flooding due to rain showers **[34]***

4.7. SELECTION OF CASE STUDY SAMPLES

The selected case study is the last example shown in (figure 39), located in the street Karel Doormstraat and composed of 9 buildings that were developed between 1957 and 1958 (except for two of them). The interest in this group is due to the variety in typologies, High-Rise, Mid-Rise and Low-Rise buildings, which at a first sight, look like the same construction system. The files were consulted at the Municipality Archive of Rotterdam. These resulted to be registered under two different dossier numbers:

- **B2-1495-1954:** High-Rise and Low-Rise
- **B2-24-1955**: Mid-Rise

Thanks to the 3D explorer of Google Maps, it is possible to see that on the High-Rise and Mid-Rise typologies, an extensive green roof system has been implemented already. Unfortunately, the updated files of the building were not available in the municipality yet, which according to them means that the intervention was carried out after 2010. The project is composed of 9 buildings arranged in groups of 3. Each group is composed of a High-Rise (14 story building), a Mid-Rise (10 story building) and a Low-Rise (3 story building) typologies in 3 separate blocks. The numeration goes from 1 to 10 but building 5 does not belong to this arrangement.

The selected case study group are in the first block, on Joost Banckertsplaats (figure 35):

- **Building III:** High-Rise 14 story building.
- **Building VII:** Mid-Rise 10 story building.
- **Building IV:** Low-Rise 3 story building.

It is possible to see that all buildings but 9 and 10 have the same façade system and the structural arrangement looks very similar, if not the same. All developed between 1956 and 1958. Buildings 9 was developed in 1970 and 10 in 1999.

The Low-Rise buildings are Porch Fat Typologies with commercial functions in basement and ground level and housing units above. The rest are Gallery Typologies with commercial functions and in some cases offices on the ground floor as well.

For the Gallery Typologies, all roofs are accessible and have a rail crane for façade maintenance. Its in Buildings III and VII that the installation of an Extensive Green Roof system was installed. For the Porch flats, an access hatch is available for maintenance.

Figure 35 - Urban Plan - Location of Buildings

Building III: High-Rise 14 story building + partial basement	
Typology	Gallery Building
Height	14 Stories + Basement
Roof Dimensions	1335.86 m^2
Roof Accessibility	Yes – Elevator + Stairs
Roof Materials	Cement insulation panels 70mm Bituminous waterproof barrier Gravel
Loadbearing Structure	Concrete casted walls 200 mm + 2 edge reinforcement columns
Roof Horizontal Structure	Concrete slab 140mm Reinforcement concrete Beams

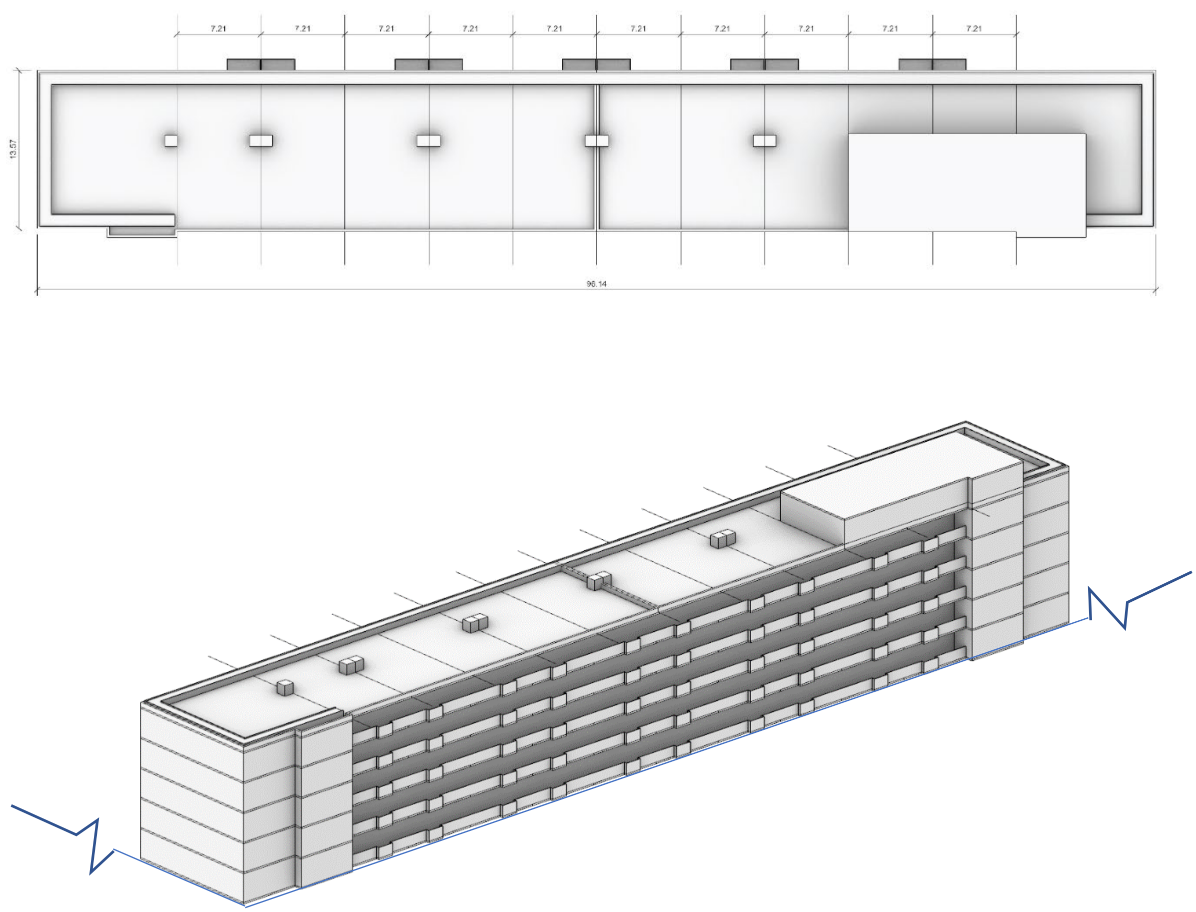
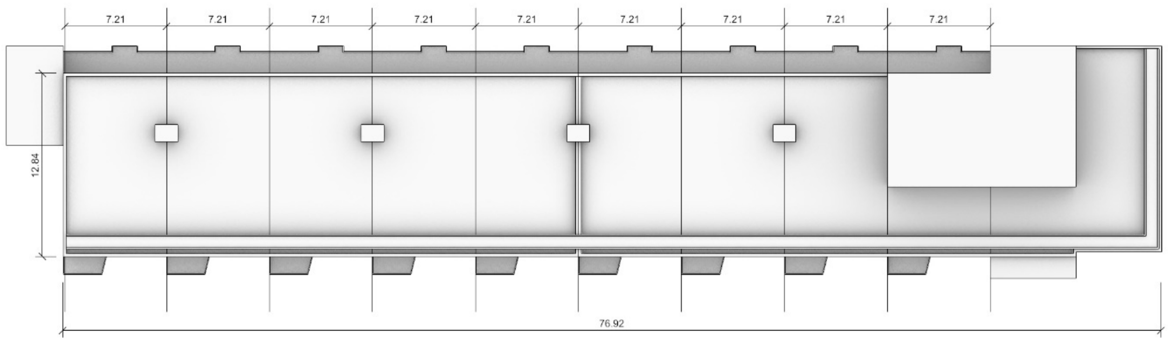


Table 16 - Selected Case Studies - Building Block III

Building VII: Mid-Rise 10 story building	
Typology	Gallery Building
Height	10 Stories
Roof Dimensions	1143.47 m^2
Roof Accessibility	Yes – Elevator + Stairs
Roof Materials	Cement insulation panels 70mm Bituminous waterproof barrier Gravel
Loadbearing Structure	Concrete casted walls 210 mm
Roof Horizontal Structure	Concrete slab 140mm Reinforcement concrete Beams



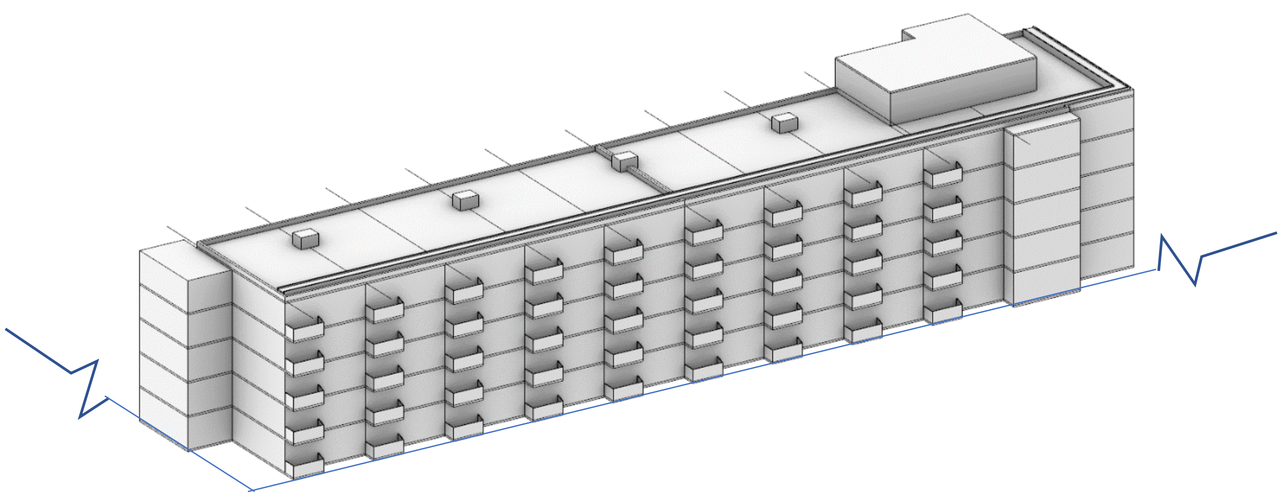
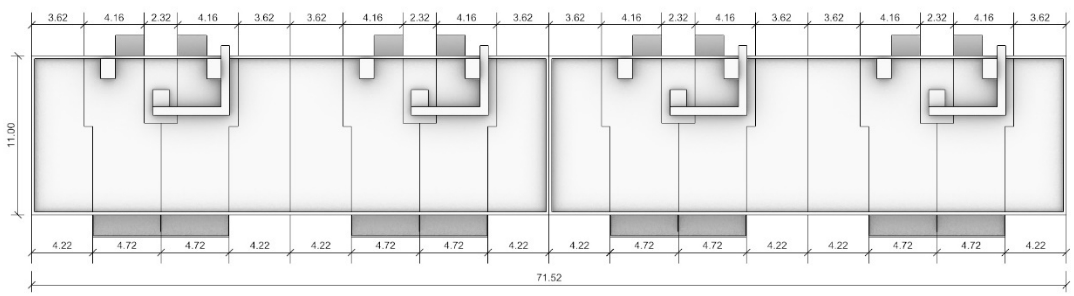


Table 17 - Selected Case Studies - Building Block VII

Building IV: Low-Rise 3 story building + Basement	
Typology	Porch Flats
Height	3 Stories + Basement
Roof Dimensions	786.72 m^2
Roof Accessibility	No – Roof Hatch
Roof Materials	Bituminous waterproof barrier Gravel
Loadbearing Structure	Concrete casted walls 210 mm
Roof Horizontal Structure	Concrete prefabricated hollow beams 120mm + 10 cm concrete layer



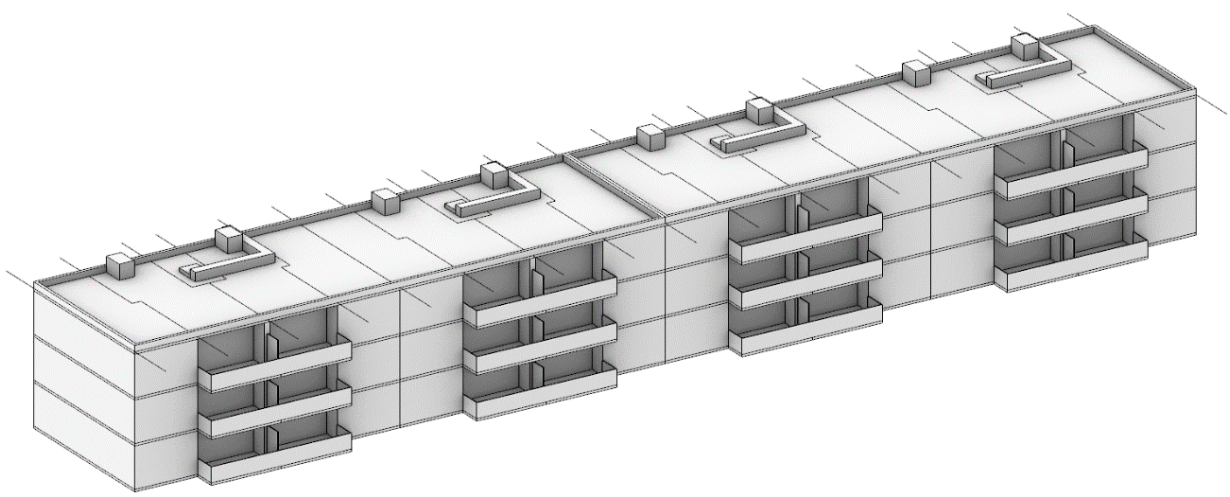


Table 18 - Selected Case Studies - Building Block IV

After analyzing the files on the Municipality Archive, many considerations were found, very relevant for the understanding of the possible situations that might make different solutions more suitable for the different cases.

Gallery Buildings

Vertical Loadbearing Configuration: It was possible to see that the main structure of the building is based on loadbearing walls braced by a configuration of a casted slab and beams. A combination of loadbearing walls and columns is present only on the vertical circulation blocks and the edge dwelling typology. As seen in figure 36, the loadbearing walls are reinforced by two column segments on building III to increase the stability due to the incremented height. For building VII the cross-section of the loadbearing wall is continuous and same in dimension from floor +2 till the roof.

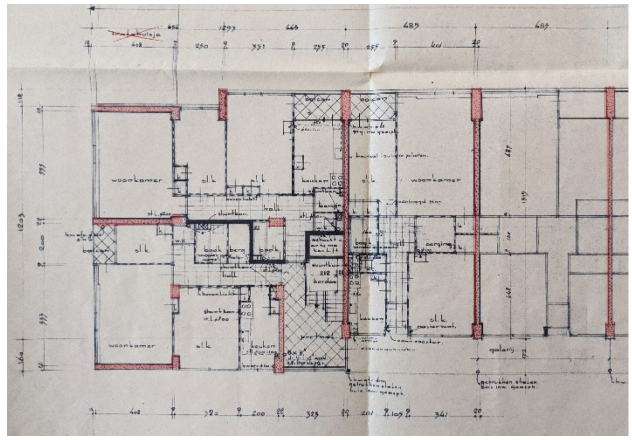


Figure 36 - Block III: Floor +2 - Column and Loadbearing wall combination.

The structure has the expansion joint in the middle of the building, separating the structure in two individual blocks (figure 37). The span from wall to wall on the modular configuration of building III is of 6.85 m and of 6.95 on the las segment of the expansion joint, where the double wall can be observed. This modular configuration is repeated 9 times between the corner dwelling and the circulation block. The same happens in Building VII, where the span between walls on the modular configuration is of 7 meters and the double wall on the expansion joint. Again, the configuration is repeated 9 times between both circulation blocks.

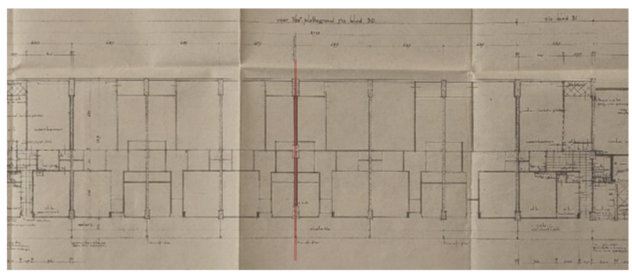


Figure 37 - Block III: Floor +2 - Expansion joint

For building 3 the loadbearing structure increases in section in floors +1 and +2 and additional reinforcement columns in ground floor. In this case, the basement is only present on the vertical circulation block. For building VII, again an increased section of walls can be seen in the ground level and +1 with no reinforcement beams. Both buildings are supported by a bracing grid of the piling system.

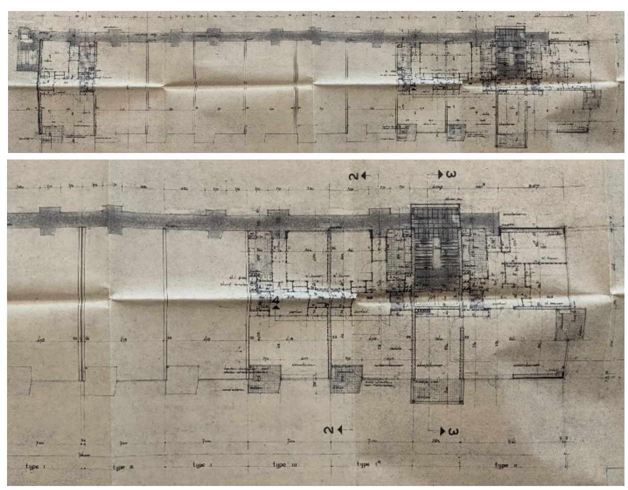


Figure 38 - Block VII: Floor +2 - Loadbearing wall distribution

Roof Structure and Configuration: As mentioned before, the rooftops of both buildings are accessible, by stairs and elevator, through the maintenance room designed on the rooftop. It is possible to see on the sections that the same slab thickness was used for the roof floor with an additional set of lightweight concrete panels that were implemented as an insulation system. It was possible to verify through the calculations included on the archive file, that the slab is designed for a load of 2 kN/m^2 on section R and S and for 3 kN/m^2 in section Q of the roof. The system of the lightweight prefabricated slabs is designed for a load of 1 kN/m^2, the load of water/snow and the ballast of the floor finish, which in this case is a bituminous waterproofing layer with gravel. Specifications on the drainage system was not found on the drawing details but through photos it can be seen drainage pipes running through both facades, collecting the rainwater from the galleries and balconies as well.

An additional consideration is the ventilation shafts from the building, which are interspersed every two house-modules. Apart from the maintenance crane installed on the roof edge of the south façade on building III and west façade on building VII, these are the only installations to consider at the roof level.

Porch Building

Vertical Loadbearing Configuration: The porch building number IV is composed of a mixed structure of columns and loadbearing walls only on base ground level. As mentioned before, the presence of the basement makes the edge load bearing walls the start of the structure. In basement and ground floor levels, to keep open spaces for the commercial functions, a set of columns are the main structure arranged along the partition of the house modules, aligned to match the loadbearing walls from floors +1 and +2 (*figure 42*).

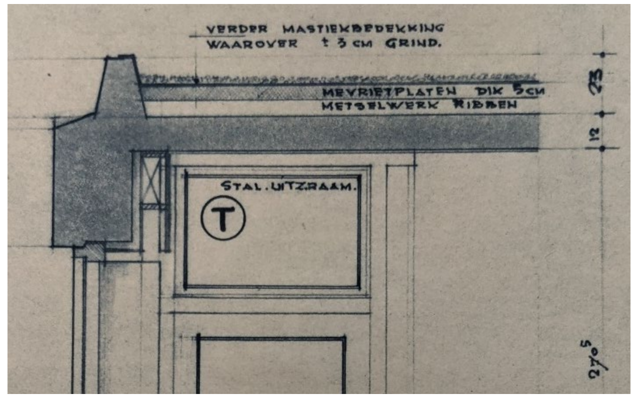


Figure 40 - Block VII: Roof structure - Concrete slab and concrete insulation panels

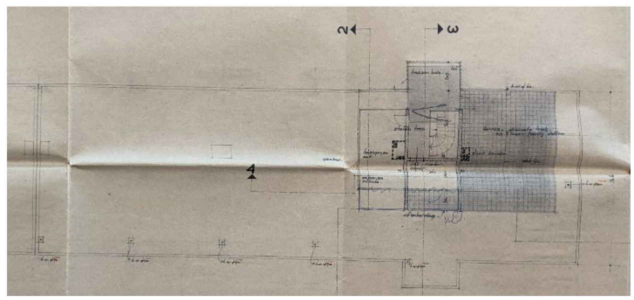
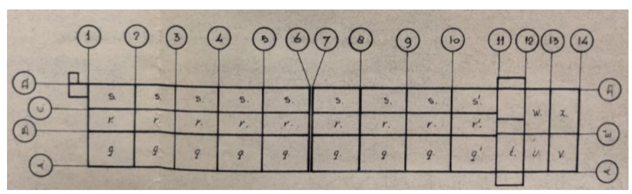


Figure 39 - Block VII: Roof level - Access and maintenance room



Floor Capacity per area:
q = 200 kg/m^2
r = 300 kg/m^2
s = 300 kg/m^2

Figure 41 - Block VII: Roof floor loading areas

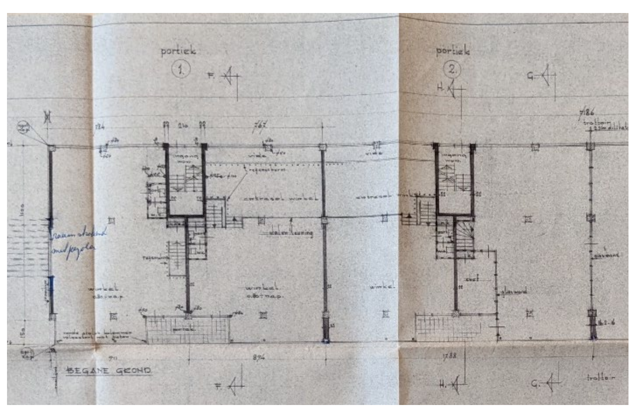


Figure 42 - Block IV: Base Ground - Combination of Wall and Column Structure

In this case the span between walls is not regular, as it follows the set of stairs accessed through the North Façade of the building to enter the flats. The stairs cover a span of 2.1 m, followed by a span of 3.65 for the first room and followed by an additional partition of 4m to reach the partition wall between flats. Then the configuration is mirrored for the next dwelling and repeated for every module. On the south façade there are only two spans of 4.2 and 4.5 m. The building is configured by 4 of these modules. Between the two of them, a dilatation joint for the building with double bearing walls can be found as well.

In this case the structure is again braced by a beam and slab reinforced concrete system. The foundation is again a braced structure for the piling system.

Roof Structure and Configuration: In this case, through the sections and available information on the roof structure, it is possible to see the presence of a slab + a series of prefabricated elements for the insulation and the final roof finish, same as in the gallery buildings. It is specified that these panels have a 5cm insulation layer below and an asphalt finish for the waterproofing layer on top. A system called "Cusveller Vloer"was used for the roof slab (figure 44). Information about the system was found online. It is based on a set of prefabricated hollow beams arranged along the span between supports on top of a wooden from work, which is later used to pour in a layer of concrete. The height of these hollow prefab beams gives the slab a total thickness of 15 cm but are much lighter than a regular casted slab. Information about the loads for which it was designed was not found but it is assumed that this lightweight system was intended to support the minimum requirement for a flat roof for inspections, rain, and snow load of 1kN/m^2. In the sections is specified as well that the drainage systems run towards both east and west facades.

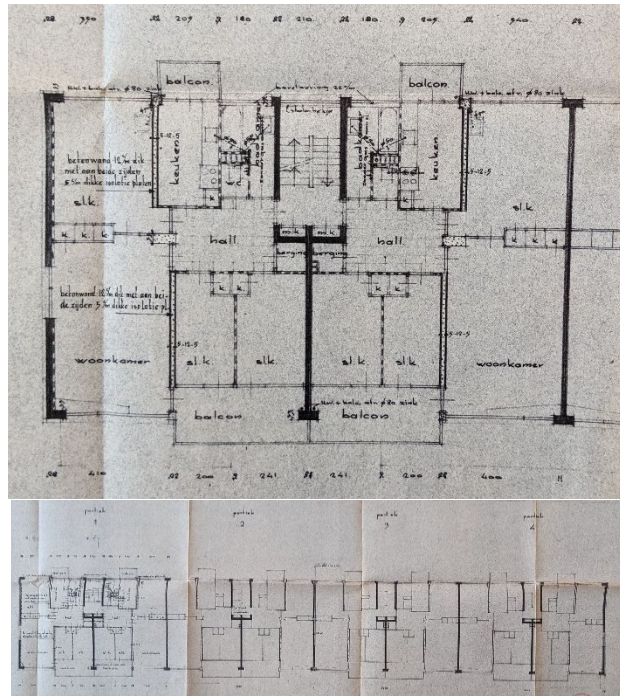


Figure 43 - Block IV: Level +1 and+2- Loadbearing wall distribution

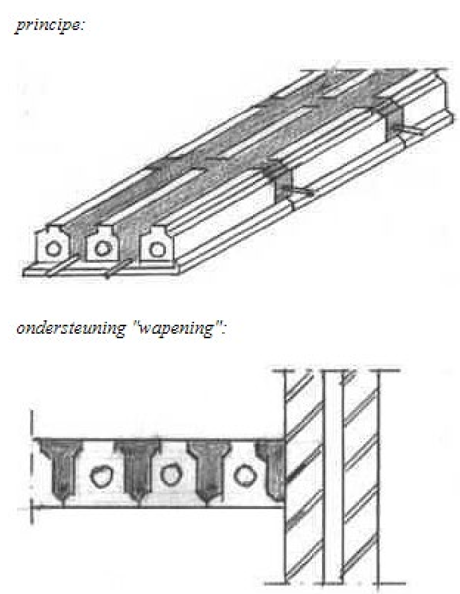


Figure 45 - Cusveller Vloer. Source: https://www.joostdevree.nl/shtmls/cusveller_vloer.shtml

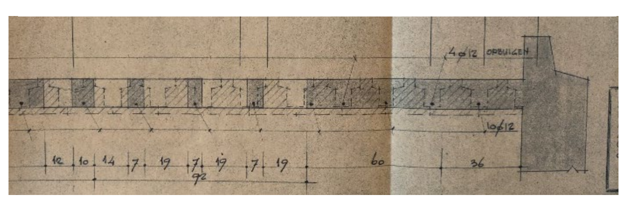


Figure 44 - Block IV: Roof structure - Cusveller Vloer

4.8. FOUNDATIONS AND WALL LOADBEARING CAPACITY

The addition of load on a roof will influence the overall structure, including the vertical structure at every level and the total received force on the foundations. This is an aspect considered in the same research on wood structures by L. Rovers **[29]**, in which it is pointed out that the most common foundation types in Rotterdam are pile foundations and strip foundations and that due to the absence of negative skin friction with the predominant sand composition of ground, for which problems with foundations settlements are very common.

Foundations: This issue was discussed with a structural engineer from DakDokters, who pointed out that a thumb rule of 5 to 10% of additional load could be withstand due to the safety factors used on the design of the foundations for a building.

The same issue was discussed with a member of the structural engineering team from the Solar Decathlon project of the SUM team from TU Delft **[36]**. For their project, they intend to calculate the additional weight that can be added to the foundations of post-war typologies for the addition of new floor levels. In accordance with the previous interview, their research and consultation with specialists pointed out that the threshold capacity that can be added to the foundations is 10% of the total weight of the existing building weight.

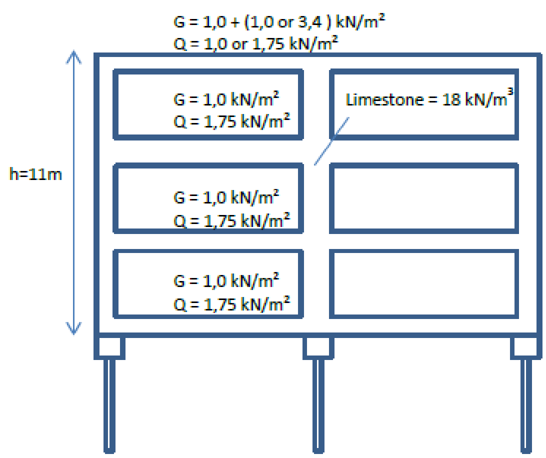


Figure 46 - Weight Estimation of simplified building [29].

An example of this calculation was done by L. Rovers **[29]**, taking an example of a building of wooden floors of three stories height (11 m height). With this quick estimation, it was shown that the weight of an extensive roof could increase by 5% the estimated weight of the building, and the implementation of an intensive green roof could create an increase of 20% of increase that would not be suitable anymore without additional studies or interventions on the foundations.

The drawings from the selected building samples were consulted to see if any calculations for the foundations was available. Unfortunately, only the location and capacity of the implemented pilots were found with incomplete pages of the calculations.

Loadbearing Walls: To understand the limitations of the building and the design, it is also important to know the load that the loadbearing wall supporting the roof can take. Two of the studied typologies showed solid concrete walls that appear to have been casted on site. The Low-Rise typology on the other hand, shows a masonry system combined with a column system for the ground floor. In any case, the worst possible scenarios need to be considered, as the idea is to make the reinforcement system as universal as possible for the existing buildings of the selected group.

The compressive strength of the wall materials will be able to resist the additional weight of any intervention. The risk is for the walls to fail due to buckling. A solid prefab concrete wall will in most cases be more resistant than masonry systems. For this reason, two of the most vulnerable masonry construction typologies were selected to conduct calculations and determine the maximum force they can receive before reaching failure by buckling. The selected samples were PRONTO, a Clay Brick double layer construction, and MUWI, a single layer hollow concrete block construction. Both options were considered as empty cells and without any internal reinforcement.

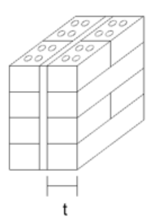
The material values specified in *figure 47* were used as a reference based on the normative and producer websites. The calculations were conducted based on the following Eurocodes:

- NEN-EN 1990 Basis for structural design
- NEN-EN 1996 Design for Masonry Structures

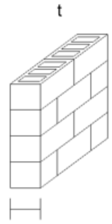
The calculations were conducted for both, the maximum distributed force and the maximum concentrated force for both options, considering the best-case scenario (with the highest material values) and the worst-case scenario (with the lowest material values).

Construction System		Values [N/mm2]
Clay Bricks Perforated Hollow	Lowest	29.40
	Highest	42.50
Concrete Hollow	Lowest	14.00
	Highest	24.00
Mortar M4 – M10	Lowest	4.00
	Highest	10.00

Clay Bricks	
System	PRONTO
Thickness [m]	0.17



Concrete Blocks	
System	MUWI
Thickness [m]	0.21



Construction System	Clay Bricks – Perforated Hollow - Lowest

$$h_{ef} = \rho_n h$$

Variable	Value
ρn	0.75
H [m]	2.80
Result (mm)	
2100	

$$t_{ef} = \rho_t t$$

Variable	Value
t	0.17
ρt	1
Result (mm)	
170	

Slenderness Ratio	
Hef/ tef	12.35

$$f_k = K f_b^{\alpha} f_m^{\beta}$$

Variable	Value
k	0.55
Fb	29.40
Fm	4.00
α	0.75
β	0.30
Result (N/mm2)	
10.52	

$$f_d = \frac{f_k}{\gamma_m}$$

Variable	Value
fk	10.52
Ym	3
Result (N/mm2)	
3.51	

$$N_{Rd} = \Phi\, t\, f_d$$

Variable	Value
Φ	0.80
t	170.00
fd	3.51
Resut (kN/m)	
477.15	

$$e_i = (M_{id} / N_{id}) + e_{he} \pm e_{init} > 0{,}05t$$

Variable	Value
(Mid / Nid)	0.00
ehe	0.00
einit = hef/450	4.67
ei	4.67
Ei / t ef	0.03
Minimum value	0.05

Result	
Φ	0.80

Figure 47 - Loadbearing Capacity Calculations - Distributed Load

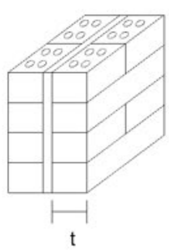
The results of all options are shown on *table 19*. It is possible to see that the MUWI system, under the worst-case scenario performed the worst, reaching a maximum load of 274.53 kN/m before failure by buckling. Clay bricks obtained a maximum of 477.14 kN/m in the worst-case scenario.

Construction System		Nrd [kN/m]
Clay Bricks Perforated Hollow	Lowest	477.15
	Highest	629.06
Concrete Hollow	Lowest	274.53
	Highest	531.52

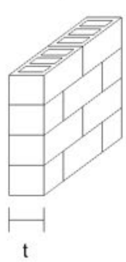
Table 19 - Distributed Load Maximum Capacity Results

Construction System		Values [N/mm2]
Clay Bricks Perforated Hollow	Lowest	29.40
	Highest	42.50
Concrete Hollow	Lowest	14.00
	Highest	24.00
Mortar M4 – M10	Lowest	4.00
	Highest	10.00

Clay Bricks	
System	PRONTO
Thickness [m]	0.17



Concrete Blocks	
System	MUWI
Thickness [m]	0.21



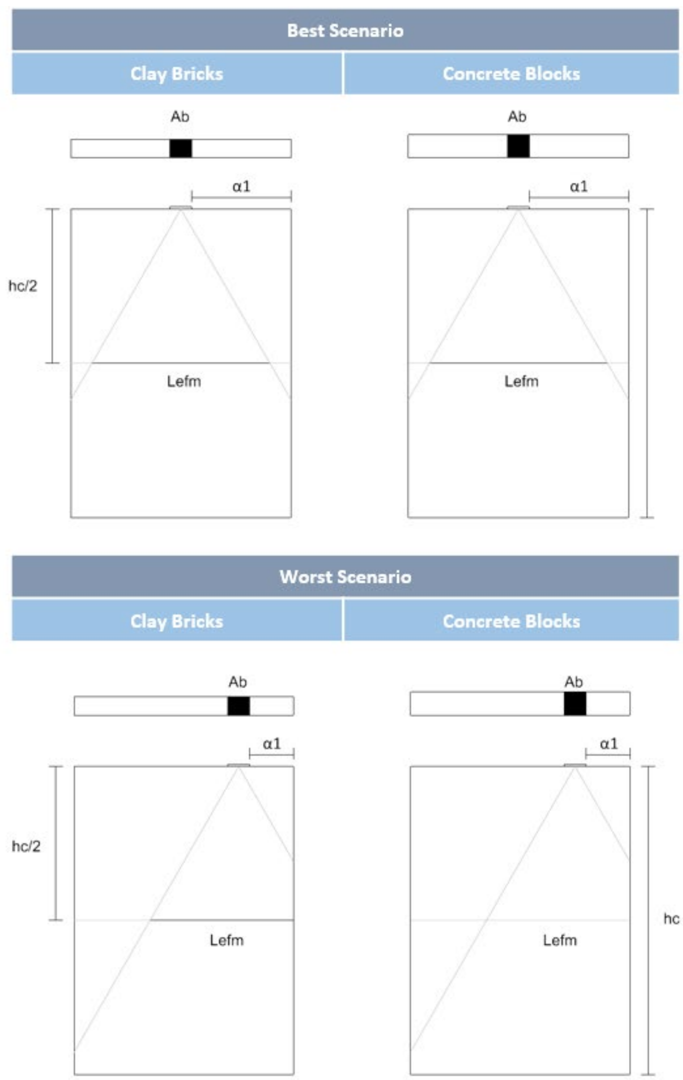


Table 20 - Loadbearing Capacity Calculations - Point Load

Concentrated loads were also tested to understand the maximum load that could be transferred in concentrated points along the wall. For example, a beam system.

For this, the constructions and same material properties were used. Two calculations were conducted for each scenario and for both, worst- and best-case scenario:

- Force at the middle of the wall: 2000 mm
  At a safe distance from the edges, where the capacity will be higher.

- Force at the closest loading point to the edge: 500 mm
  In case the beam is resting near the wall end, which would be the weakest point with a safety margin.

Table 21 shows the results from all samples. These values will be very important for the design process, to verify that the force distribution strategies satisfy all scenarios.

Example	
Clay Bricks	Best Scenario

$$N_{Rdc} = \beta A_b f_d$$

$$\beta = \left(1 + 0{,}3\frac{a_1}{h_c}\right)\left(1{,}5 - 1{,}1\frac{A_b}{A_{ef}}\right)$$

Result
210.34

Variable	Value
A1 [mm]	990.00
Hc [mm]	2800.00
Ab [mm2]	40000.00
Aef [mm2]	324000.00
l efm [mm]	1620.00
t [mm]	200.00
b [mm]	200.00
Result	
β	1.51

Or	1.3375
The Lesser	

Clay Bricks			
Highest [kN]		Lowest [kN]	
Worst Scenario	Best Scenario	Worst Scenario	Best Scenario
210.34	207.81	170.19	157.63

Concrete Blocks			
Highest [kN]		Lowest [kN]	
Worst Scenario	Best Scenario	Worst Scenario	Best Scenario
161.12	159.26	114.78	106.30

Table 21 Loadbearing Maximum Capacity Results - Point Load

4.9. ROOF RESIDUAL CAPACITY

Literature on roof residual load capacity was consulted to have an estimate of the load for which concrete roofs were designed. This will give an idea of what it is possible to install today with their current conditions.

M. Karim, from Hogeschool Rotterdam, researched on Repurposing Existing Concrete Roofs **[37]**. With the objective of analyzing the residual capacity of concrete structures for the implementation of green roofs in large surface areas in the city of Rotterdam, she analyzed buildings constructed during 1955 and 1975 (as, explained before, the largest growth period of Rotterdam). In her Research, she established the most common system to be the Cast-In-Place, 4-Side line supported roof slab. The goal was to establish a Quick-Scan method to evaluate the existing structure and approximate its structural capacity and the residual capacity of reuse.

The conclusions were that concrete values are likely to be higher than in the design calculations due to the increase of strength caused by the Hydronation Process, the residual capacity gain during the lifespan of the material. Moreover, the safety standards of production of today are lesser due to the increase of accuracy and reliability in calculations and fabrication procedures. During that time, the Working Stress Method was used for the calculation of concrete’s capacity, which gives more conservative results than the methods used today.

Additionally, she points out the importance of the Archival Research process to understand the design and possible constraints that need to be accounted for. By doing so, determining the requirement of Non-Destructive, Destructive or Visual Assessment to complement the deductions and results of a case study.

Lastly, the comparison between the safety factors used in regulations back then to the ones established today for roofs show that the combined factors (Loads + Materials) Is higher than on the current EC-2 regulations.

(1962) TGB' 62 = **1.64 kN** - (1992) EC-2= **1.34 kN** / Residual Capacity = **0.29 kN.**

"Kennispaper: Duurzame begroeide daken" (Knowledge Paper: Sustainable vegetated roofs), by C.M. Ravesloot **[38]** is the result of two years of research on green roofs on the Dutch context and climatic conditions financed by the municipality of Rotterdam. In this report, among relevant performative characteristics of green roofs, the structural capacity of steel roofs and concrete roofs is discussed.

It is stated that, based on calculations, no residual strength can be found on steel or concrete roof structures. For concrete, a residual capacity might be present in practice due to added strength of materials and production process to ensure the safety of the products. According to theoretical calculations, concrete roofs have no residual force for the green roof ballast. Ideally, additional capacity could be saved by the replacement of the gravel and tiling ballast, which could account for an additional **0.50 to 0.80 kN.**

The research on "Structural Assessment of Existing Timber Roof Structures for Green Roofs in Rotterdam", by L. Rovers **[29]** analyzed the potential of reinforcing wood structures of traditional construction systems for the implementation of vegetative roofs in Rotterdam.

As part of the research, for the determination of the minimum capacity for which they were designed implied studying the construction normative from TGB to the current Eurocodes, comparing if the loading conditions for roofs varied over the years.

The comparison shows the norms from 1920, 1933, 1949, 1955, 1972, 1991 and 2012. Norms stayed more or less the same over the years. Variable loads have been the same, where 1.00 kN/m2 maintenance load is always governing over snow and a maximum allowable deflection around L/400 is determined. Only from 1972, additional considerations for the deflection are accounted for, including permanent deformations due to creep. Load combinations have also stayed the same through the years. The conclusion of this research is that no design code was too conservative, meaning that for wood structures, there is not an overdesign that could be accounted for residual capacities.

Summary

In summary, it can be expected that roofs were designed for a variable load of at least 1.00 kN/m2 in accordance with all previous norms. Moreover, by replacing the current roof finish of gravel or tiling, an additional ballast of 0.50 to 0.80 kN/m^2 could be saved as an additional reserve. An additional residual capacity might be found and present in concrete structures. Specially for these new construction systems, for which higher safety factors would have been applied to ensure the safety of the products. Nevertheless, this last assumption can only be proven by performing destructive or non-destructive testing that could allow to find out the actual capacity of the floor.

4.10. CONCRETE REINFORCEMENT SYSTEMS

Research on literature about roof reinforcement systems was carried on. Information on reinforcement of wood and steel structural systems was found **[38]**. A few companies were consulted to gain more knowledge on the field, but unfortunately with no response.

Figure 48 - De Boel Project - Heeswijk Architecten -Amsterdam [39.]

Through the contact with the companies of Metropolder and DakDokters **[17]**, a few design cases were discussed in which a reinforcement system for a concrete structure was applied, from which they could share their experience. The most relevant case for this research was for the "De Boel" project, by Hans van Heeswijk Architecten in DeBoelenlaan, Amsterdam **[39]**. A renovation project of a Post-War gallery building for residential and office functions. For this project, the concrete slab from the roof needed to be reinforced to make it accessible for the users and to implement new housing units as well.

Figure 49 - Figure 40 - De Boel Project - Heeswijk Architecten - Amsterdam - Section overview [39.]

It was explained that the incremental costs come from the process and required machinery rather than the material costs, as concrete is a very economic option. Moreover, the additional costs of analysis and testing, required to determine the adequate intervention, add up to the process as well.

Analysis: In most cases, determining the current loadbearing capacity of the structural element will be needed to properly assess the reinforcement requirements. This could require simple visual inspections, or also non-destructive or destructive testing as well. In case testing is required, accessing the structure is required, which will imply to remove the finish layers from the testing points. The process of testing and evaluation is an additional cost that needs to be considered.

Process: Once the reinforcement requirements are defined, first the roofing finishes must be removed. This implies the need to dispose of the gravel finish or tiling system and the difficult process of removing the bituminous waterproofing layer. This is a very labor-intensive task, followed by a similar intensive process of grinding the surface of the concrete slab to add porosity and roughness. This, to create a coherent joint between the existing slab and the new layer that will be poured on top. An additional grid of reinforcing steel is added as well before pouring the concrete. In case the slab will be reinforced from below, the removal of the roof finishes will not be required, but an intervention from below will imply accessing all the apartments and the removal of the interior finish layers. Moreover, If the ceiling height is not enough, the visual impact and change of height needs to be considered. The machinery required to pour the concrete will be the most demanding equipment for this intervention. It is not clear the amount of strength that can be added to the slab through this process and if there is a limit.

Figure 51 - Alternative Reinforcement Systems - I&S Repository TU Delft.

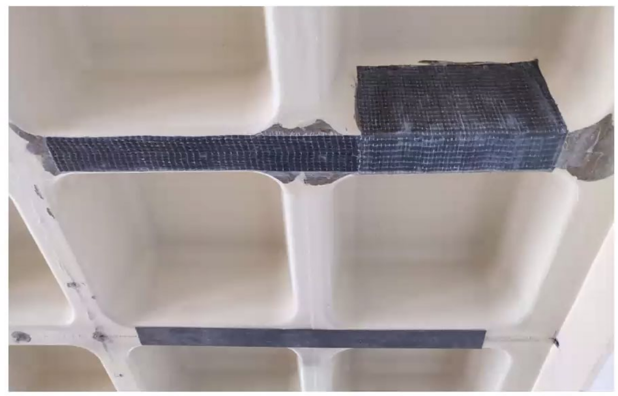


Figure 50 - CFRP Concrete Reinforcement System - Eckersley O'Callaghan (2021) - Sustainable Structural Design Seminars.

24 kg/m2 can be expected for every centimeter of reinforced concrete added to the structure, for which a minimum of 5 cm could be expected, making an additional 120 kg/m^2 of deadload for the structure. For some systems of prefabricated elements this process might not be possible. Nevertheless, as shown in the The Boel project, this approach results in a fully functional roof that can be used for intensive interventions and additional functions like the penthouses included on 2 thirds of the building. A very profitable investment for the building owner. Moreover, no structure interrupts neither the slab nor the ceiling below, giving a complete design freedom for any roof intervention.

An additional reinforcement technique was presented by the Eckersley O'Callaghan firm at the Sustainable Structural Design seminars (SSD) organized by the faculty of Architecture in TU Delft. A series of CFRP reinforcement bands is joined to the concrete elements to increase the flexural resistance of the desired elements. The example was shown on the reinforcement of a grid of beams for the renovation of a building structure (figure 50), for updated functions and requirements.

As mentioned in the "Kennispaper: Duurzame begroeide daken" (Knowledge Paper: Sustainable vegetated roofs) by C.M. Ravesloot [38], investment on measures that will bring more benefits for the specific design case will likely balance the costs. A higher permissible load will bring more possibilities for these surfaces and allow combining functions for the benefit of everyone, which is the future of the sustainable use of roofs.

4.11. BUILDING WEIGHT ESTIMATION

For the building weight estimation, the three selected case studies were analyzed. The building components considered for the estimation were the following:

Structural Elements: Columns, beams, loadbearing walls and slabs will be quantified by volume of reinforced concrete.

External Walls: The walls that compose the façade were categorized based on the drawings. It was possible to see that the same materials were used in both gallery buildings and as well some repetitions for the Porch Flat typology.

Three main groups are considered for the weight estimation:

- Brickwork Front Façade
- Concrete Blocks Basements
- Wooden Framework Glass Façade

For the quantification, the internal partitions were not considered and are assumed to be included in the occupancy load assigned to the building, as renovations and redistributions might vary along the lifespan of the building and their weight is not that impactful. A value per linear meter of each wall typology was calculated for the floor height of the building to conduct the quantification per linear meters of wall.

Occupancy: Based on the loads defined by the norms, the different spaces were categorized into the following groups:

- Living spaces: Household areas
- Circulation areas: Galleries, stairs, halls etc.
- Balconies and terraces
- Roof areas: In this case, only the deadload of non-accessible areas is taken as an example for all cases.

Analyzed Segment: As explained before, the buildings were designed under modular configuration. To simplify the process, only the representative module of the building was selected for the analysis. It is assumed that these modular segments of the building, which represent 80 to 90% of the total area, are the lightest areas as well, as the rest is occupied by the vertical circulation bocks that will quite likely have a heavier load.

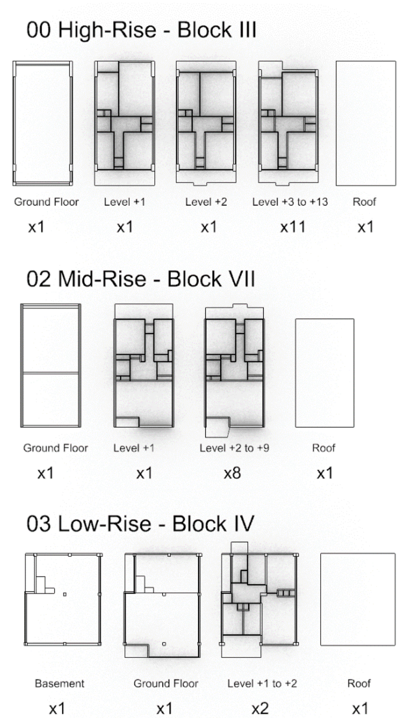


Figure 52 - Building Case Study - floor plans for weight estimation.

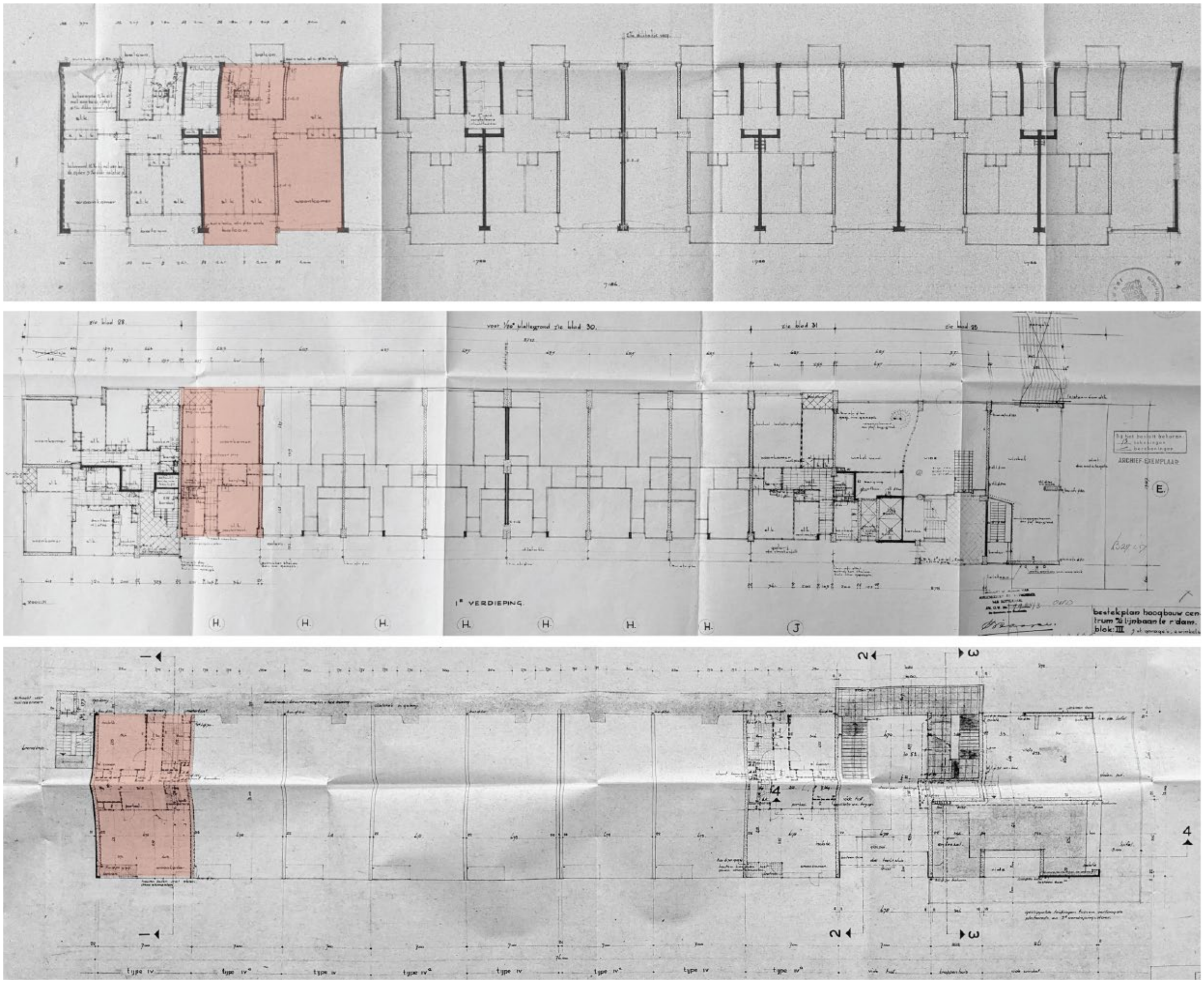


Figure 53 - Building Case Study - Analyzed Segments of the Buildings

Wall Typologies			
Typology	Components (% Façade Coverage)	Height (m)	Weight (m)
External - Wooden Frame Glass/Laminated	• **100%** • Glass • Wood framing • **50%** • Insulation • Limestone lightweight blocks • Plaster	2.40	**1.12 kN/m**
External – Brick + Glass frames	• **50%** • Brick finish • Wood Framing • Insulation • Limestone lightweight blocks • Plaster • **50%** • Wood framing • Glass	2.40	**3.10 kN/m**
External – Concrete + Lightstone blocks + Top Window	• **80%** • Concrete Blocks • Limestone lightweight blocks • Insulation • **20%** • Wooden Frame • Glass	2.60	**9.80 kN/m**

Live Loads	
Area	Load (kN/m^2)
Living Spaces	2.00
Circulation + Balconies	2.50
Roof	1.50

Structure	
Volume	Load (kN/m^3)
Beams	2.40
Walls + Columns	2.40
Slabs	2.40

Table 22 - Material and construction weight index for weight estimation.

Loads		
Component	Item	Load (kN)
D1	Structure	10673.60
D2	Wall – 1	130.87
D3	Wall – 2	215.37
D4	Wall – 3	124.66
D5	Living Spaces 2	317.82
D6	Living Spaces 1	1639.95
D7	Circ. Areas	573.53
D8	Balconies	171.15
D9	Roof	157.79

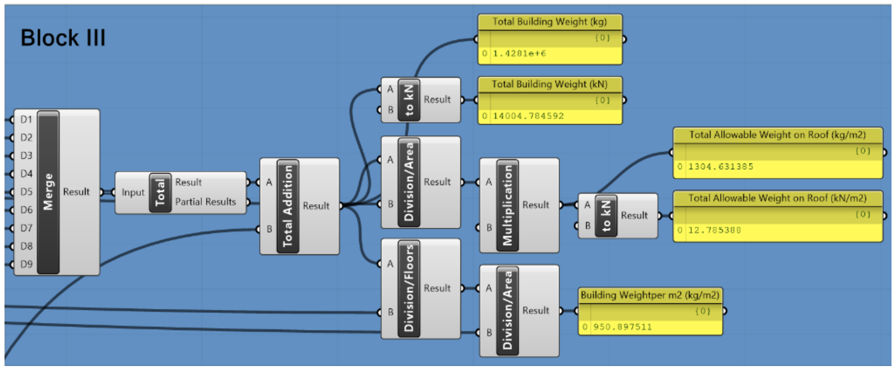


Table 23 - Weight Estimation Individual Results.

Weight Estimation of Case Studies						**Only Intervention**	5 cm Concrete Reinf. (Load + 1.18 kN/m^2)
Building	Floors (n)	Area (m^2)	Total Segment Weight (kN)	Building Weight per m^2 (kN/m^2)	Allowable Load on Roof per m^2 (kN/m^2)	Compatible Combinations	Compatible Combinations
Block III	14	103.39	14004.78	9.31	12.78	All	All
Block VII	10	91.05	9332.38	10.24	10.04	All	All
Block IV	4	98.34	5085.94	12.92	5.06	A + B + D + E	A

Table 24 - Building Weight Estimation of the Case Studies + maximum Load Combinations

Weight Estimation Based on typology VII (Basement + Levels)						Only Intervention	5 cm Concrete Reinf. (Load + 1.18 kN/m^2)
Building	Floors (n)	Area (m^2)	Total Segment Weight (kN)	Building Weight per m^2 (kN/m^2)	Allowable Load on Roof per m^2 (kN/m^2)	Compatible Combinations	Compatible Combinations
Block VII	2	91.05	2952.67	16.21	3.17	-	-
"	3	"	3730.59	13.65	4.01	A	-
"	4	"	4508.51	12.38	4.85	A + B + D + E	A
"	5	"	5286.43	11.61	5.69	A + B + D + G + H	A + B + D + E
"	6	"	6064.35	11.09	6.52	All	A + B + D + G + H
"	7	"	6842.27	10.73	7.36	All	All
"	8	"	7620.20	10.46	8.20	All	All
"	9	"	8398.12	10.24	9.03	All	All
"	10	"	9176.04	10.07	9.87	All	All
"	11	"	9953.96	9.93	10.71	All	All
"	12	"	10731.88	9.82	11.54	All	All
"	13	"	11509.80	9.72	12.38	All	All
"	14	"	12287.72	9.63	13.22	All	All

Table 25 - Estimation of Building weights per floor based on case study + Maximum Load Combinations

As a result, it is possible to see the weight estimation of one module of the building for each typology. From these results, it's possible to have an overview of the maximum load per square meter that the building can take based on the additional 10% of load available on the foundations. Table 24 gives an overview of the capacity for each case and the compatible functions based on the loading cases previously formulated.

Moreover, based on the construction system and loads of building III, an estimation of different building heights was made to estimate possible residual capacities on gallery buildings of similar construction systems. This is a very rough estimate, but it gives an idea of the possible restrictions that different heights could have. In every case, a basement configuration is considered as a ground floor.

Table 25 shows the estimated residual capacities and the compatible functions based on the load cases. An additional overview is highlighted in dark blue, if the minimum 5 cm of reinforced concrete is considered as part of the added weight to the building.

It is possible to see that, without considering the weight of the roof reinforcement system, buildings above 5 floors can withstand the weight of all the combinations. In case concrete reinforcement is considered, the same happens with buildings above 7 floors height.

4.12. BUILDING SCALE CONCLUSIONS

The literature review on the Post-War typologies highlighted the great opportunity of developing systemic solutions for these modular and industrialized construction systems. Interventions to improve their quality for future renovations that can be applied to a large mass of buildings due to their similarities in structural configuration and distribution. The predominant Gallery Buildings and Porch flat typologies are a highly valuable target for the city of Rotterdam.

Which are the main factors increasing the costs and difficulty of current reinforcement methods?

The main factors identified for the increased cost of concrete slab reinforcement methods are:

- Determining capacity and reinforcement requirements.
- Accessing structural layers for visual inspections and testing.
- Removing roof finishing layers and disposal of materials.
- Accessing Apartments and removal of ceiling finishing layers and possible changes in aesthetics.
- Work intensiveness to prepare the concrete surface for additional layers.
- Heavy Machinery for transportation and pouring the new concrete layer.

These are assumed to be the main variables for the price range found on the SCBA tool. The increased prices of these approaches are part of the factors discouraging investors.

Which are the building parameters to determine the limits of intervention?

The main building parameters to consider the limits of a roof intervention are:

- **Foundations:** The estimated additional capacity that the foundations of a building can take are around 10% of the total weight of the building. By determining the average load of the construction, an estimation of the maximum applicable weight can be determined.
- **Loadbearing wall capacity:** It was found that the great majority of these construction systems are based on loadbearing walls. Nevertheless, the construction systems variate between Casted walls, prefabricated concrete panels and reinforced masonry concrete blocks. Sticking to the worst-case scenario to design a universal solution for these typologies, (table x) shows the limit values that should be considered for any proposed solution.

- **Span between walls:** The distance between supports will determine the possible solutions available for each case. For Gallery buildings, a uniformly repeated span is very common, facilitating the use of a repeated modular structure, but for some buildings, especially Porch flat typologies like case study number IV, variable spans can also be the case.
- **Additional design considerations**
    - **Slope:** Considering the existence of a slope and the location of the drainage system of the roof will require design considerations for the implementation of the water buffer layer.
    - **Insulation:** In case the roof was not renovated, additional insulation will play a big role on the performance of this surface and needs to be considered on the reinforcement strategy.
    - **Installations:** Ventilation shafts, access hatches, skylights, maintenance cranes, safety lines or hooks for roof inspections and other elements might be present on the roof and need to be considered on the intervention.

What alternative systems could be applied to reinforce the roof structure?

Designing for the Worst-Case Scenario: Following the objectives for the Design Scale, the ideal outcome would be to provide a solution for as many buildings as possible. Not only to upscale the implementation of roof multifunctional interventions, but also to lower any production costs of the developed solution even more. To take advantage of the replicability potential for post-war buildings, it is important to consider the worst-case scenarios of the building's structural capacity and requirements. If the system is designed considering these minimum requirements, it ensures that the system is suitable for any building of the target group. The variables that should be considered are:

- Loadbearing capacity of foundations and the vertical loadbearing structure
- Roof loadbearing capacity
- Maximum and minimum span and variable span distances

External solutions: Moreover, based on the consultations with companies and insights given by the reviewed literature, a big opportunity could be presented by developing an external structural solution. The objective of such an approach would be to avoid (or reduce as much as possible) any intervention on the current structure or finish layers. An external system that can be mounted to the current structure with as minimum intervention as possible.

Residual Capacity: The case of building number VII shows that there might be cases in which the roof was designed for larger capacities. Especially for Mid-Rise and High-Rise gallery buildings, where access to the terrace through the maintenance units on the roof are normally provided. This might lead to more opportunities and possibilities for functional accessible areas, for which the evaluation of a larger sample to verify how often this situation is repeated would be of great value.

As mentioned before, the use of the existing structure for the intervention is a sensible approach from a sustainable point of view. Roofs might not have a residual capacity, but the minimum capacity determined by the norm can be assumed. The use of the existing structure for the implementation of some layers like the water buffering system, the insulation, and others, could reduce the load factor for the new structure and therefore reduce wight and costs. For this, a feasible way of combining both structures would be necessary.

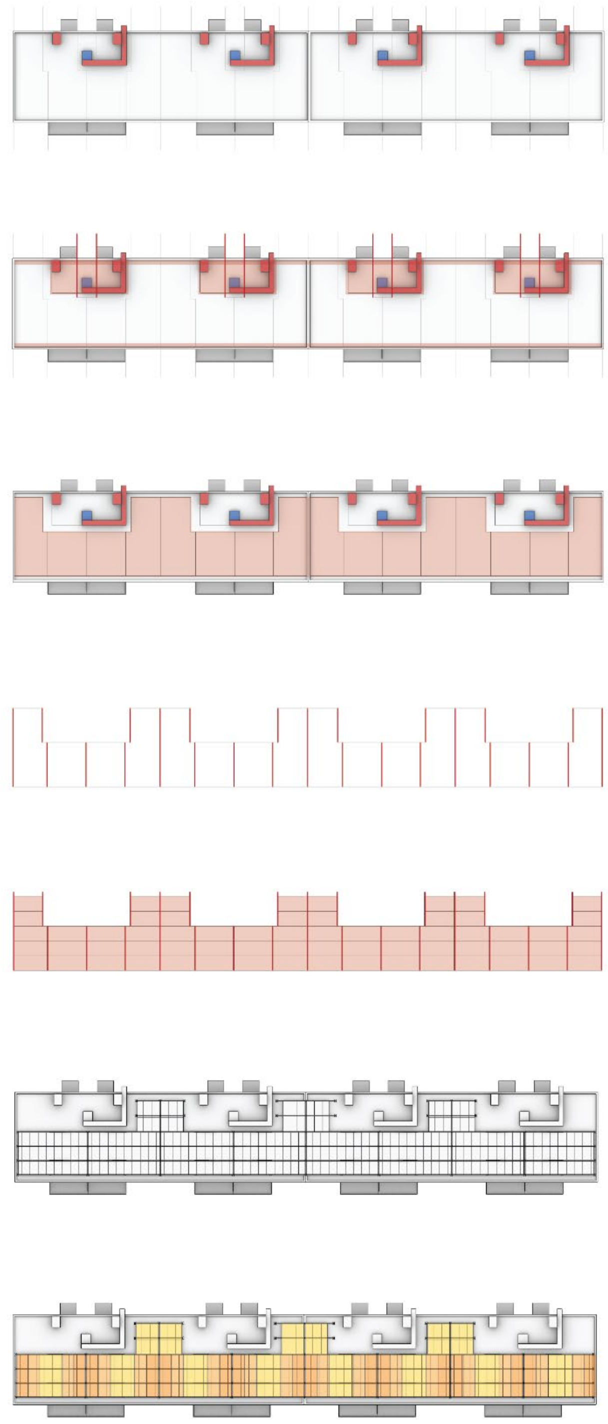
Functionality: A targeted investment for a specific case might be the greatest approach to balance the investment costs of a reinforcement strategy. The function that will bring the most value for the specific function of the building might be the best incentive for the investor.

Post war typologies belong mostly to the rental group in the category of social housing. Increasing the value of the building by adding accessible and functional terraces might lead to an increase of rent which would not be ideal in this case. This is an aspect mentioned on the Life@Urban Rooftops [18]. Nevertheless, this should not be a reason to not increase the quality of social housing, for which the combination of functions makes even more sense.

Projects like De Boel [39], combining Offices, Additional housing units and Terraces for the users is a good example. The project of DakAkker in Schieblock [28] shows the social cohesion and education that open terraces can bring. Of course, making all roofs accessible is not economically feasible, but creating solutions to allow it as much as possible will be the best approach.

5. DESIGN STAGE

On this chapter, the design exploration of options will be conducted based on the design premises and strategies established on the previous chapters. The two proposed design hypotheses are tested to quantify their potential application. The different design proposals are evaluated and compared based on qualitative and quantitative factors to conclude with the selection of the most suitable solution. The selected strategy and the design tool are developed, testing their application on the three selected building cases. Two design iterations are proposed on one of the cases to show how the solution could look like.



5.1. DESIGN GUIDELINES AND PREMISES

Based on the conclusions arrived in previous chapters, design premises were proposed for the exploration of design alternatives. These take into consideration all the requirements for the functioning of a green roof and the polder roof system, as well as the building's constructive and structural and considerations.

Cost-reliving Factors

Assume Building Capacity by Norm and Design Specifications: Simplify the structural evaluation process of the building and reduce or avoid the requirement of Non-destructive and Destructive testing.

Reduce Intervention on Existing Construction: Avoid removal of upper or bottom finish layers to reduce costs and prevent disturbance and interruption on building functions.

Weight of Structure: The weight of the structure concerning price.

Number of Elements: Ease of assembly, transportation, and installation.

Adaptability: A system that can cover the different building and design requirements to lower production costs.

Building Factors

Load Distribution - Wall Loadbearing Capacity: Loading the wall without reaching values close to the ones arrived through the calculations of maximum capacity under the worst-case scenarios.

Span Between Walls: A system suitable to cover different spans and variable lengths.

Water Drainage System: Requirements for the adequate functioning of the drainage system considering the slope and location of drainage points.

Installations: Considering the presence of ventilation ducts, climatization appliances, and other installations that are required to be integrated with the intervention.

Insulation System: Considering the insulation of the roof in case of an old-inefficient or non-existing one.

Design Factors

Design Freedom: Allow an unrestricted design process.

Compactness: Compact construction system to reduce the overall height.

Accessible Waterproof Layers: Easily removable upper layers for inspections and repairs.

Compatibility with Polder Roof System: Inclusion of Polder Roof drainage and retention system requirements.

Compatibility with Existing Products: Avoid creating custom and unique products.

Material Durability: Resistance to humidity and organic substances present in the GR systems.

Sustainability: Consider material and design factors for a sustainable approach.

External Structural Solutions

Based on the premises and guidelines, the exploration of external structural solutions was carried on. The objective is to find a system that can work independently from the existing roof to prevent intense interventions on the building structure and finishing layers to address the previously mentioned cost-reliving factors. Adaptable for the building conditions of similar characteristics than the post-war samples analyzed in the previous chapter, to make it suitable for a larger group in the building stock.

Different ideas were explored based on the design premises and initial concepts. These were tested and evaluated in the following stages:

	Step	Description	Strategy
1	Design Hypothesis	Test effect of proposed design hypotheses: - Reuse of roof residual capacity - Load Distribution of forces	Digital modeling and analysis of testing models. Rhinoceros, Grasshopper, and FEA analysis in Karamba-3D.
2	Initial Design Iterations External Systems	The proposition of External Reinforcement Systems based on the ideated concepts	Exploration and representation of design options in 3D models. Rhinoceros
3	Validation of Options	Evaluate and discard options based on: - Overcomplexity - Impractical solutions - Construction/ Function feasibility	Evaluation of options based on design premises and the stated criteria
4	Material Evaluation	Evaluation of physical properties and design suitability of relevant material and products: - Structural capacity - Weathering resistance - Adaptability for the structural requirements and building characteristics	Literature review and exploration of material properties and relevant products in the market.
5	Configuration and Comparison	Configuration of options for analysis Evaluate structural performance Compare results	Digital modeling and analysis of design options and configurations. Rhinoceros, Grasshopper, and FEA analysis in Karamba-3D.

Table 26 – Testing and evaluation stages of the design options

5.2. DESIGN HYPOTHESES

Two Design Hypotheses were proposed in the previous chapter to decrease the structural demand and therefore reduce the weight of the reinforcement system. These two ideas will be described and tested in this sub-chapter, concluding with the findings as considerations for the proposed options in the following stage.

5.3. ROOF RESIDUAL CAPACITY

The idea is to relieve the load of the Insulation, Filtration, and Water Buffer Layers and Solar panels from the new structure. These three layers added together, are below the minimum load and make it possible to separate the green roof components in two. The load of the solar panels could be mounted on the support structure to transmit the load to the vertical structure directly. The new structure can be designed above the water height limit as a permeable structure that will allow the flux of water for evacuation and the absorption of it through capillarity for irrigation.

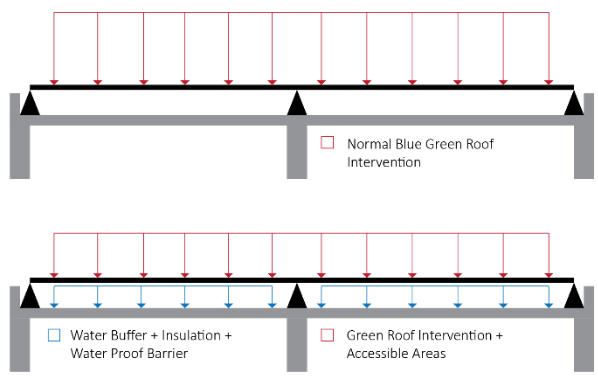


Figure 54 - Reusing Roof Loadbearing Capacity

Hypothesis: Reuse of the minimum capacity for which the roofs were designed by the norm. This will assure that every building will support this minimum amount of load, which will be relieved from the new external structure to decrease its demand and therefore, weight. While analyzing the 3 selected case studies it was possible to see that some buildings were designed for loads of 2.00 and 3.00 kN/m2. Nevertheless, the objective is to create a system adaptable to the best and worst design conditions. The feasibility of this option will depend on the following considerations:

- The compactness of the system will reduce the distance between the substrate layer and the water buffer. If the distance is too large, irrigation through capillarity will not be possible.
- The materiality of the structure will be in constant exposure to humidity and organic components. The structure should be able to operate under these conditions.
- The reduction of weight will have to be balanced against a more complex system that will allow the flow of water and achieve a compact layering with weather-resistant materials and an accessible water barrier layer for inspections.

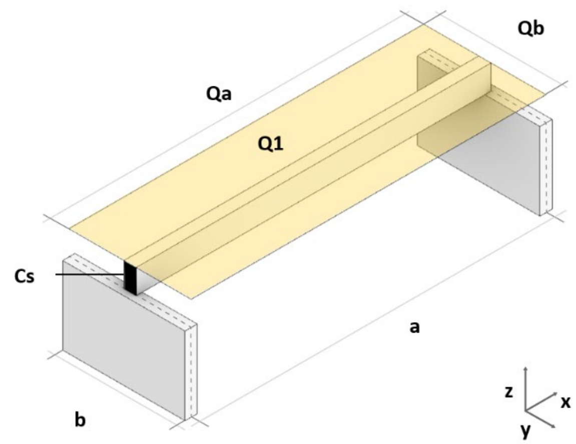
Testing Setup: To test the effect of this modification, an extended load chart was calculated. Table 27 contains the load for the SLS and ULS conditions with the weight reduction. By comparing the original load chart, we can see the reduction percentage in each loading case. The reduction is twice as much for the lighter solutions than for the heavier ones. The testing setup will allow to observe how this percentage affects the cross-section selection requirements.

Comb.	Accessible Functional Areas – Variable Loads (kN/m²)			Vegetative Areas – Permanent Load (kN/m²)			Ful Load		Reduced Load		Weight Reduction (%)
							Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	3.66	5.13	2.31	3.31	- 36.88
	1.87	2.87	3.87	2.31	3.49	4.79					
B	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	4.84	6.68	3.49	4.86	- 27.89
	1.87	2.87	3.87	2.31	3.49	4.79					
C	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	5.79	7.96	4.79	6.61	- 17.27
	1.87	2.87	3.87	2.31	3.49	4.79					
D	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	3.72	5.36	2.87	4.22	- 22.84
	1.87	2.87	3.87	2.31	3.49	4.79					
E	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	4.84	6.68	3.49	4.86	- 27.89
	1.87	2.87	3.87	2.31	3.49	4.79					
F	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	5.79	7.96	4.79	6.61	- 17.27
	1.87	2.87	3.87	2.31	3.49	4.79					
G	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	4.72	6.86	3.87	5.72	- 18.00
	1.87	2.87	3.87	2.31	3.49	4.79					
H	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	4.84	6.86	3.87	5.72	- 20.04
	1.87	2.87	3.87	2.31	3.49	4.79					
I	Maintenance	Private	Public	Extensive	Semi-Intensive	Intensive	5.79	7.96	4.79	6.61	- 17.27
	1.87	2.87	3.87	2.31	3.49	4.79					

Table 27 - Comparison of Ful-Load and Reduced-Load

The effect will be tested by analyzing the Full-Load and the Reduced-Load of the different loading combinations into a single beam and determining the required cross-section to fulfill the maximum deflection and utilization.

The maximum span from the study cases was taken as an example, where the variables to be tested will be the load value and the selected cross-section. First, IPE Standard Steel beams were tested to select the option from a cross-section family.



a	Span Length	7.00 m
b	Building Section	2.00 m
Qa	Load length	6.00 m
Qb	Load width	2.00 m
Q1	Load value	Variable 1
Cs	Selected Cross-section	Selected by the Algorithm

SLS = Maximum Deflection = Non-Accessible L/240

= Maximum Deflection = Accessible L/340

ULS = Maximum Utilization = 100%

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	1	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X		X	X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X		X	X

Material Properties

Steel	
E	21000 [kN/cm2]
G12	8076 [kN/cm2]
G3	8076 [kN/cm2]
gamma	78.5 [kN/m3]
alphaT	1.2E-5 [1/C°]
fy	23.5 [kN/cm2]

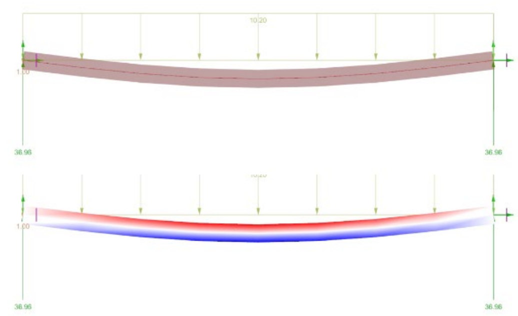
Cross Section (Cs) List for selection

EU – I Beam – IPE Family

Figure 55 - Analysis parameters and Boundary Conditions

Results: The result of each case is shown in (Annex A), where the selected cross-section is specified as well as its maximum displacement, Maximum Utilization, and the resultant reduction in weight of the model with reduced weight.

Configuration	A



	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	270	240
- Max Height [mm]	270.00	240.00
- Max Width [mm]	135.00	120.00
Max Displacement [mm]	20.29	19.02
Allowed Displacement	20.58	20.58
Utilization Max	+/- 55.70	+/- 64.80
Weight	252.22	214.85
Weight Reduction [%]	- 14.81	

Table 28 - Example 01 - Load Combination A

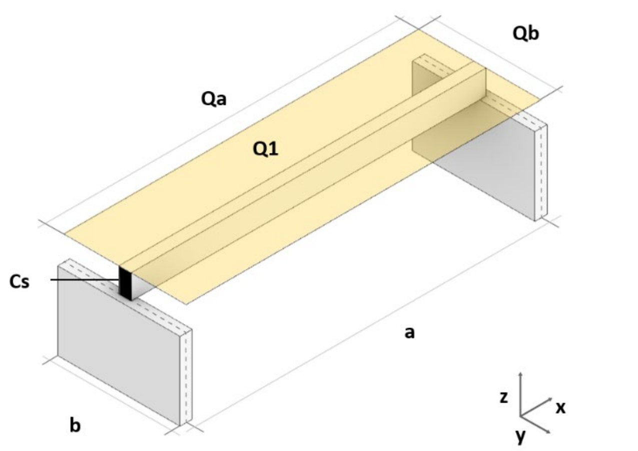
The following table shows the results of all loading combinations, where it is possible to see that a reduction between 14.05 and 14.81 % was reached. In some cases, the reduction of weight is 0.00. This is due to the cross-section family member sizes, as the reduction of weight is sometimes not enough to go down one family member on the list.

Configuration	A		
Combination	Beam [kg/m2]	Beam [kg/m2]	Weight Reduction [%]
A	18.01	15.34	- 14.81
B	21.11	18.01	- 14.68
C	24.57	21.11	- 14.05
D	18.01	18.01	0
E	21.11	18.01	- 14.68
F	24.57	21.12	- 14.05
G	21.11	21.11	0
H	21.11	21.11	0
I	24.57	21.11	- 14.05

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

Table 29 - Overview of results - All Combinations

The same process was conducted with the Sawn Lumber CAN/CSA cross-section family, which provided a higher variety of member sizes and allowed to observe larger variations in percentages.



a	Span Length	7.00 m
b	Building Section	2.00 m
Qa	Load length	6.00 m
Qb	Load width	2.00 m
Q1	Load value	Variable 1
Cs	Selected Cross-section	Selected by the Algorithm

SLS = Maximum Deflection = Non-Accessible L/240

= Maximum Deflection = Accessible L/340

ULS = Maximum Utilization = 100%

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	1	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X		X	X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X		X	X

Material Properties

Wood	
E	1050 [kN/cm2]
G12	360 [kN/cm2]
G3	360 [kN/cm2]
gamma	6 [kN/m3]
alphaT	5.0 W-6 [1/C°]
fy	1.3 [kN/cm2]

Cross Section (Cs) list for selection

CAN/CSA – Sawn Lumber – Standard

Figure 56 - Analysis parameters and Boundary Conditions

Configuration	A		
Combination	Beam[kg/m2]	Beam [kg/m2]	Weight Reduction [%]
A	27.53	15.99	**- 41.91**
B	39.11	27.53	**- 29.74**
C	39.19	33.36	**- 14.87**
D	27.53	21.82	**- 20.74**
E	27.53	21.82	**- 29.73**
F	39.19	33.36	**- 14.87**
G	33.36	27.63	**- 17.46**
H	39.19	27.53	**- 29.75**
I	39.19	33.36	**- 14.87**

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

Table 30 - Overview of results 2 – Sawn Lumber - All combinations

As seen in the results table for Sawn Lumber, the percentages variate from 41.91 % for the lightest intervention to 14.87 % on the heaviest one. This gives a more direct relation to the literal percentage weight reduction of the load. The individual results can be seen on *Annex A* as well.

Conclusion: The Effect on weight reduction will depend on the structural members to be used. By using members with a larger variety of cross-section sizes, the effect will be more pronounced. Nevertheless, it will provide a weight reduction that will be more significant for lighter interventions and a beneficial weight reduction for small buildings of lower capacities.

The effect on cost reduction due to weight will depend on the proposed solution, as the complexity of the system increases and therefore weight, price and workload might increase as well.

5.4. LOAD DISTRIBUTION

Heavier loaded areas are designed near the vertical structure and lighter loaded areas for the furthest weaker parts of the roof. This is applied to the design based on rules of thumb, where additional load percentages are determined in a 1 or 2 m radii around the loadbearing structure.

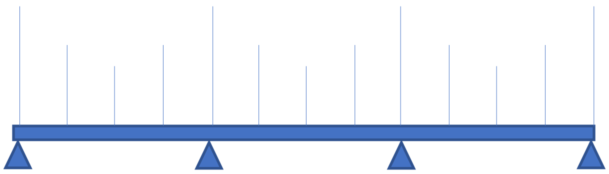


Figure 57 - Load Distribution Strategy

Hypothesis: The idea is to consider the load distribution from the design stage. Instead of designing a structure for the selected load combination, design it for a lower one and account for areas of higher capacity for the design stage. The goal of the test is to see the percentage of load that could be increased and the percentage of the roof area that would belong to a higher capacity category. If the accessible areas, which are the lightest in most cases, are designed in the middle and then incremental weights are added towards the vertical supports, larger loads will be available for more variated vegetation and additions.

The output of this strategy could be the designed structure in addition of a floorplan of the areas with different capacities. Although this might be more restrictive for the design of the roof, it would increase the potential benefit for the GR System and the applicable functions.

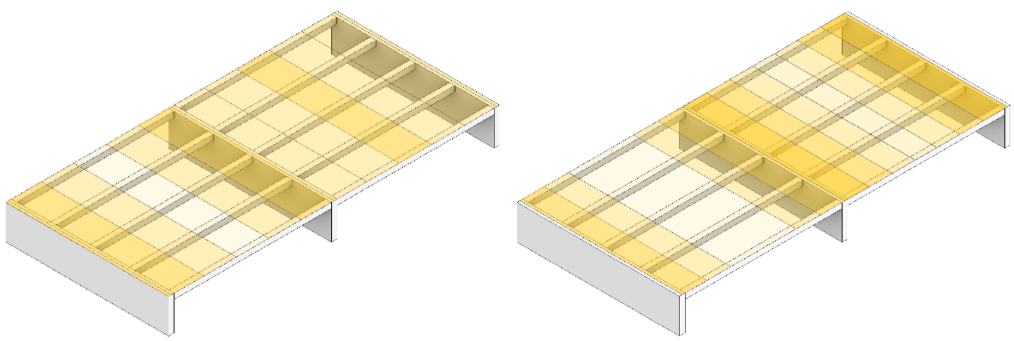


Figure 58 - Concept output of strategy - Design Tool

Testing Setup: As shown in *Figure 63*, two examples are presented to observe the behavior of a simply supported beam under a point load applied at different distances away from the support.

- Example A is a single point load applied in points A B and C

- Example B is an equally distributed load with one higher point load on points A B and C.

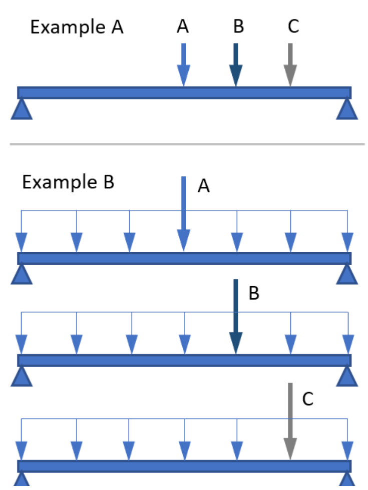
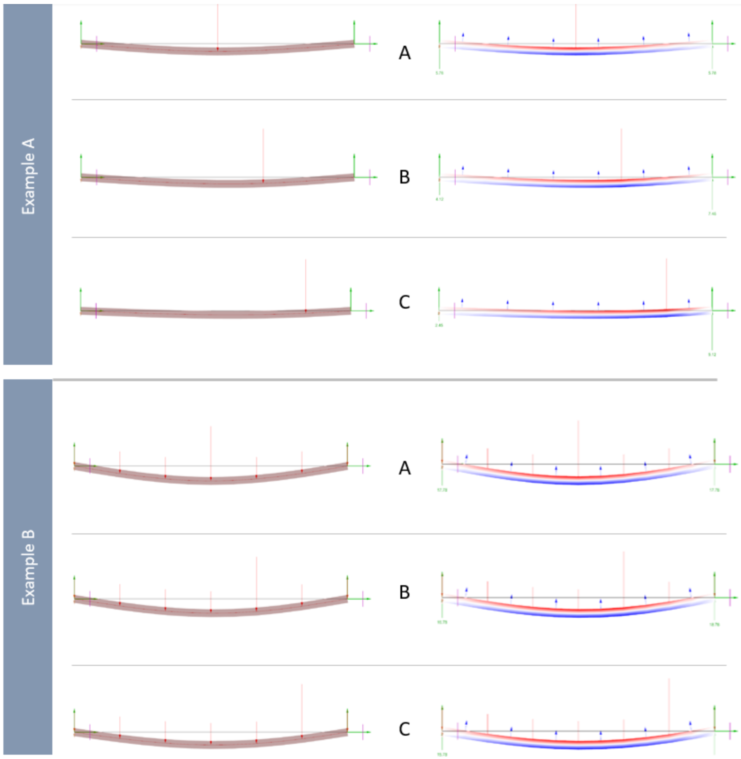


Figure 59 - Options for initial test

A steel IPE 240 cross-section was used for a quick comparison, where the maximum deflection and the maximum utilization are compared under the specified loads (Table A and B). On the right of each table, it is possible to see the percentage reduction for each case. Example B is a more accurate description of the possible effect that can be expected.



Example A			
Main Load [kN]	10		
A – Mid			
Def. Max [mm]	19.40		
Util. Max [%]	41.30	Reduction	
B – 2/3		B – 2/3	
Def. Max [mm]	16.70	Def. Max [%]	- 13.91
Util. Max [%]	36.70	Util. Max [%]	- 11.13
C – 1/3		C – 1/3	
Def. Max [mm]	10.30	Def. Max [%]	- 46.90
Util. Max [%]	23.00	Util. Max [%]	- 44.30

Example B			
Main Load [kN]	10		
Secondary Load [kN]	4		
A – Mid			
Def. Max [mm]	38.20		
Util. Max [%]	72.00	Reduction	
B – 2/3		B – 2/3	
Def. Max [mm]	36.60	Def. Max [%]	- 4.18
Util. Max [%]	64.30	Util. Max [%]	- 10.69
C – 1/3		C – 1/3	
Def. Max [mm]	32.70	Def. Max [%]	- 14.39
Util. Max [%]	56.70	Util. Max [%]	- 21.25

Table 31 - Results Initial Test

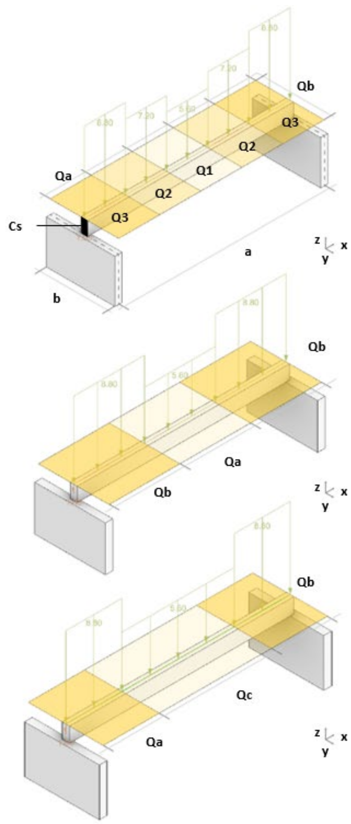
To test the effect under the different load chart combinations, a similar setup to the previous design hypothesis was configured. A single simply supported beam with the same fixed span and loaded area. In this case, reduced loads are considered for the SLS and ULS analysis.

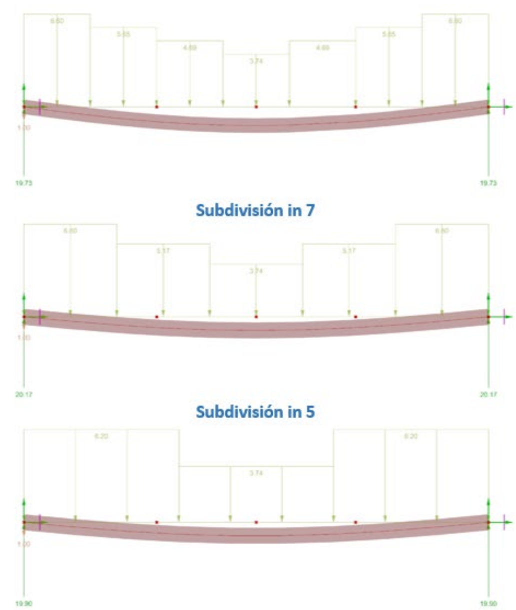
For this test, the variables will be the Loaded Area and the Load Value. The selected cross-section is assigned by the Equally Distributed Load (EDL) model so that both options are tested under the same conditions.

Subdivisions: Three options are tested. One which is subdivided into 7 segments, one into 5 and one into 3. This, to see the effect of a linearly incremented load in different segmentations.

Load Assignment: The load is linearly incremented in each segment, where the minimum load is set by selected function and the maximum load is the highest it can reach before surpassing the maximum deflection or maximum utilization, creating an Unequally Distributed Load (UDL) model.

Comparison: To evaluate the result, the total reaction force is added to compare the additional gained load.





Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)
A	2.31	3.31
B	3.49	4.86
C	4.79	6.61
D	2.87	4.22
E	3.49	4.86
F	4.79	6.61
G	3.87	5.72
H	3.87	5.72
I	4.79	6.61

a	Span Length	7.00 m
b	Building Section	2.00 m
Qb	Load width	2.00 m
Qa	Load length	Variable 1
Q1/2/3	Load value	Variable 2
Cs	Selected Cross-section	Selected by the Algorithm

SLS = Maximum Deflection = Accessible L/340

ULS = Maximum Utilization = 100%

Loads

Mesh Load = (Q(x) x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	1	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Tables	Z-Global

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X		X	X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X		X	X

Material Properties

Steel	
E	21000 [kN/cm2]
G12	8076 [kN/cm2]
G3	8076 [kN/cm2]
gamma	78.5 [kN/m3]
alphaT	1.2E-5 [1/C°]
Fy	23.5 [kN/cm2]

Cross Section (Cs) List for selection

EU – I beam – IPE Family

Figure 60 - Analysis parameters and Boundary Conditions

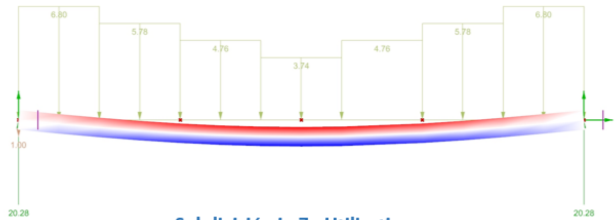
Results: The result for each case is shown in *Annex D*, where the selected cross-section properties are shown, as well as the maximum displacement, the maximum utilization, the total reaction force, and the percentage of the incremented load in comparison to the equally loaded model.

Table 33 shows all the results of the different combinations, where it is possible to see that the percentage of incremented load is higher when the difference between the minimum load for the UDL model is higher than the load for the EDL model.

Combination C for example, where the minimum load for the UDL model is 1.87 kN/m2 and the governing load for the EDL model is 4.79, Allowed the peak force of the UDL to rise and reach a higher total incremented load.

The subdivision of segments does not show much variation on the total incremented load, variating around 1% up and down on the different loading combinations.

Again, the same example was carried out with the Sawn Lumber CAN/CSA cross-section family to compare the behavior under a larger cross-section family. As a result, it is possible to see that in many cases the incremented load is not as high as with the IPE Steel beam cross-section family. Especially in the last 3 load combinations. This is caused by the fact that the selected cross-section of the EDL model reaches faster or is already close to the Max Deflection or Utilization limit of the structural element, and therefore the incremented load that can be reached is lower.



Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	240			
- Max Height [mm]	240.00			
- Max Width [mm]	120.00			
Max Displacement [mm]	20.81	20.59	20.53	20.40
Allowed Displacement	20.58			
Utilization Max (%)	+/- 50.70	+/- 58.30	+/- 58.00	+/- 56.70
Total Reaction Force (kN)	37.57	40.56	40.34	39.80
Weight Increment [%]	0	9.20	8.59	7.16

Table 32 - Results example 1 - Load combination A

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

Table 33 - Results Overview - All load combinations

Loads

Mesh Load = (Q(x) x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	1	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X		X	X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X		X	X

Material Properties

Wood	
E	1050 [kN/cm2]
G12	360 [kN/cm2]
G3	360 [kN/cm2]
gamma	6 [kN/m3]
alphaT	5.0 W-6 [1/C°]
fy	1.3 [kN/cm2]

Cross Section (Cs) list for selection

CAN/CSA – Sawn Lumber – Standard

Comb.	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 3.92	+ 5.00	+ 4.81
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.94	+ 17.02	+ 16.43
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 20.52	+ 20.87	+ 19.09
D	2.87	4.22	Private 2.87 kN/m2	+ 4.62	+ 5.09	+ 4.13
E	3.49	4.86	Private 2.87 kN/m2	+ 9.13	+ 9.43	+ 8.52
F	4.79	6.61	Private 2.87 kN/m2	+ 13.27	+ 13.45	+ 12.58
G	3.87	5.72	Public 3.87 kN/m2	+ 0.32	+ 0.41	+ 0.62
H	3.87	5.72	Public 3.87 kN/m2	+ 0.32	+ 0.41	+ 0.62
I	4.79	6.61	Public 3.87 kN/m2	+ 6.02	+ 6.04	+ 6.07

Table 34 - Results Overview 2 - All load combinations

The results in both cases showed that too many variables can influence this testing setup. Therefore, an additional setup was carried out.

Testing Setup: For this comparison, the same subdivision system was used. A UDL model in 7, 5, and 3 segments will be compared against an EDL model. The difference for this test is that the selected cross-section member is preselected based on the initial EDL calculation. The comparison will show the difference between the maximum load that can be reached through a EDL and a UDL before reaching the Deflection and Utilization Max of the structural element.

Mesh Load = (Q(x) x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	1	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Tables	Z-Global

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X		X	X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X		X	X

Material Properties

Steel	
E	21000 [kN/cm2]
G12	8076 [kN/cm2]
G3	8076 [kN/cm2]
gamma	78.5 [kN/m3]
alphaT	1.2E-5 [1/C°]
fy	23.5 [kN/cm2]

Cross Section (Cs) List for selection

EU – I beam – IPE Family
IPE 240 - Min **IPE 270 - Med** **IPE 300 - Max**

Function	Maintenance			
IPE 240	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length [m]	7.00	1	1.4	2.33
Maximum Load [kN/m]	4.96	6.80	6.60	6.40
Minimum Load [kN/m]	4.96	3.74	3.74	3.74
Total Reaction Force	36.86	40.57	40.34	40.74
Weight Increment [%]	0	+ 10.03	+ 9.41	+ 10.50

Function	Private			
IPE 270	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length [m]	7.00	1	1.4	2.33
Maximum Load [kN/m]	7.46	10.00	9.80	9.40
Minimum Load [kN/m]	7.46	5.74	5.74	5.74
Total Reaction Force	54.74	59.74	59.75	59.78
Weight Increment [%]	0	+ 9.13	+ 9.15	+ 9.20

Function	Public			
IPE 300	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length [m]	7.00	1	1.4	2.33
Maximum Load [kN/m]	10.92	15.40	15.00	14.20
Minimum Load [kN/m]	10.92	7.74	7.74	7.74
Total Reaction Force	79.39	87.77	87.62	87.28
Weight Increment [%]	0	+ 10.55	+ 10.36	+ 9.93

Table 35 - Results Overview 3 - All load combinations

Results: The results shown in *table 35* show more consistent results, where it is possible to observe an increment of total reaction force between 9.13 and 10.55 % through the implemented strategy. The difference between a subdivision in 7 or a subdivision in 3 does not show a significant impact on the incremented percentage, variating again around 0.50 %.

Function	Value	SDL	UDL (Sub 7)	UDL (Sub 5)	UDL (Sub 3)
Maintenance Functions	Load Max [kN/m2]	2.48	3.40 **(+37.1%)**	3.30 **(+33.1%)**	3.20 **(+29.0%)**
	Area of Load	100%	28.57%	40.00%	66.57%
Private Functions	Load Max [kN/m2]	3.73	5.00 **(+48.1%)**	4.90 **(+45.4%)**	4.70 **(+39.5%)**
	Area of Load	100%	28.57%	40.00%	66.57%
Public Functions	Load Max [kN/m2]	5.46	7.70 **(+41.0%)**	7.5 **(+37.4%)**	7.1 **(+30.0%)**
	Area of Load	100%	28.57%	40.00%	66.57%

Table 36 - SDL vs UDL loading conditions - Incremented percentages in relation to covered area

Conclusion: The results presented in Table 36 show the potential increase of applicable load on the structure by the distribution of forces. The potential use of this strategy could allow designing structures for lower capacities, but still, obtain areas for larger capacities. This could be beneficial for buildings with reduced capacity, where the force distribution could allow to obtain segments for heavier and more beneficial interventions while remaining below their structural limit. Implementing this strategy as part of the design tool will give a design aid for the force distribution to reduce the structural demands and to enable even more buildings for heavier roof interventions.

5.5. INITIAL DESIGN ITERATIONS: EXTERNAL SYSTEMS

As previously explained, all the presented solutions are concepts based on external structures to prevent intervening on the building structure and its internal or external finish layers. Multiple ideas were proposed based on three strategies to distribute the loads and on 3 different layer configurations.

Load Distribution

Mainly, how forces will be transported and distributed towards the vertical structure

Linear System: Set of beams and panels that will distribute the forces between both loadbearing walls.

Grid System: Set of beams in two directions to reduce the number of beams across the whole span and therefore reduce the cross-section requirements for the beams and panels in the second direction.

Box System: A composite cross-section of wood or FRP, where the infill is used as the insulation layer to make a compact system. A box-like structure that evenly distributes the load along the wall

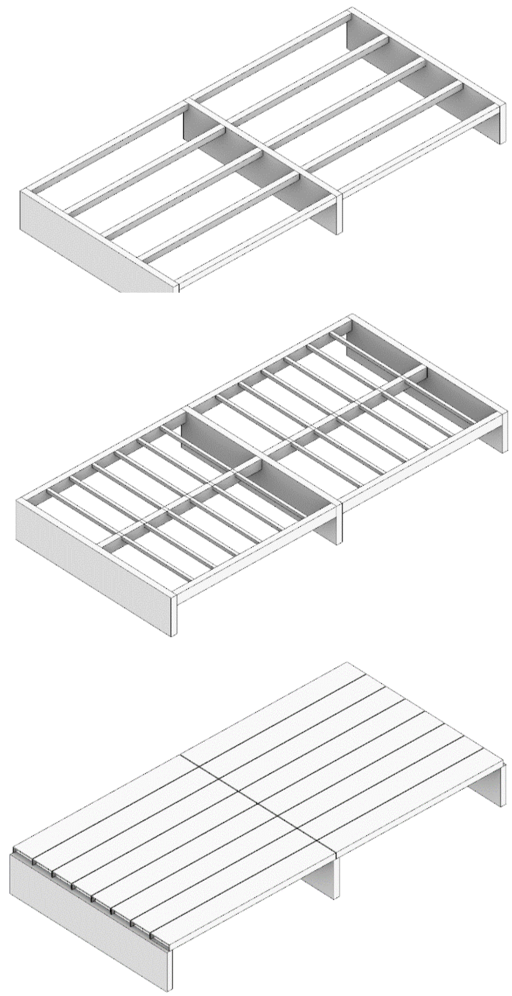


Table 37 - Load Distribution Options

Layer Configuration

The configuration of the multiple layers in relation to the new external structure.

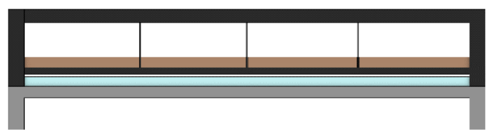
Base Structure: A structure underneath all new layers, operating on top of the old structure.

Advantages	Disadvantages
▪ The simplicity of installation and components ▪ Compatibility with current products ▪ Inclusion of Insulation on cross-section height area	▪ New Water-Resistant Layer Required ▪ Unused Existing Structure

Intermediate Structure: A Permeable structure that allows the flow of water to the existing roof, using its current capacity for the drainage, water buffer, drainage, and insulation layers.

Advantages	Disadvantages
▪ Reuse of existing structure = Reduce structural requirements ▪ Avoid box system ▪ Design freedom	▪ Exposed to humidity (Inside) ▪ Complex floor panel system

Suspended Structure: Elevated structural system that will leave the external structure exposed and use its height for the cross-section demands, leaving a suspended compact system at the bottom.



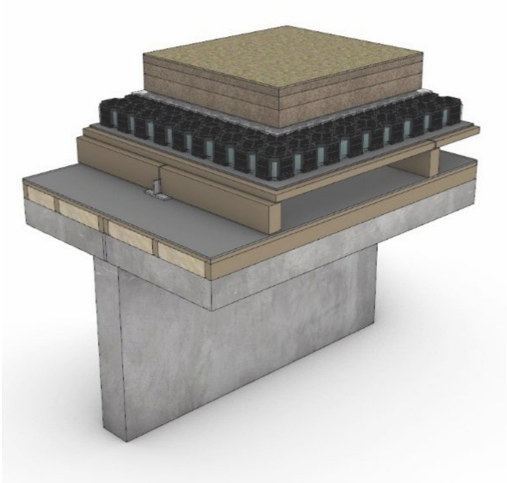
Advantages	Disadvantages
▪ Reuse of existing structure = Reduce structural requirements ▪ Increase compactness of base layer ▪ Integration of functions to external structure (Coverings, PVP, Railing, etc.) ▪ Avoid box system	▪ Exposed to Humidity (In and Outside) ▪ Exposed Structure = Design Restrictive ▪ Additional Level Height = Construction Regulations ▪ Complex floor panel system

Table 38 - Layer configuration options

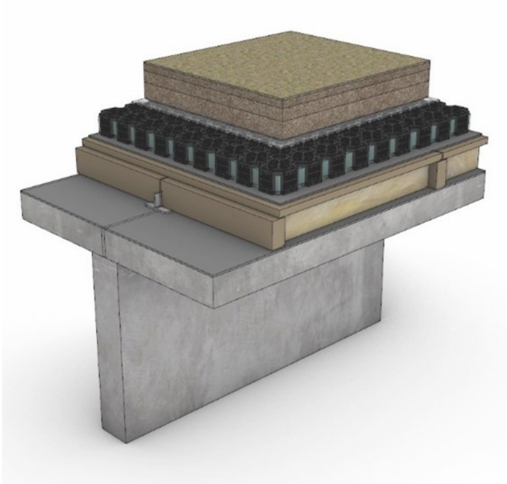
Combinations

Multiple solutions were arrived from combining the 3 layering configurations and load distribution concepts. These solutions were explored at a conceptual stage to assess potentials, risks, and feasibility.

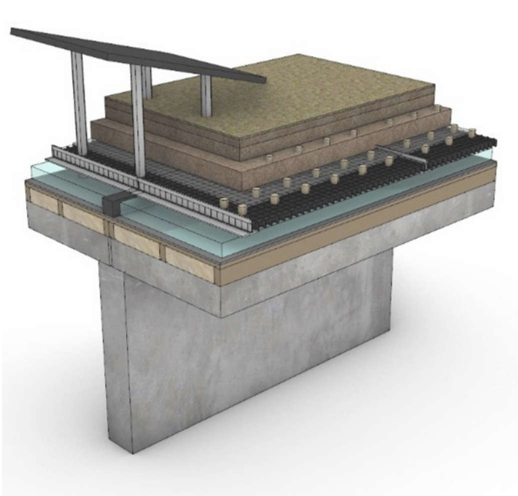
Option 1	
Distribution	**Linear System**
Layer Configuration	**Base Structure**
Description	Insulation system on the bottom and linear independent structure on top, creating a new water barrier to create a flat and free surface, compatible will all multifunctional roof systems.
Reuse of Structure	No
Insulation	Separate



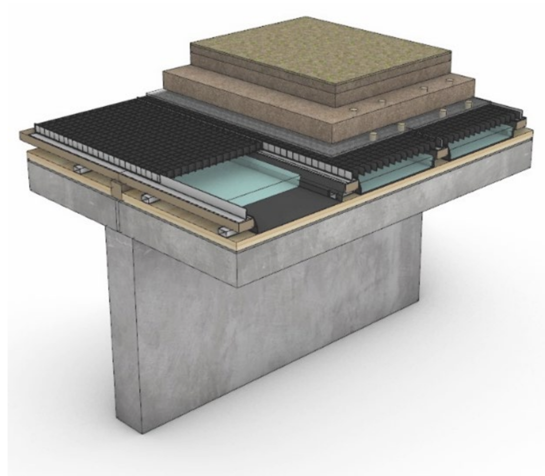
Option 2	
Distribution	**Linear System**
Layer Configuration	**Base Structure**
Description	Insulation system imbibed on cross-section height to gain compactness. New water barrier on top to create a flat and free surface, compatible will all multifunctional roof systems as well.
Reuse of Structure	No
Insulation	Imbibed



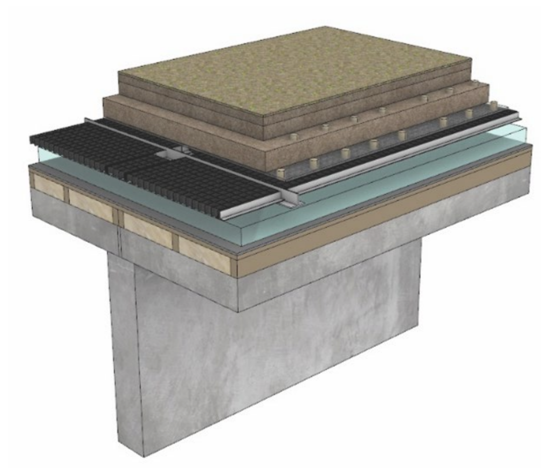
Option 3	
Distribution	**Linear System**
Layer Configuration	**Intermediate Structure**
Description	Insulation layer with the new water barrier on top, for the water buffer and drainage system. A linear permeable structure on top, allowing the water flux in both directions.
Reuse of Structure	Yes
Insulation	Separate



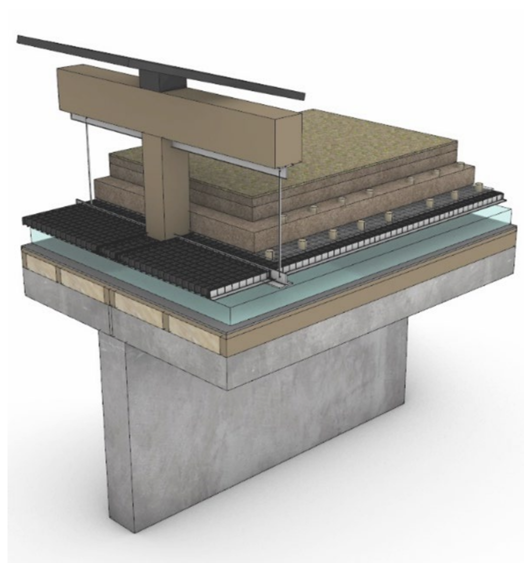
Option 4	
Distribution	Linear System
Layer Configuration	Intermediate Structure
Description	A modular and recyclable PBC water tank module to avoid the water barrier layer. Imbibed in between and bottom, the insulation layer. On top, the permeable structure to allow the flux of water.
Reuse of Structure	Yes
Insulation	Separate



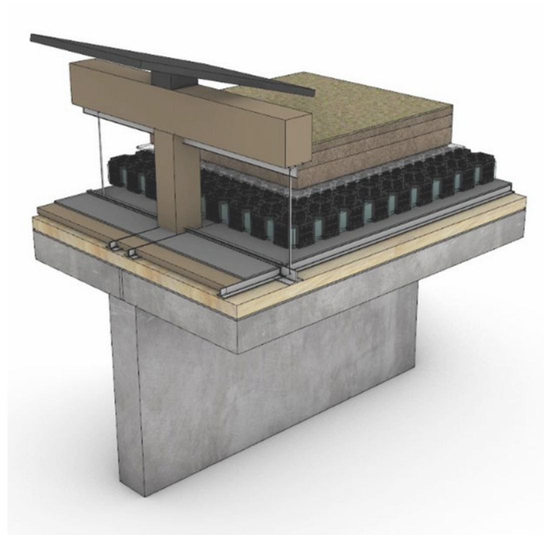
Option 5	
Distribution	Grid System
Layer Configuration	Intermediate Structure
Description	Insulation layer with the new water barrier on top, for the water buffer and drainage system. The grid structure on top. With a set of beams on the main direction to break the span for shorter and more compact beams in the second direction.
Reuse of Structure	Yes
Insulation	Separate



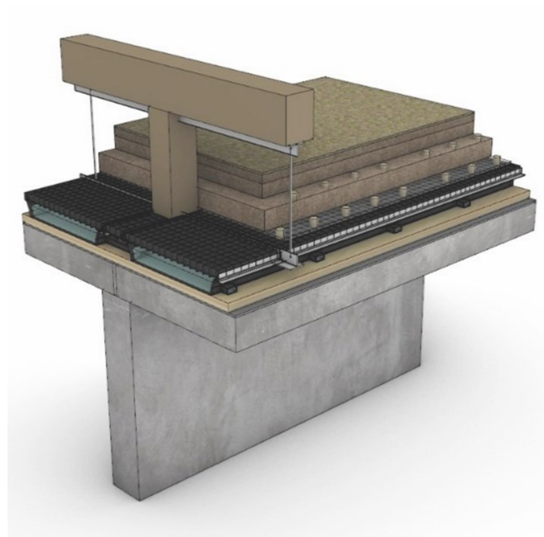
Option 6	
Distribution	Grid System
Layer Configuration	Suspended Structure
Description	A suspended structure that will create a flat and leveled surface for the new water barrier. On the bottom, the roof insulation layer and on top the traditional multifunctional system, compatible with all products.
Reuse of Structure	Yes
Insulation	Separate



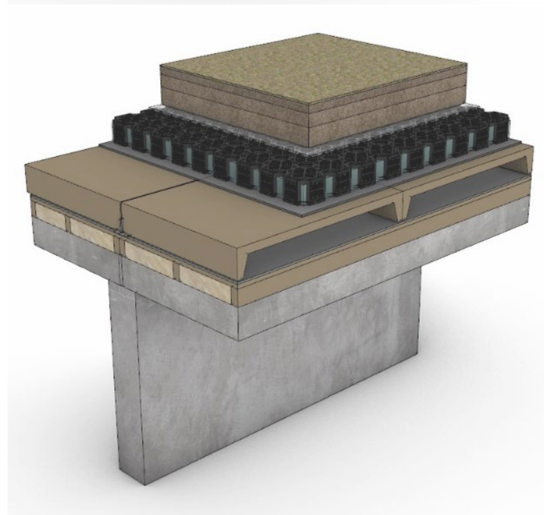
Option 7	
Distribution	Grid System
Layer Configuration	Suspended Structure
Description	Insulation layer with the new water barrier on top, for the water buffer and drainage system. On top, a suspended structure with a compact and permeable floor for the flux of water.
Reuse of Structure	No
Insulation	Separate



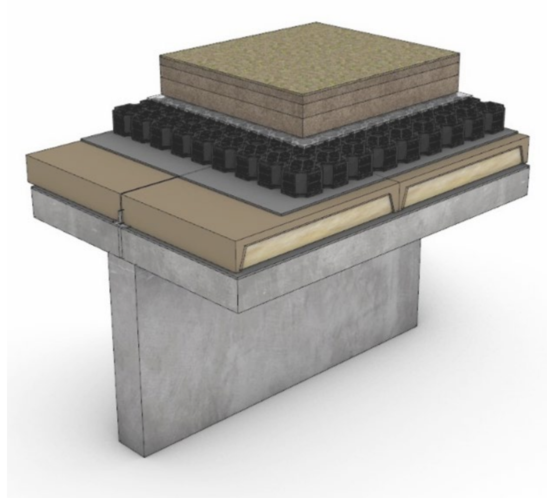
Option 8	
Distribution	Grid System
Layer Configuration	Suspended Structure
Description	A suspended structure that will create the base for the installation of modular and recyclable water tank modules. Underneath, the insulation layer. On top, the permeable structure to allow the flux of water.
Reuse of Structure	Yes
Insulation	Separate



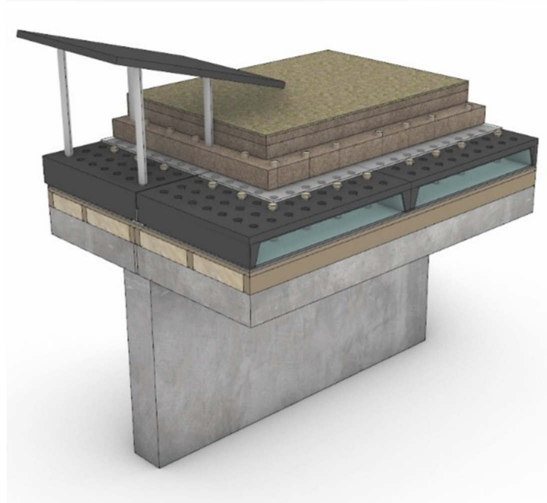
Option 9	
Distribution	Box System
Layer Configuration	Base Structure
Description	Insulation system on the bottom. On top, a box system spanning from wall to wall, distributing the load equally along the wall.
Reuse of Structure	No
Insulation	Separate



Option 10	
Distribution	Box System
Layer Configuration	Base Structure
Description	A box system, spanning from wall to wall to equally distribute the load along the support structure. Insulation layer imbibed on the box to create a compact system. The water barrier on top for a traditional multifunctional roof.
Reuse of Structure	No
Insulation	Imbibed



Option 11	
Distribution	Box System
Layer Configuration	Intermediate Structure
Description	Insulation layer with the new water barrier on top, for the water buffer and drainage system. On top, a permeable box system that will allow the flux of water through the floor, spanning from wall to wall to equally distribute the forces along the supports.
Reuse of Structure	Yes
Insulation	Separate



Option 12	
Distribution	Box System
Layer Configuration	Intermediate Structure
Description	A complex Box system with an insulation layer imbibed on the bottom and a water buffer system for the water storage and drainage on top. The cover of the box, permeable to allow the water flux.
Reuse of Structure	No
Insulation	Imbibed

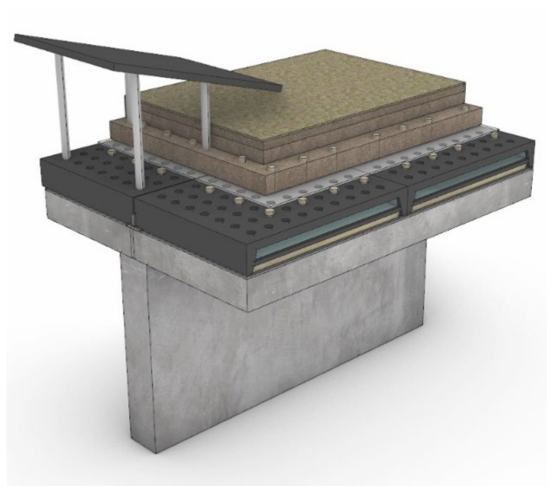


Table 39 - Overview and description of design options

5.6. VALIDATION OF OPTIONS

After assessing the first set of design iterations, some of the ideas were discarded from start based on the following criteria:

- **Overcomplexity:** Solutions that could lead to a higher installation complexity, restricted adaptability, and risk of leakages of the water buffer layer.
- **Constructive Feasibility:** Solutions that could lead to a risk of failure and leakages due to layer configuration or incompatibility of components.
- **Inefficiency:** Solutions with an inefficient use of space and compactness, lack of adaptability and other factors that are addressed with other similar solutions.
-

Options 4, 8 and 12 – Overcomplexity: These options propose modular interconnected water tanks to retain and evacuate the water. These solutions elaborate on an approach that could lead to a more sustainable solution by replacing the current waterproofing materials. Nevertheless, such an approach could compromise the safe functioning of the system. Moreover, addressing a problem for which specific components have been developed already.

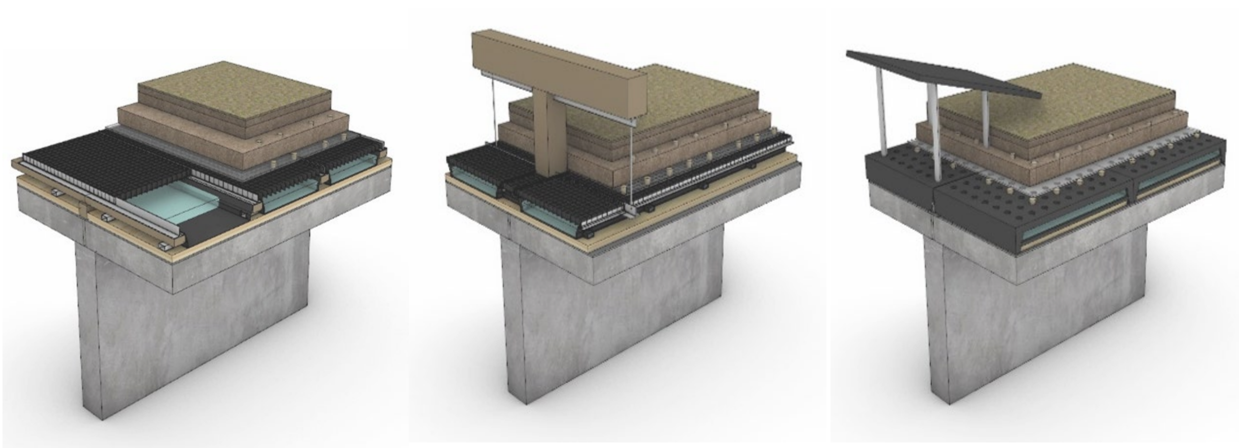


Figure 61 – Options 4, 8 and 12 - Discarded due to overcomplexity

Main disadvantages:

- Water buffer systems more likely to fail/create leakages compared to existing systems, which is one of the main discouraging factors of investment.
- Increased installation and drainage complexity.
- Less flexible to be adapted for different designs without modifying the components.
- Rethink water level control system.
- Production Complexity

Option 5 - Construction feasibility: The cable structure of this suspended structure would need to pierce through the water barrier system. The cable system would have to be designed with additional components to prevent damage due to water exposure and an uninterrupted and smooth surface for the waterproofing layer. Again, the risk of water leakages is the main discouraging factor.

Main Disadvantages:

- Waterproofing layer interrupted by connections. Connections will require certain movement tolerance and therefore a complex solution.
- More likely to failure/leak.
- Less compatible with box system unless designed according
- Rethink water level control system.

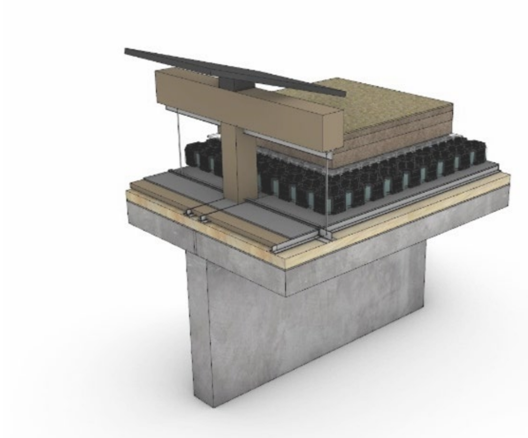


Figure 62 – Option 5 - Discarded option due to construction feasibility.

Options 1 and 9 – Inefficient Solutions: The separation of each layer creates a less compact intervention that does not take advantage of empty spaces. Although the simplicity might decrease the cost, compactness is a very valuable factor to prevent a substantial increase in height to make the intervention compatible with the building and the functions.

- Lack of compactness
- Similarity to other better-performing options

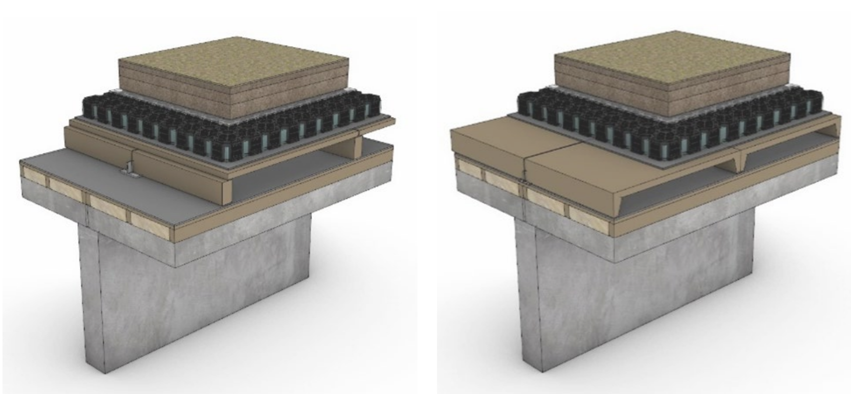


Figure 63 - Options 1 and 9 - Discarded due to inefficiency

5.7. MATERIAL EVALUATION

Based on the selected design iterations, a list of material options was elaborated for each solution considering their specific requirements. Additionally, research on existing products suitable for the different solutions was carried on, verifying the feasibility of their implementation and additional considerations. The outcome can be seen in the material tables and product details that allowed to estimate the requirements for the structure and therefore, the weight and material costs for the comparison process (table 40).

Database for Material Properties and Cost Estimation

Structural Analysis: Database of material properties for the structural evaluation of the different design options.

Constructive and Economic Considerations: Material and product properties for the approximation of material weight and costs from the different options for the comparison process. The information was obtained based on specifications from providers of relevant products for the design options. The economic estimations will ruffly represent the final cost of the design option. Nevertheless, the price per kilogram of material was estimated based on product specifications and the results of the structural analysis for a basic comparison of the different solutions.

GRANATA Edu Pack was used as the main database of material properties for the different options. GFRP and Glulam material properties were updated based on provider's information. The final material properties and the list of companies for each case are listed in *table 40*.

Data Base for Profile Lists		Country
FRP	ProForms - Bedford	USA
	FibroLux	Germany
	FiberLine	Denmark
Sawn Wood & Glulam	DluBal	Germany
Steel	Montanstahl	Switzerland
Aluminum	HIS – Markit Aluminum Associations Standard	UK

Box Systems		Country
FRP	FibroLux	Germany
	FiberLine	Denmark
	STRONGWELL	USA
Laminated Timber	LIGNATURE	Switzerland

Grating Systems		Country
FRP	FibroLux	Germany
	FiberLine	Denmark
	ProForms	USA
Steel and Aluminum	STACO	Netherlands

Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

Profiles	CES Database [€/kg]	MIT Resource [€/kg]	Price Estimation [€/kg]	CES – General Gratings and Panels [€/kg]
Sawn Wood	0.51	-	0.41 - 0.55 **0.48**	-
Glulam	1.29	-	0.94 – 1.198 **1.06**	**2.35**
Aluminum	2.47	1.80	1.59 – 2.10 **1.84**	**2.50**
GFRP	3.29	3.90	2.55 – 4.33 **3.44**	**8.70**
Steel	0.37	0.50	0.25 – 0.50 **0.37**	**1.10**

Table 40 - Material Properties for the analysis and Referred Companies.

Based on the provided information, some of the options had to be discarded because of material incompatibility due to exposure to humidity and organic materials, and because of reduced structural capacity specifications.

Option 10

The idea of this option is to create a compact structural sandwich panel that can provide the insulation layer imbibed on its operable height. The cross-section can be distributed in multiple thin sections that will allow to decrease the cross-section height and evenly distribute the load on the loadbearing walls. Moreover, it would be a product that is fabricated off-site and the simplicity of the on-site installation could substantially reduce construction and material costs.

This product was found to be developed by the company LIGNATURE from Switzerland [40]. It's a timber composite panel that provides a wide range of variations for different use scenarios, but mostly for slabs and rooftops. Different thermal and acoustic barriers can be added to the product. The loading charts show as well that the product can cover larger distances than the limit span set by our case studies, fulfilling the standard of L/240 for maximum deflection.

The company replied to an inquiry on product specifications and price estimations, where they provided insightful information and explained why the product is not suitable for green roof intervention, nor to be combined with an existing concrete structure.

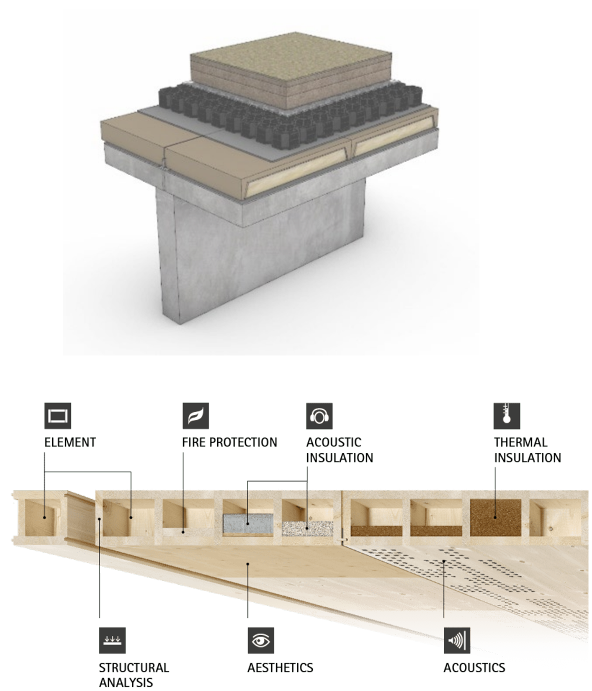


Table 41 - LIGNATURE products [40].

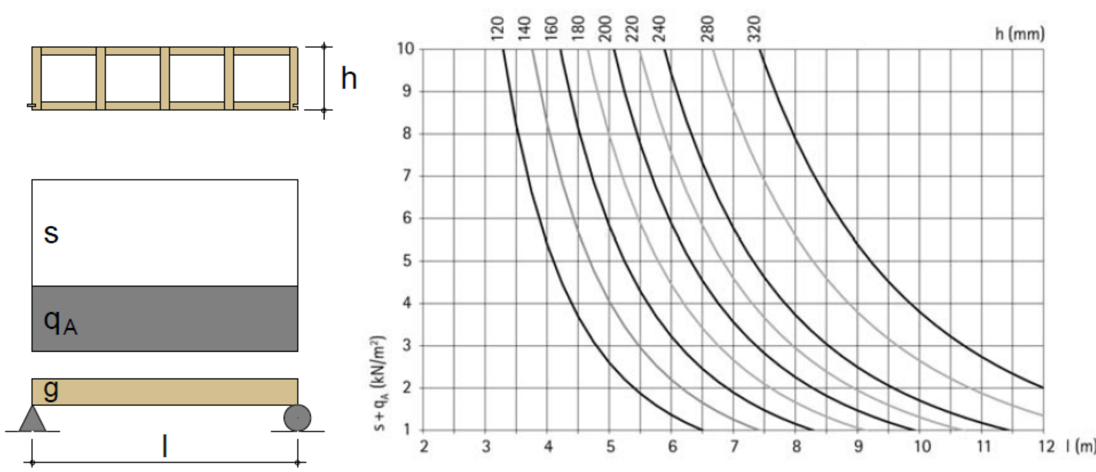


Table 42 - LIGNATURE Products Loading Chart. [40]

Span [m]				
4	5	6	7	Load Combinations
120	140	180	200	A
120	160	200	240	B
120	160	200	280	C

Table 43 - LIGNATURE Products - Span Range

Due to the material properties of wood, the cavities are ventilated through diffusion. Because of the layering of the structure in combination with a GR, the dew point of the construction is inside the box (figure 65). This will cause the element to accumulate humidity on the insulated cavities and eventually rot after a few years. The solution for this case, is to install a vapor barrier on top of the box, then the insulation layer, and then the new waterproof barrier for the GR.

Even so, this would cause two additional considerations that still make the option unsuitable. If the insulation layer is installed on top, not only compactness is lost and therefore one of the main advantages of the system, but an additional structural layer would be needed on top to prevent the weight of the function installed on top to damage the insulation layer in case of a heavier GR system (figure 66).

In case the system is combined with the existing concrete structure, the gap between the concrete slab and the new structure would have to allow ventilation as well, which would neglect the insulative effect of the new system. Otherwise, damping could still occur inside the box creating the same problem.

For these reasons, the Wood Insulated Box Structure was discarded.

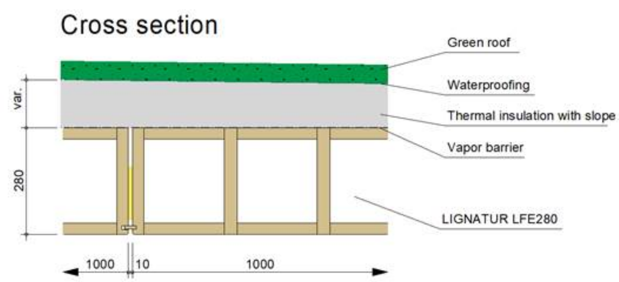


Figure 64 - Detail Provided by LIGNATURE

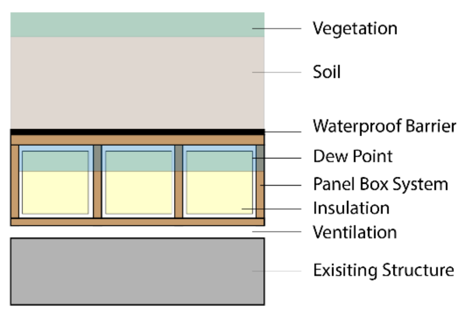


Figure 65 – Dewpoint of construction system

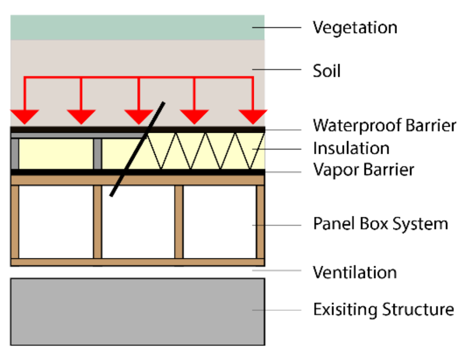
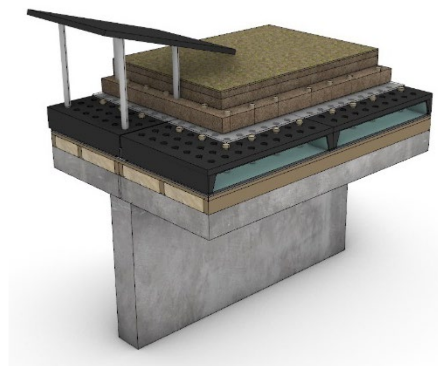


Figure 66 – Possible solution for Box Panel System

Option 11

The GFRP and FRP slab plates are being developed by many companies. These products are meant to replace grating systems due to their capacity to cover larger spans, their weather-resistant properties and reduce weight to lower the structural requirements.

On the websites of the referred companies, it was possible to find plenty of slab solutions. But for the box system, only one of the listed companies had available products to fulfill the span requirements set by the selected case studies.



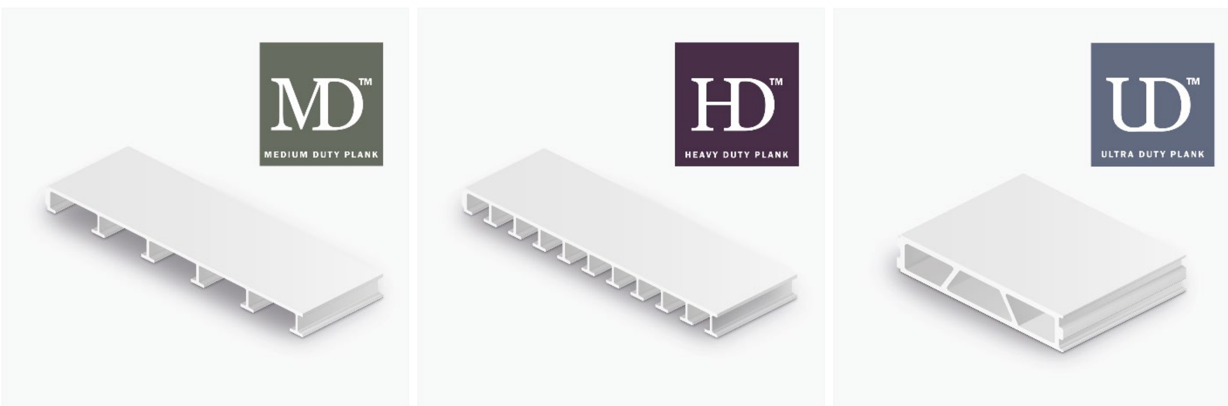


Figure 67 - FIBERLINE – Slab Solutions. Source: https://fiberline.com/products/c/decking-and-planks

Span [m]				
1	**2**	**3**	**4**	**Load Combinations**
MD	HD	UD	?	**A**
MD	HD	UD	?	**B**
MD	HD	UD	?	**C**

Table 44 - FIBERLINE - Slab Solutions - Span Range

The most relevant example is provided by FIBERLINE, which offers the MD, HD and UD (Medium, Heavy and Ultra Duty) slab solutions (figure 67). The cross-section is distributed on thin consecutive fins that allow reducing the cross-section height. These elements can be insulated inside and covered with a bottom lid that will allow the minimum ventilation to prevent the accumulation of humidity, which in this case, won't be a problem for the product.

By comparing the loading charts of the products, it was found that only the UD planks are suitable for spans larger than 3.00 m fulfilling the standards of an L/300 maximum deflection. The high loading capacity that the UD product can cover in a 3.00 m span leads to assume that the product could cover larger spans as well. Nevertheless, this is not specified on the product details. Moreover, the price of the products offered by this provider is above the referral price listed on the problem statement.

Other products are also unsuitable to cover larger spans. Designing a suitable one is possible, but the problem comes in the price, where an average estimation shows that with a simpler design of higher cross-section, the Eur/kg range would still exceed the price stated on the problem statement.

Additionally, products offered by the company STRONGWELL show that the same typology of slab panes can be designed with perforated tops to allow the flux of water, showing its potential application for the permeable structure (fig 70).

The possibility of combining this option with the Linear-Distribution and the Grid-Distribution was evaluated. By covering spans larger than the ones of a steel, aluminum or FRP grating, the number of beams could be reduced, and therefore, the number of pieces to be installed. Nevertheless, by comparing the loading charts of these panels with the loading charts of the steel and aluminum grating solutions, the price per m2 is still higher than these other options, making it still unsuitable.

This solution has great potential for this intervention due to its potential to cover larger spans while providing a lightweight solution and suitability for exposure to water and organic materials. Further material research and product development could make it a valuable option in the future.

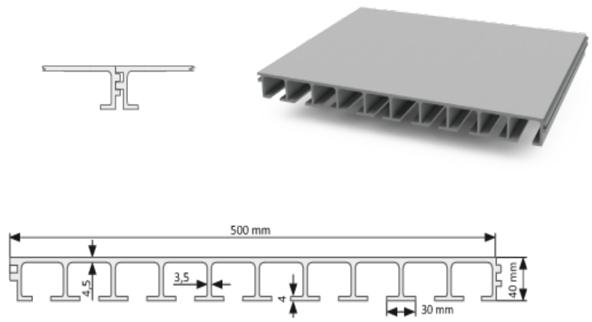


Figure 68 - FIBERCORE - Slab Solution. Source: https://fibrolux.com/es/division-de-materiales-compuestos/rejillas-prfv/perfiles-de-panel/pa-500-xl-9/

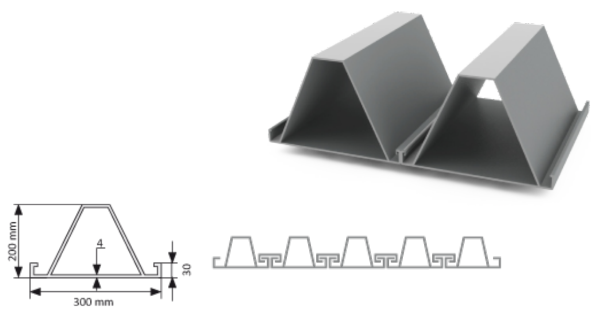


Figure 69 - FIBROLUX - Large Range Solution. Source: https://fibrolux.com/es/division-de-materiales-compuestos/rejillas-prfv/perfiles-de-panel/pa-200/

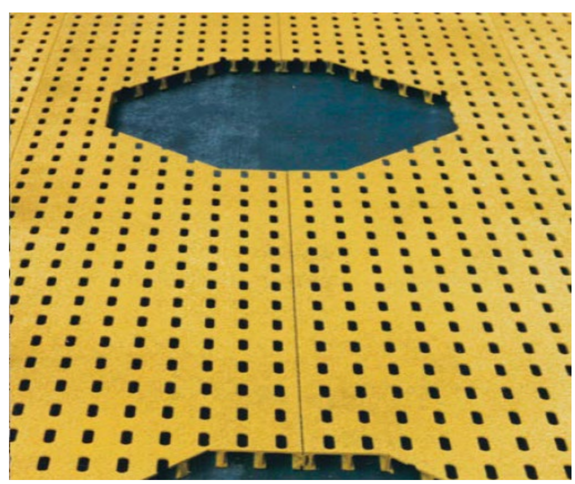
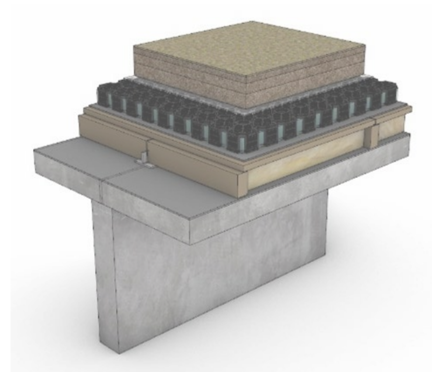


Figure 70 - STRONGWELL - Permeable Slab Solution. Source: https://www.strongwell.com/products/decking-and-planking/

Option 2

After the research on the panel box systems, the Wooden Insulated Base Structure was discarded as well, as the construction layering would be similar to the box system. This will create the same risk of rotting on the structural members due to humidity absorption. Therefore, Wood solutions were discarded from the remaining options.



From the initially presented options, the following options were discarded.

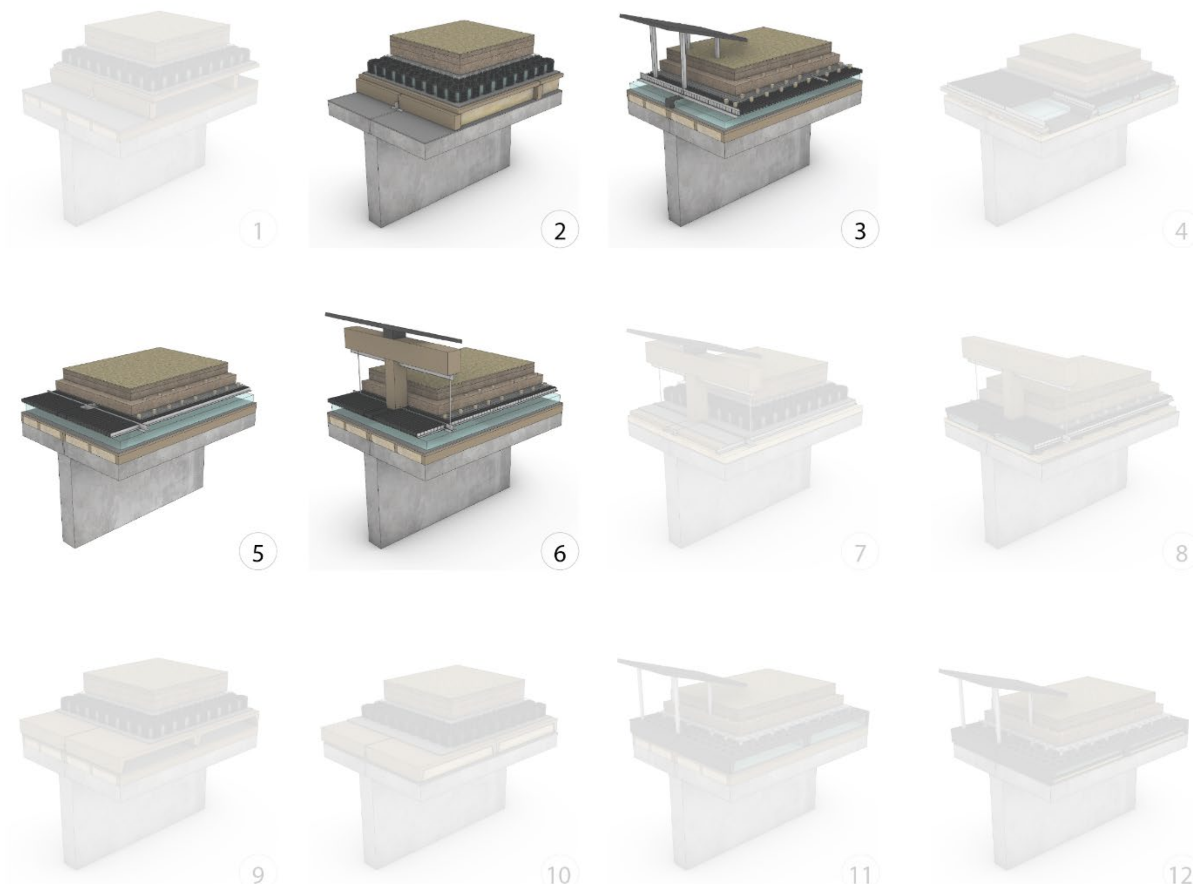
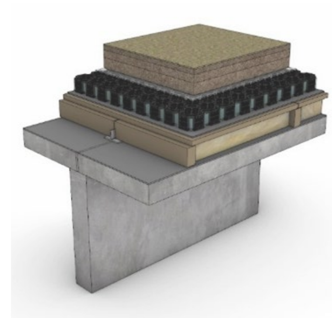
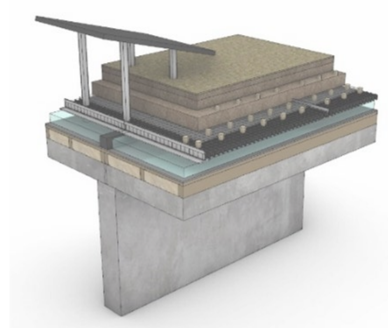


Figure 71 - Updated List of Options

5.8. COMPARISON OF SELECTED OPTIONS

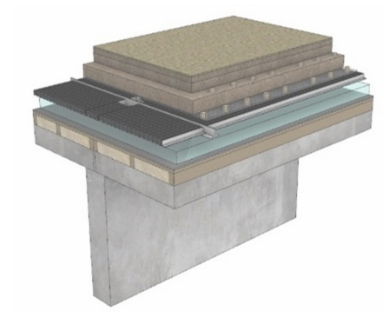


Option 2		
Material Options	Aluminum – GFRP – STEEL	
Loading Conditions	Full Load	
Description	To save on costs of grating systems and composite panels, FRP Plates will be used for the base of the waterproof barrier. The structure will rise a safe distance for the operable deflection. On top, a traditional blue-green roof system will be installed.	
Layers considered for compactness	1) Operable Area 2) Cross-section Area 3) Waterproof Barrier 4) Water Buffer System 5) Filtration Mat	
	Advantages	Disadvantages
Comparison	- Compactness - Compatibility with existing products - Design freedom	- No reuse of existing Structure



Option 3		
Material Options	Aluminum – GFRP – STEEL	
Loading Conditions	Reduced Load	
Description	The insulation panels will be installed on the bottom, on top of the current waterproof barrier. On top, the new waterproof barrier will be installed to support the water buffer layer, avoiding the need of the box system. The grating system will be installed as low as possible to facilitate the irrigation through capillarity.	
Layers considered for compactness	1) Insulation Layer 2) Waterproof Barrier 3) Water Buffer Area 4) Operable Height 5) Grating Height 6) Filtration Mat	
	Advantages	Disadvantages
Comparison	- Reuse of current structure - Design freedom - Avoid box retention system	- Structure exposed to water - Heavier and complex floor structure

Option 5		
Material Options	**Aluminum – GFRP – STEEL**	
Loading Conditions	**Reduced Load**	
Description	The same conditions will be used than for Option 3. The grating system will be installed as low as possible on the transversal grid later, to facilitate the capillarity cones to absorb the water.	
Layers considered for compactness	1) Insulation Layer 2) Waterproof Barrier 3) Water Buffer Area 4) Operable Height 5) Grating Height 6) Filtration Mat	
	Advantages	Disadvantages
Comparison	- Reuse of current structure - Reduction of span for secondary beams - Design freedom - Avoid box retention system	- Structure exposed to water - Heavier and complex floor structure



Option 6		
Material Options	**Aluminum – GFRP – STEEL**	
Loading Conditions	**Reduced Load**	
Description	The main cross-section will be suspended one story higher, from which the secondary beams will be hanging above water level, making the system more compact. The grating system will be installed as low as possible to shorten the distance between the substrate and water layers. The upper structure will be available to install solar panels and other additions.	
Layers considered for compactness	1) Insulation Layer 2) Waterproof Barrier 3) Water Buffer Area 4) Operable Height 5) Grating Height 6) Filtration Mat	
	Advantages	Disadvantages
Comparison	- Reuse of current structure - Reduction of span for secondary beams - Avoid box retention system - Functional external structure	- Structure exposed to water - Heavier and complex floor structure - Additional structure to raise and stabilize top beams.

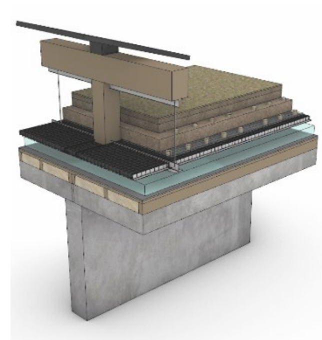


Table 45 - Remaining Options - Main characteristics and testing settings

Geometry Definition and Structural Analysis

The software of Rhinoceros and Grasshopper were used for the geometric definition of the boundary conditions and the structural elements to be analyzed. The Plugin of Karamba 3D was used for the FEA structural analysis. This allowed to parametrize the main variables and test the same models under variable conditions. These were defined by the characteristics of the different constructive systems described in the previous chapter, setting the maximum and minimum spans to be covered and average transversal lengths of the different typologies.

Calculations: The parametrized model allowed to calculate the structure under Serviceability Limit State (SLS) and Ultimate Limit State (ULS) conditions, under the considerations defined in the NEN-EN 1990 – Basis of Structural Design **[NEN]**. As the Accessibility of the roof will be prioritized for different functions, a maximum deflection value of L/340 was considered for the SLS calculations, in accordance with the norms. The load charts presented in the previous chapter, Full-Load and Reduced-Load, were included in the algorithm to test the different options under the different load combinations.

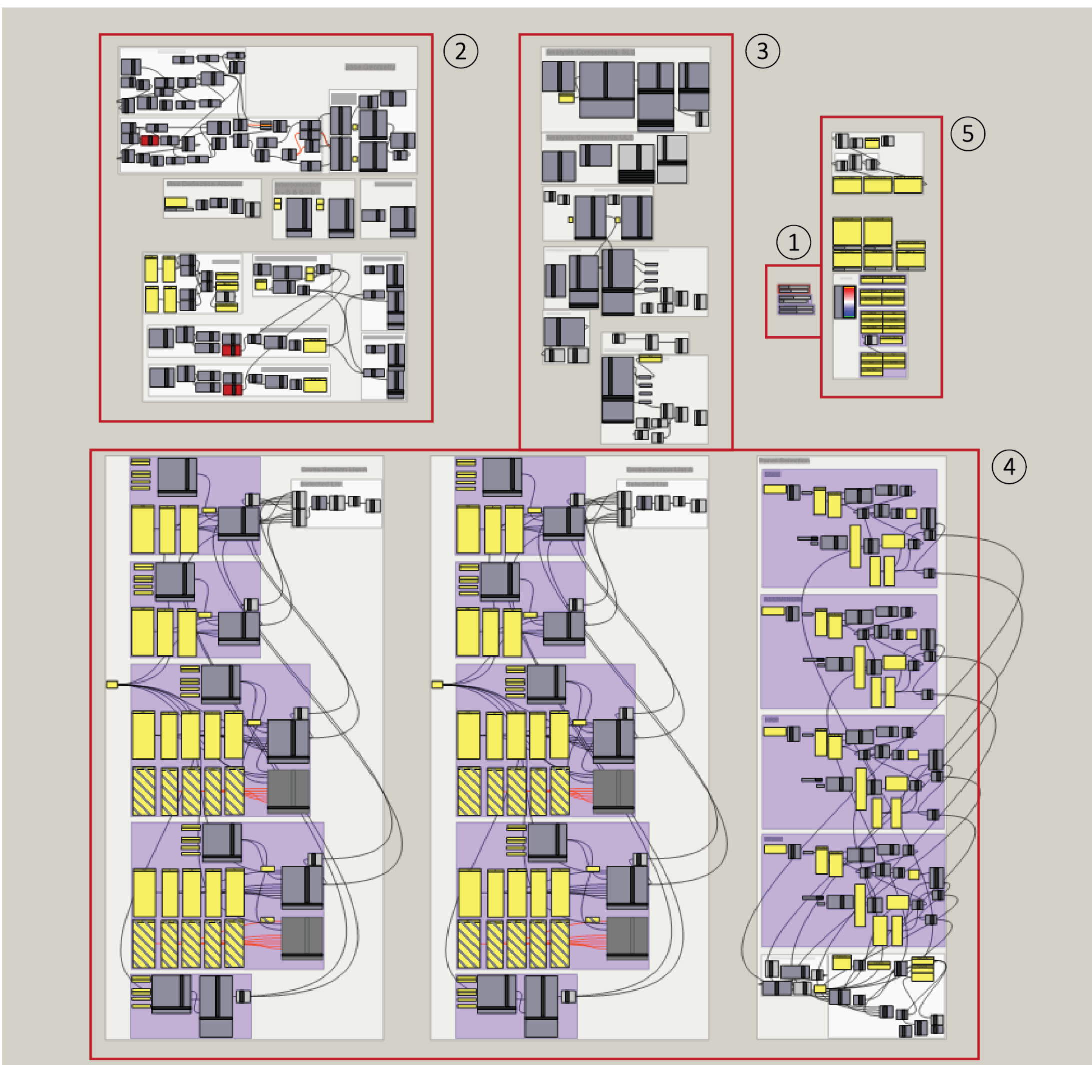


Figure 72 - Structural Analysis - Algorithm Organization and Structure

The algorithm is divided into 5 pats (figure 72):

1) Building: The variable parameters to test the solutions under different scenarios.

2) Geometry: The geometric definition of the elements under the given parameters.

3) Boundary conditions: The configuration of supports, connections and load combinations.

4) Structural Optimization: The selection of the optimal cross-section requirements for beams and panels based on the given limits (deflection and utilization), geometry, load combination and selected material.

5) Computation and Visualization: The calculation of the options and visualization of the results and relevant values for the comparison of the different options.

Testing Setup

Building Parameters: The required geometry is generated based on the selected parameters of the building. The structure is configured to cover the maximum available area based on the distance between elements and considering the required clear drainage areas. To analyze the best and worst-case scenarios, spans of 4.00 to 7.00 m were set to observe the solutions under different conditions (table 46).

System Name	COIGNET	ROTINGUIS	PRONTO	MUWI	RBM I & II	ERA
Transversal	10.95 m	9.65 m	10.53 m	11.90 m	11.40 m	11.80 m
Wall to Wall Span	4.35 – 4.50 m	2.70 - 4.70 m	**3.99** – 2.91 m	4.31 – 3.21 m	3.60 – 4.30 m	**7.30 m**
Span			4.00 m			7.00 m
			Best-Case Scenario			Worst-Case Scenario

Table 46 - Span Best- and Worst-Case Scenario Options

Boundary Conditions: Once the geometry is configured, the connectivity between the elements (if there are different groups) are established, as well as the support conditions and the loads. To accelerate the testing process, only load combinations A, B and C were tested, as they provide the minimum medium and maximum load of all combinations. The Full load and Reduced Load values are considered depending on the analyzed option. All options with Reduced Load conditions were tested using Steel Gratings, as it is the only option that covers all the ranks of spans. The effect of a lighter grating or alternative solutions will be considered in a later stage.

Comb.	Full Load		Reduced Load	
	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)
A	3.66	5.13	2.31	3.31
B	4.84	6.68	3.49	4.86
C	5.79	7.96	4.79	6.61

Table 47 - Load Combinations for Analysis

Methodology for comparison: Once the system is analyzed, all the relevant results are compiled to be compared and assess the advantages and disadvantages of each option under the selected parameters. Based on the four remaining options, the following characteristics were set as the base for the comparison:

Quantitative	
Structure Weight	
Total Weight	[Kg/m2]
Material Cost Approximation	[€/m2]
Ease of Assembly	
Number of Segments	[Numb.]
Weight of Segments	[Kg]
Complexity of Assembly	
Compactness of system	[mm]
Load Distribution	
Peak Reaction Forces	[kN] / [kN/m]

Qualitative	
Accessibility for maintenance and repairs	
Accessibility	[Y/o]
Design freedom	
Design restrictiveness	[table 3]

Table 48 - Qualitative and Quantitative parameters

Results

All options were tested under the described conditions. All the results are included in (Annex C). The Weight, number of beams, Cross-section height and utilization max was registered for each combination. For the selection process of each registered combination, the following criteria were mediated but under the following priority:

1. Max Deflection
2. Lighter option
3. Cross-section Height
4. Lesser number of elements
5. Max Utilization achieved

Additionally, the results for the shortest and longest spans under the highest load combination were compiled with all the evaluation criteria parameters. These results allowed us to arrive at the first set of conclusions.

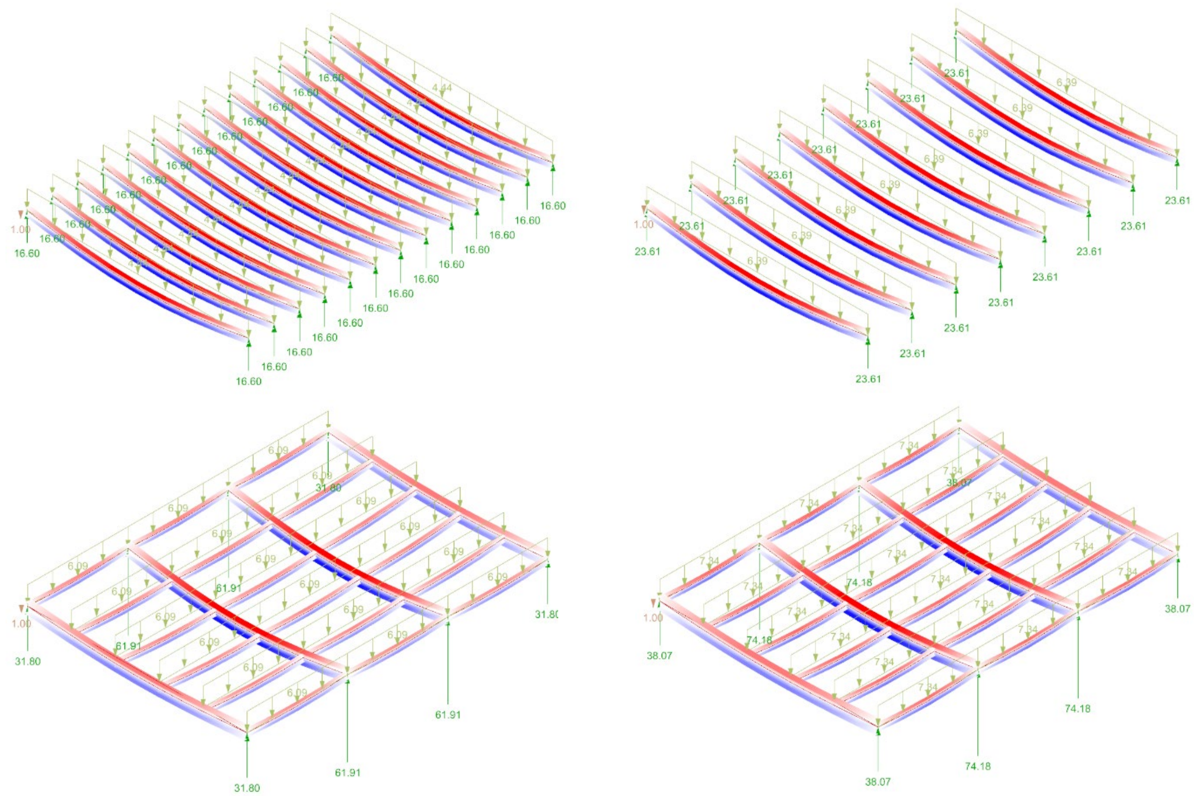


Figure 73 - Compared options 2, 3, 5 and 6 - Graphic output of beam utilization

Option 2

As seen on the tables, steel appears to be the optimal solution. Achieving the most compact and cheaper price per m^2 although aluminum is the lightest solution. The most compact solution under the largest span and heaviest load combination is of 420 mm.

Span Length [m]												
4.00			5.00			6.00			7.00			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.46	11	140	0.50	13	160	0.58	11	200	0.63	11	220	A
+25.7		-25.7	+24.5		-24.5	+24.1		-24.1	+26.1		-26.1	Utilization
0.46	13	140	0.54	11	180	0.60	13	200	0.69	11	240	B
+27.0		-27.0	+28.9		-28.9	+25.3		-25.3	+26.2		-26.2	Utilization
0.50	13	160	0.55	13	180	0.66	13	220	0.73	13	240	C
+22.9		-22.9	+27.8		-27.8	+23.2		-23.2	+25.3		-25.2	Utilization

Table 49 - Results Option 2 - Aluminum solution

Aluminum	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	203	0.39	116.06	13	34.44	383	9.05	Y	Y	100
Longest Spann	355	0.60	148.37	13	156.69	535	16.31	Y	Y	100

GFRP	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	200	0.52	207.41	13	68.35	420	9.22	Y	Y	100
Longest Spann	300	0.60	232.06	13	158.95	480	16.32	Y	Y	100

Steel	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	160	0.50	86.01	13	63.11	340	9.19	Y	Y	100
Longest Spann	240	0.73	100.27	13	214.84	420	16.60	Y	Y	100

Table 50 - Results Option 2 - All solutions

Option 3

Span Length [m]												
4.00			5.00			6.00			7.00			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.53	7	140	0.57	8	160	0.53	9	180	0.67	8	220	A
+24.9		-24.9	+27.7		-27.7	+25.1		-25.1	+24.1		-24.1	Utilization
0.64	7	160	0.69	7	200	0..58	8	220	0.62	8	240	B
+27.5		-27.5	+25.3		-25.3	+24.1		-24.1	+26.2		-26.2	Utilization
0.66	8	160	0.57	9	200	0.61	9	220	0.67	11	240	C
+32.6		-32.6	+25.5		-25.5	+27.9		-27.9	+25.9		-25.9	Utilization

Table 51 - Option 3 - Steel solution

Steel seems to be the optimal choice in this solution as well, achieving the most compact and cheaper option. In this case, the compactness is higher than the previous options. Again, aluminum is the lightest solution, but still more expensive and higher cross-section requirements than galvanized steel.

In this case, two numbers can be observed for compactness. This is due to the different heights at which the installation of soil layer and the accessible floor areas can start, because of the interruption that the remaining portion of the cross-section height would cause on accessible areas.

Aluminum	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	228	0.46	104.79	9	46.66	280 – 478	11.06	Y	Y	100
Longest Spann	355	0.57	122.20	9	156.69	280 – 605	19.72	Y	Y	100

GFRP	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	200	0.52	184.45	9	68.35	280 – 450	11.16	Y	Y	100
Longest Spann	300	0.57	194.72	11	158.95	275 – 550	16.78	Y	Y	100

Steel	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	160	0.66	90.31	8	63.11	280 – 410	13.10	Y	Y	100
Longest Spann	270	0.67	99.84	8	214.84	275 – 490	23.61	Y	Y	100

Table 52 - Option 3 - All solutions

Option 5

Span Length [m]												
4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.57	4 - 12	180 – 140	0.66	4 - 12	220 – 140	0.71	4 - 15	240 – 160	0.66	4 - 18	300 – 140	A
+27.5	-27.5		+28.1	-28.1		+29.2	-29.2		+27.3	-27.3		Utilization
0.59	4 – 9	220 - 160	0.62	4 - 12	240 – 160	0.68	4 - 15	300 – 160	0.68	4 - 18	300 – 160	B
+30.3	-30.3		+30.6	-30.6		+26.0	-26.0		+32.3	-32.3		Utilization
0.63	4 - 12	220 - 160	0.68	4 - 15	270 – 160	0.71	4 - 18	300 – 160	0.78	4 - 18	360 – 180	C
+30.5	-30.5		+29.9	-29.9		+31.4	-31.4		+32.1	-32.1		Utilization

Table 53 - Option 5 - Steel solution

For the Grid distribution option, it is possible to see that the only material capable of covering spans larger than 6.00 meters is the steel solution. Aluminum and GFRP are suitable for shorter spans, but above 6.00 m they require more beams in the main direction, which will defeat the main purpose of this option. Steel performs the best in the compactness and economic aspects as well. Aluminum provides the lightest solution for shorter spans.

The compactness of the system is the lowest, as the height of the main beams will reach 360 mm (in the best case) to cover the largest span. Again, increasing the number of beams in the main direction to decrease the height will defeat the whole purpose of this solution.

Moreover, the reaction force caused by the main beams is 60.58kN. Considering that the reaction force will be twice as big due to the spans on both sides of the walls, it reaches a close value to the worst-case scenario wall loadbearing capacity from the calculated samples. This is an important consideration for the following option.

Aluminum	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	304 203	0.48	102.03	4 15	65.74 27.55	275 – 554	33.18	Y	Y	100
Longest Spann	355 101	0.60	126.73	9 48	156.69 3.66	280 – 605	22.20	Y	Y	100

GFRP	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	300 200	0.63	218.55	4 12	90.83 54.68	280 – 550	34.01	Y	Y	100
Longest Spann	500 150	0.58	193.07	6 40	182.57 15.46	275 – 750	33.18	Y	Y	100

Steel	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	220 160	0.63	72.87	4 16	104.87 50.48	280 – 470	33.93	Y	Y	100
Longest Spann	360 180	0.78	82.16	4 18	399.46 60.03	280 – 610	60.58	Y	Y	100

Table 54 - Option 5 - All solutions

Option 6

Span Length [m]												
4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.57	4 - 12	180 – 140	0.66	4 - 12	220 – 140	0.71	4 - 15	240 – 160	0.66	4 - 18	300 – 140	A
+27.5	-27.5		+28.1	-28.1		+29.2	-29.2		+27.3	-27.3		Utilization
0.59	4 – 9	220 - 160	0.62	4 - 12	240 – 160	0.68	4 - 15	300 – 160	0.68	4 - 18	300 – 160	B
+30.3	-30.3		+30.6	-30.6		+26.0	-26.0		+32.3	-32.3		Utilization
0.63	4 - 12	220 - 160	0.68	4 - 15	270 – 160	0.71	4 - 18	300 – 160	0.78	4 - 18	360 – 180	C
+30.5	-30.5		+29.9	-29.9		+31.4	-31.4		+32.1	-32.1		Utilization

Table 55 - Option 6 - Steel Solution

This option presents the same consideration as the previous one. Steel will be the only available solution to cover spans larger than 6.00 m.

As the main cross-section will be one level above the roof level, the compactness of the system depends on the secondary beam cross-section only, making this option the most compact solution.

Nevertheless, the reaction forces will be even higher than with the previous option, as the additional support system and stabilization requirements will have to be added to the total weight received on each support. Moreover, the weight of additional implementations on the top structure will add to the total weight as well.

Aluminum	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	304 203	0.48	102.03	4 15 + 20	65.74 27.55	275	33.18	Y	Y	80
Longest Spann	355 101	0.60	126.73	9 48 + 54	156.69 3.66	280	22.20	Y	Y	0

GFRP	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	300 200	0.63	218.55	4 12 + 16	90.83 54.68	280	34.01	Y	Y	80
Longest Spann	500 150	0.58	193.07	6 40 + 48	182.57 15.46	275	33.18	Y	Y	80

Steel	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	220 160	0.63	72.87	4 16 + 24	104.87 50.48	280	33.93	Y	Y	80
Longest Spann	360 180	0.78	82.16	4 18 +24	399.46 60.03	280	60.58	Y	Y	80

Table 56 - Option 6 - All solutions

5.9. FIRST COMPARISON:

To compare the results, a radar graph was used based on the 6 variables compared for every option. A range between 0 and 10 was created based on the worst and best results, where 10 would correspond to the worst and 0 to the best outcome for every variable and from all the compared options. An example is shown in *table 57* for the variable of N of Pieces.

Correspondent value = (Value – ValueMin) x 100 / (ValueMax – ValueMin)/10	Example: (13 -11) x 100 / (46-11))/10 = **0.57 > 1**			
Comparison	Option 2 – Steel	Option 3 – Steel	Option 5 – Steel	Option 7 – Steel
N of Pieces [units]	13	11	22	46
Correspondent Value	**1**	0	3	10

Table 57 – Quantitative Values - Calculation of values for radar graphic comparison.

For the Qualitative value of Design Freedom, the results were set from 1 to 4 based on the criteria described in *table 58*. This allowed to have a graphical overall comparison of the different options, which can be seen in figure 74.

Design Freedom Parameters of evaluation	
0	The solution provides a surface with no interruptions, obstacles, or limitations for the distribution of functions.
3	The solution provides a surface with obstacles that do not interrupt on the distribution of functions.
6	The solution provides a surface with obstacles that partially interrupt the distribution of functions.
10	The solution provides a surface with obstacles that completely interrupt the distribution of functions.

Table 58 – Qualitative values - Design Freedom: Parameters for evaluation

The results for the best solution of every option were used for the comparison:

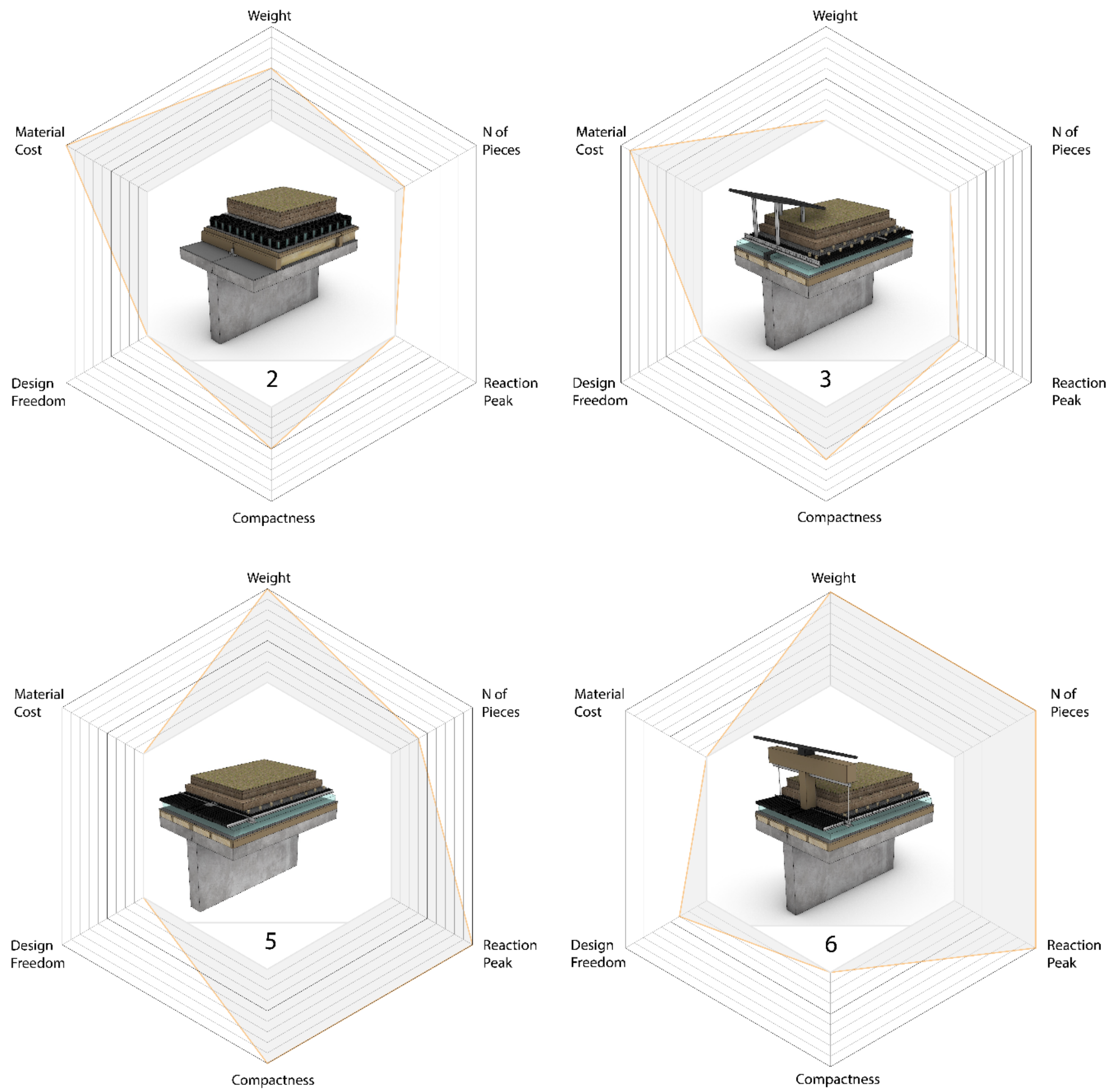


Figure 74 - Comparison of results - Average of parameters

Options 2 and 3 seem the most feasible and approachable options for the reinforcement strategy. Although they don't reach the compactness of option 8, these are the most lightweight and economic options. Moreover, the reduced number of pieces in comparison to options 5 and 8 could lower the costs of installation depending on the selected assembly strategy.

The functionality of the top structure and the compactness of option 8 are its biggest advantages. Nevertheless, the tensile structure will affect the design freedom. Additionally, the installation of solar panels and sunshades should be carefully planned due to the uplift wind force exerted at that height.

Moreover, avoiding decreasing sun exposure from the below-vegetated areas is important, as it would impact on their health and cooling performance.

5.10. COMBINATION OF STRATEGIES

During the testing process, the potential combination of options 8 and 3 were noted. Creating additional support positions along the beams in the linear arrangement to reduce the cross-section requirements of the beam and allow a more compact and lightweight solution. Moreover, splitting the beam in segments to facilitate their transportation on the rooftop, as for spans longer than 6.00 m, the weight per element of all the solutions are exceeding 150 kg. This will increase the machinery requirements for the installation.

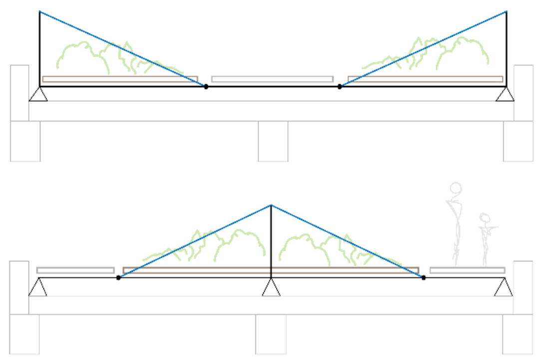


Figure 75 - Initial design concept for structure with tensile supports.

The initial concept of option 8 was to create additional supports along the main span through the implementation of a tensile structure, as shown in *figure 75*. The idea evolved to option 8 (*figure 76*) after evaluating the potential use of the upper structure to reduce the design restrictiveness of the cables and for the integration of additional functions on the above structure, like roofs, sunshades, and solar panels.

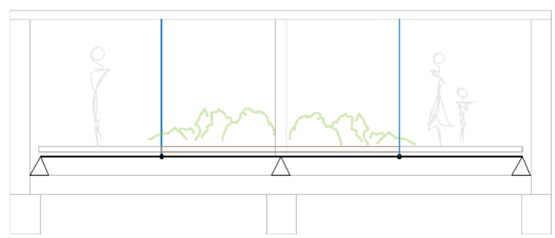


Figure 76 - Final design concept for suspended structure

Based on the initial idea of option 8, an additional option was evaluated under the same parameters (figure 77).

This option would be only compatible with the permeable structure of option 3, as with option 2, the tensile cable would require piercing through the waterproofing layer, creating a more complex connection to prevent interrupting the box system and creating again a higher risk of leakages or failure. Moreover, as the connection complexity increases, a solution with a reduced number of beams would be preferable.

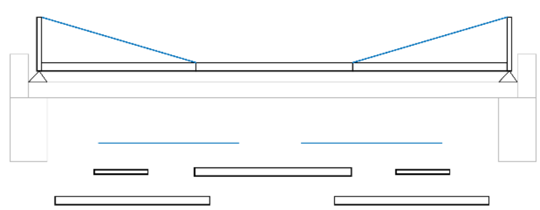


Figure 77 - Design Concept - Combination of Options

Option 13		
Material Options	Aluminum – GFRP – STEEL	
Loading Conditions	Reduced Load	
Description	The bottom layer configuration is the same as in option 3. The installation of additional supports for the segmented beam through a tensile structure to the post supports installed on the loadbearing walls. These supports will also be used for the implementation of additional functions. The cable structure will be covered by a protective sleeve.	
Layers considered for compactness	1) Insulation Layer 2) Waterproof Barrier 3) Water Buffer Area 4) Operable Height 5) Grating Height 6) Filtration Mat	
	Advantages	Disadvantages
Comparison	- Reuse of current structure - Reduction of span for main beams - Avoid box retention system - Functional external structure - Reduced number of beams	- Structure exposed to water - Heavier and complex floor structure - Additional structure to raise and stabilize top beams. - Force balancing required

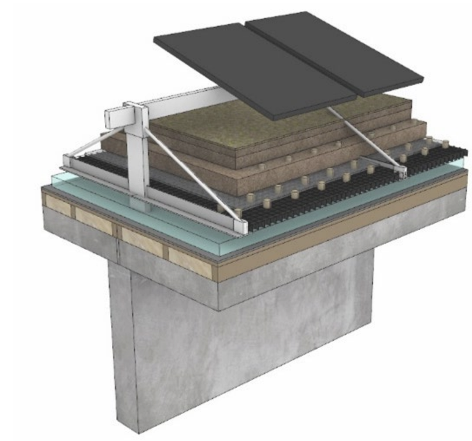


Table 59 - Option 13 - Main characteristics and testing settings

Testing: The option was evaluated under Reduced-Load conditions, as it would operate as a permeable structure as well. Two additional connections were created, dividing the beam in 3 pieces, and preventing the cable structure to disrupt the circulation in the central piece. For the calculations, the 3 segments were divided in equal length pieces.

For the cable structure, a new set of supports were created on top of the original supports at a variable height. This, to evaluate the rection forces for which such a connection would need to be designed for.

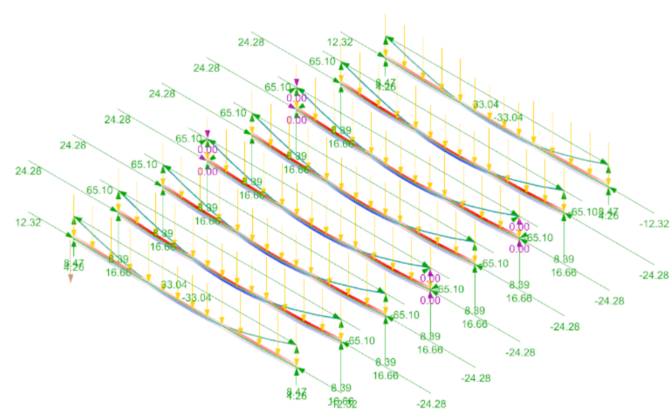


Figure 78 - Structural analysis option 13 - Graphic output of beam utilization

Aluminum	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	101 101	0.52	106.91	12 + 12 6	4.12 3.96	285 – 351	21.25	Y	Y	75
Longest Spann	177 177	0.48	98.53	12+12 6	18.66 18.66	285 - 427	33.23	Y	Y	75

GFRP	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	100 100	0.53	114.03	12 + 12 6	6.13 5.90	285 - 350	21.28	Y	Y	75
Longest Spann	150 150	0.49	111.81	12+12 6	20.19 19.76	285	33.29	Y	Y	75

Steel	Quantitative							Qualitative		
	Cross Section Height [mm]	Weight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Peak Reaction Force [kN]	Access to Layers [Y/N]	Adaptability [Y/N]	Design Freedom [%]
Shortest Spann	80 80	0.54	105.43	12 + 12 6	8.09 7.09	285 – 330	21.3	Y	Y	75
Longest Spann	120 120	0.50	93.27	12 + 12 6	24.35 26.16	285 – 370	33.32	Y	Y	75

Table 60 - Option 13 - Structural analysis results

Results: As shown in the results, a significant improvement is added for both short and long-span combinations.

Weight: The weight per m2 of the structure remains in the same average for the short span but lowers the average for the longer span combination.

Number of pieces: The number of pieces increases substantially compared to the linear arrangement options. Nevertheless, it is still a reduced amount compared to the Grid Suspended structure and reaching the same level of compactness.

Compactness: The beam cross-section is significantly reduced compared to the previous Linear Arrangement options.

Price: The structure remains with the same price estimate as previous options. Nevertheless, more connections and of higher complexity would increase the time of assembly.

Weight of units: This is the point where this option stands out the most, reaching sizes of units that would be transportable by workers without the need of load carriers, which would significantly impact on the costs of assembly.

Peak Reaction: Although the number of beams is reduced. The maximum reaction force is still far below the limit.

Adaptability: For short spans that can be covered with smaller cross-sections and a compact system, the initial Linear arrangement of option 3 could be used. The new option would be implemented on larger spans, whenever the cross-section exceeds a limit of height and weight to maintain a compact and lightweight system.

Design Freedom: This option would be more restrictive than option 8, as the cable structure disrupts the transversal flow of users, restricting the functions for the areas between cables. Nevertheless, the support positions can be moved to reduce the interrupted area as long as it maintains its compactness.

5.11. SECOND COMPARISON

The same evaluation process was repeated. This time, comparing options 2, 3, 6 and the new option 13. Option 5 was discarded as the less-performing option.

Structural Aspects: It is possible to see that the latest option provides an in-between result of options 3 and 8. Although the design freedom becomes more restrictive, the number of segments decreases substantially and prevents the high peak reaction forces on the supports experienced with option 6. Moreover, the compactness reached is equal or better than for option 6, which will ensure better performance of the irrigation by capillarity.

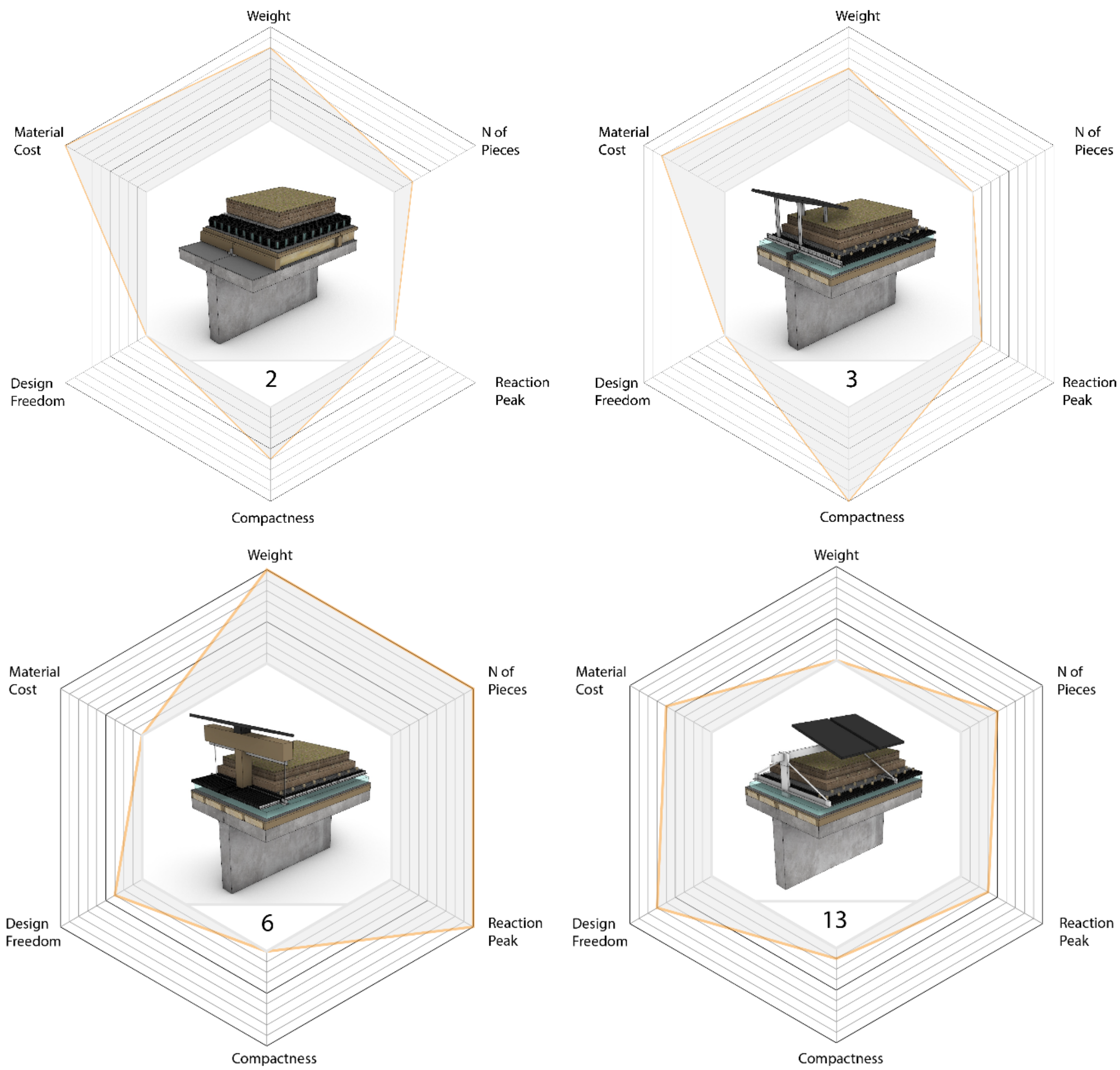


Figure 79 - Comparison of Results 2 - Average of Parameters

Ease of assembly: As seen in the results, due to the weight of individual pieces of options 2, 3 and 6 on spans larger than 5.00 m, a load carrier on roof would be required to aid workers in the assembly process. For spans of 7.00 and higher, a higher capacity crane will be required. Two possible strategies to decrease the assembly costs are considered for this situation.

Preassembled System: Preassembled modules could be transported and mounted on site. This would save on time and reduce the number of work hours required for the installation of the new structure. Nevertheless, the machinery required for the transportation and installation process of this strategy would increase costs and would be restricted by the availability of space around the building. For High-rise buildings this installation process would be suitable.

On-Site Assembly System: Individual elements could be transported and mounted on the roof. This would be dependent on the weight of the individual elements, as these might still require machinery to be transported on the rooftop. Moreover, this would increase the number of work hours of assembly. Nevertheless, the advantage of such a strategy would be its suitability for any building and urban scenario, where different machinery can be selected for the specific case.

Figure 80 - Option Comparison - Machinery Requirements

	Preassembled modules	Segmented Modules
Options	Stacker Crane / Tower Crane	Stacker Crane / Telescopic Crane / Maintenance Crane (If Available) / Tower Crane
	• Higher requirements for precision mounting. • Requires available space - more restrictions and disruptions at urban level. • High Costs - lowered if long time/usage is required • Reduce number of work hours - reduction in costs	• Transporting pieces to roof - No height restrictions • No precision for installation required • Economic for shorter work periods - will become expensive if time usage increases. • More suitable in tighter areas - Momentary disruption/No disruption. • Will increase the work hours demand.

Table 61 - Assembly Strategies

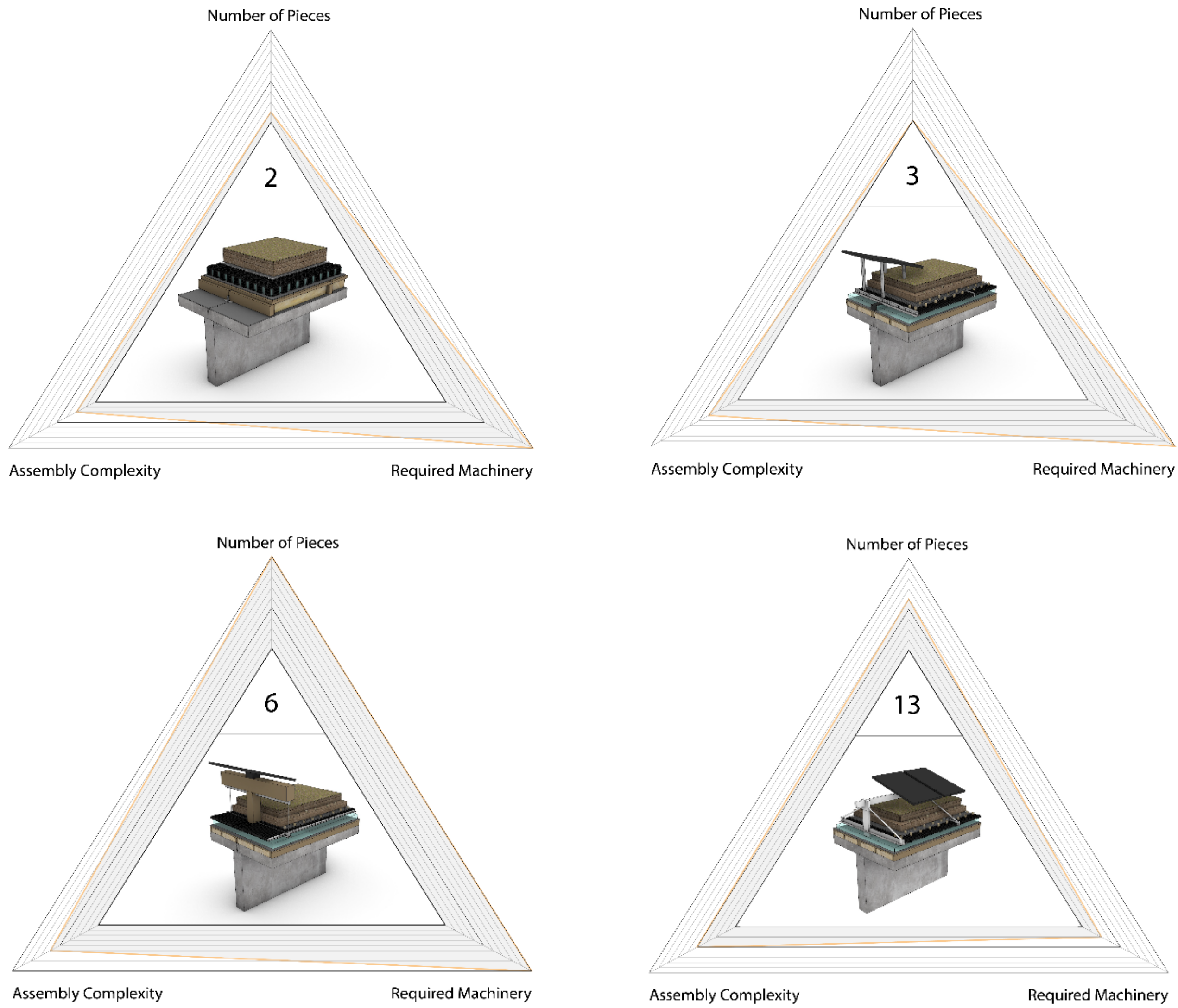


Figure 81 - Option Comparison 3 - Ease of Assembly

The latest proposal is the only option available for the On-Site mounting strategy, as even in the largest span and highest load combination, the elements won't exceed the weight limit to be carried by construction workers. The advantage is the reduction in machinery requirements to transport the elements to the roof. Other suitable crane options or lift cranes could be installed to reduce the costs of machinery and be more accessible to any building and urban scenario without the requirement of a permanent operable area or disruptions at the street level. Nevertheless, the number of work hours will increase due to the number of pieces and complexity of the connections. Therefore, the simplicity of the design and the connections would be of substantial benefit for this strategy.

5.12. SELECTION AND DEVELOPMENT OF THE STRATEGY

The selection process until this stage was driven towards finding the most suitable for the largest number of buildings, reaching the requirements for the best- and worst-case scenarios. For this reason, option 13 was considered the option with the most potential to be further developed due to the following considerations:

Structural aspects: By adding supports through the tensile structure, the cross-section heights can be reduced, creating a lighter and compact structure, beneficial for the weight on the building and the well-functioning of the green roof system. By balancing the forces, the requirements on these additional supports will have to be calculated, to achieve the most efficient and versatile structure. Moreover, in cases where the span of the building is below 4.00 m, this system can be combined with option 3 to reduce the number of cables and therefore reduce the number of connections.

Ease of Assembly: By partitioning the beams in segments, the weight of the individual elements reaches suitable ranges to be carried by workers. Although the number of pieces and connections increases, the machinery requirements are decreased for the installation process. Moreover, the selection of any suitable machinery for the building and urban context is possible. Designing the supports and connections to simplify and accelerate the assembly process will be the main goal for this option.

Load Distribution: Another important factor to consider is the load distribution tool. The grid distribution will create subdivision of loads in two directions, resting versatility to take advantage of this strategy on the design process. The linear arrangement will provide a simpler output for the load zoning of the roof, advantageous for the design freedom (*figure 82*).

Moreover, the selection of the minimum and maximum force for the strategy can be combined with the placement of the cable supports, determining the loads for the functional areas between supports and the opposite segments for the heavier loads of GR interventions.

Design Freedom: This aspect will be more limited with this solution. Nevertheless, by setting up the distances between supports, the use of the vertical structure for other functions like PV Panels and additional structures for shading systems will provide a more versatile and integrated structure.

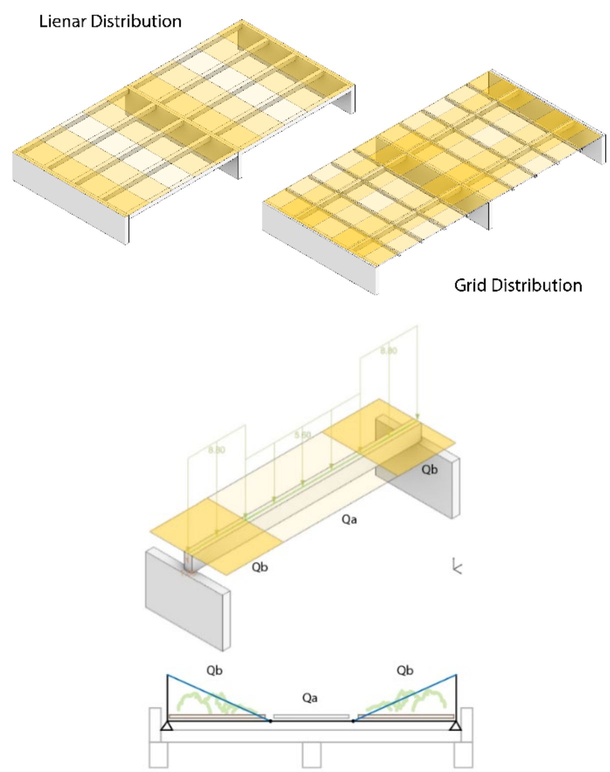


Figure 82 - Load Distribution Strategy for option 13

5.13. FINAL DESIGN OUTPUT:

As mentioned before, by combining the selected option 13 with option 3 shows 3 possible adaptations of the system to fulfill the requirements of different scenarios. The three options are shown in figure 83. Their suitability will depend on the span lengths to be covered and the peak forces on the walls. For short spans, option A would provide the simplest solution, avoiding the tensile structure. Option B, in case of mid-range spans and option C for the largest spans. Option C is used to describe the construction details of the system.

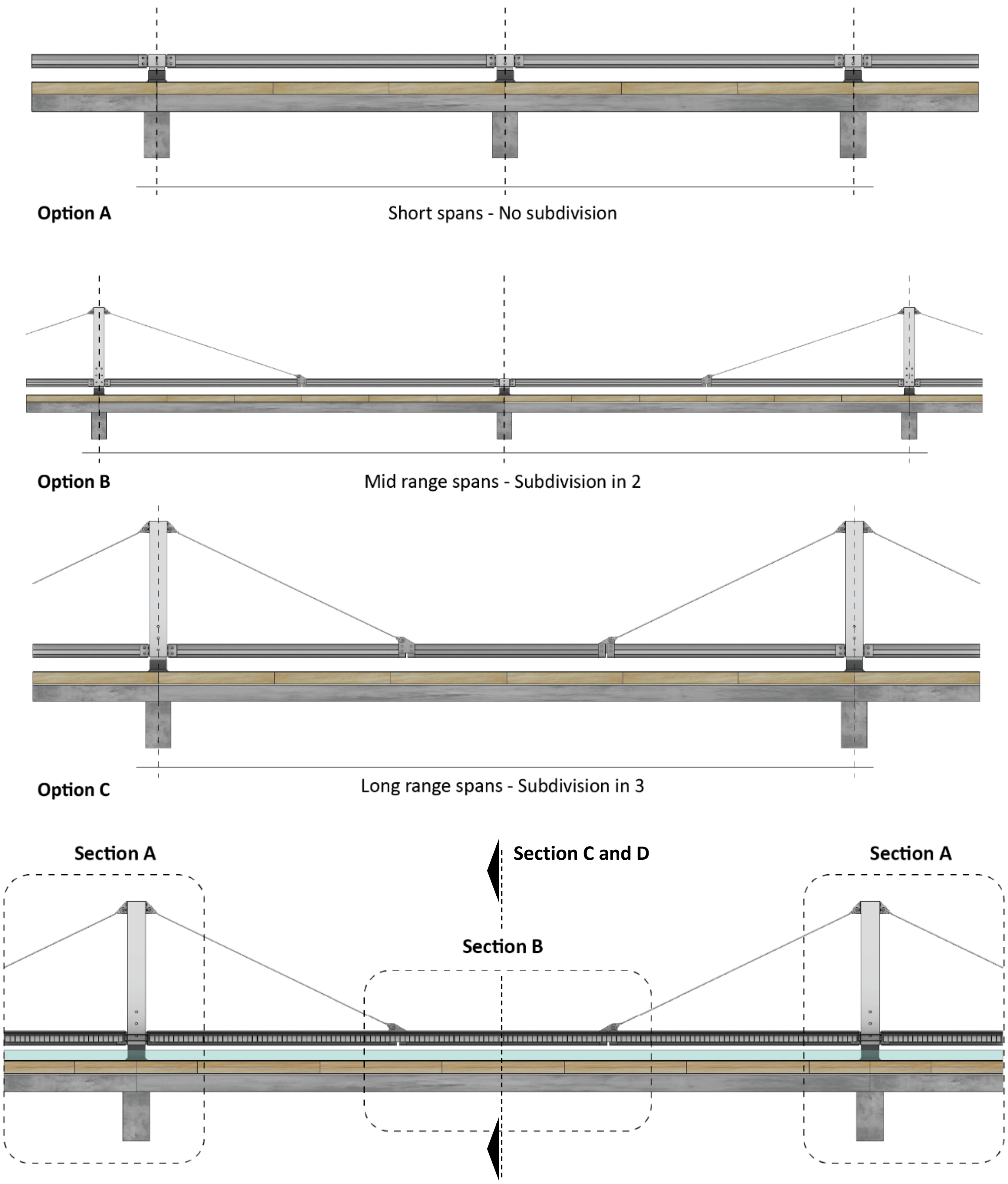
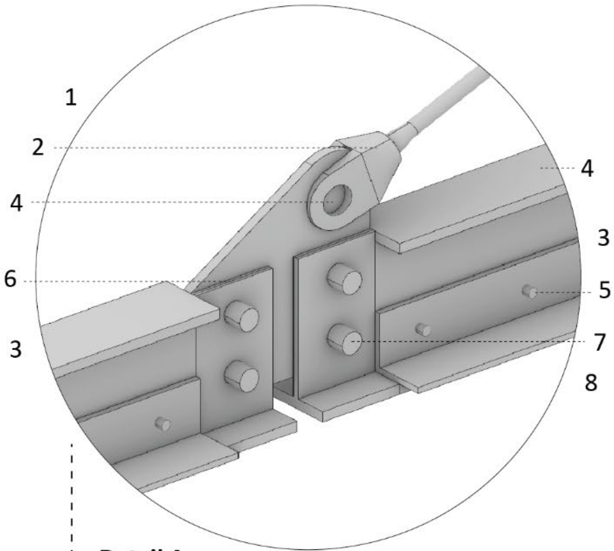


Figure83 - Structural configurations



Detail A

1- Tensile Rod **2-** Rod Anchor **3-** Junction Plate **4-** IPE 120 Beam **5-** Bolted Connection for L brackets **6-** Cut in Falange for Connection **7-** Junction Bolted Connection **8-** L Section 50mm

Section B, shown in figure 84 shows the configurations of the different components and layers at the middle of the span. Detail A shows the connection detail if the tensile structure and the two beam segments. A plate that receives the two beam segments trough a bolted connection. The top Falange of the beams is cut to allow the plate to receive the rod anchor on the top wing. As shown in Section B, A rectangular FRP section is installed between the aluminum grating panels as a spacer to distribute the gratings without the need of additional custom sizes. Moreover, this box is used as an installation duct for cable management or additional irrigation systems that might be required.

Finish Layers

- Soil class 1
- Cable protection sleeve
- Rod Anchor
- Soil class 2
- Anchor Plate
- EPDM Gasket
- Capilarity cones + PET Tubes
- Filtration Mat
- Aluminum Grating 30x3
- IPE 120
- Water buffer

Structural Layers

- Floor Finish
- Floor Structure
- FRP 10mm Sheet
- Filtration Mat
- Rectangular section 30 mm for installation duct
- IPE 120
- Operable heigth
- Water buffer
- New waterproof barrier
- Insulation panels 100 mm
- Old waterproof barrier
- Existing concrete slab

Finish Layers

- Vegetation layer
- Soil class 1
- Floor finish
- Floor finish
- Soil class 2
- Floor structure
- Steel Galavanized sheet Contention sheet
- Steel Galvanized L Secion 60x4 Support for contention sheet
- Filtration Mat
- Shear Connector Fixing point for horizontal structure
- Aluminum Grating 30x3

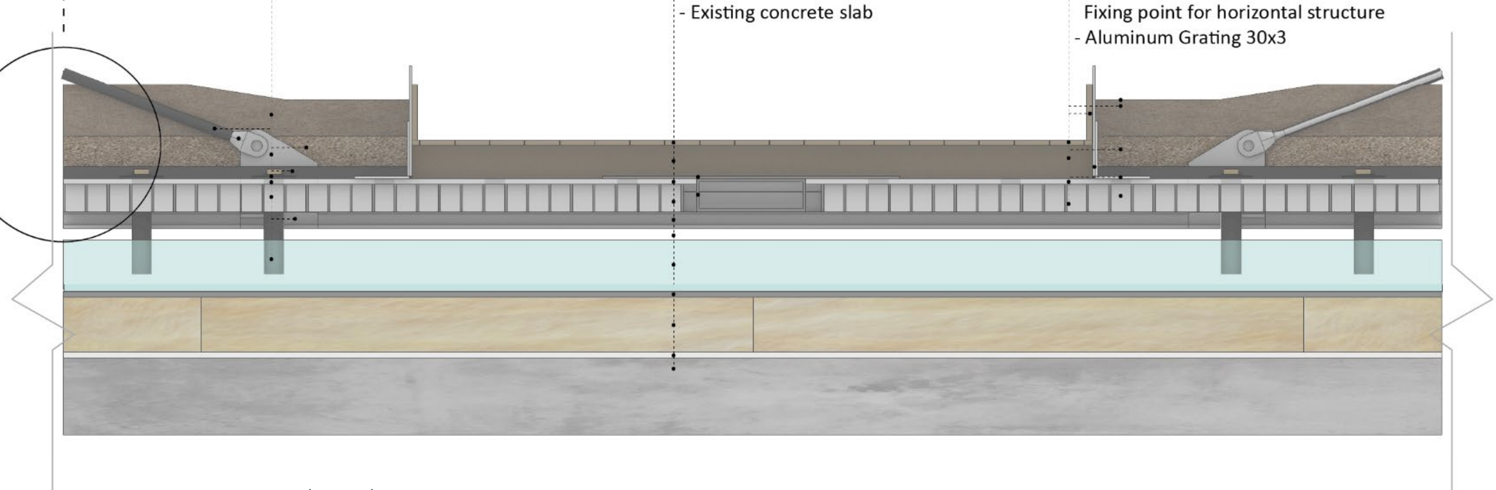
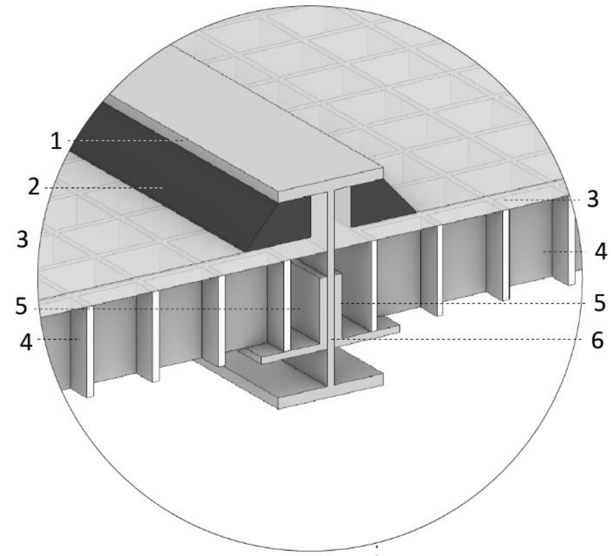


Figure84 – Section B and Detail A

Figure 85 shows Section A, the segment around the support and column. Detail B shows the configuration of the components for the floor structure. The L brackets will come pre-mounted on the I beam, which is used to receive the aluminum grating system. On top, the filtration mat is installed and fixed on the ends against the I beam through EPDM gaskets to prevent its movement and ease the installation of the rest of components. As seen on Section A, the gratings are interrupted again around the column, where an additional FRP box is installed again as a spacer and installation duct for different functions.



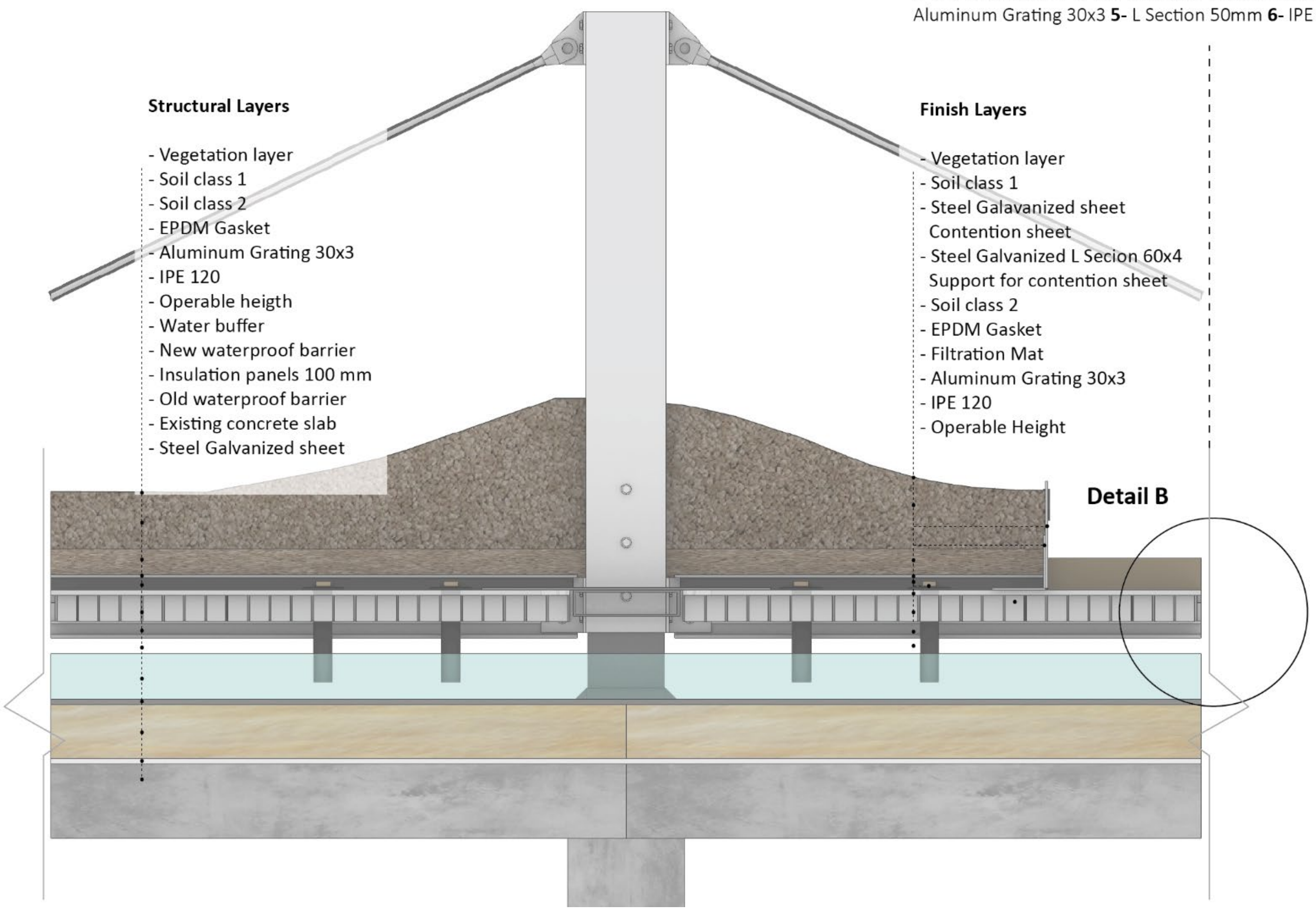


Figure85 - Section A and Detail B

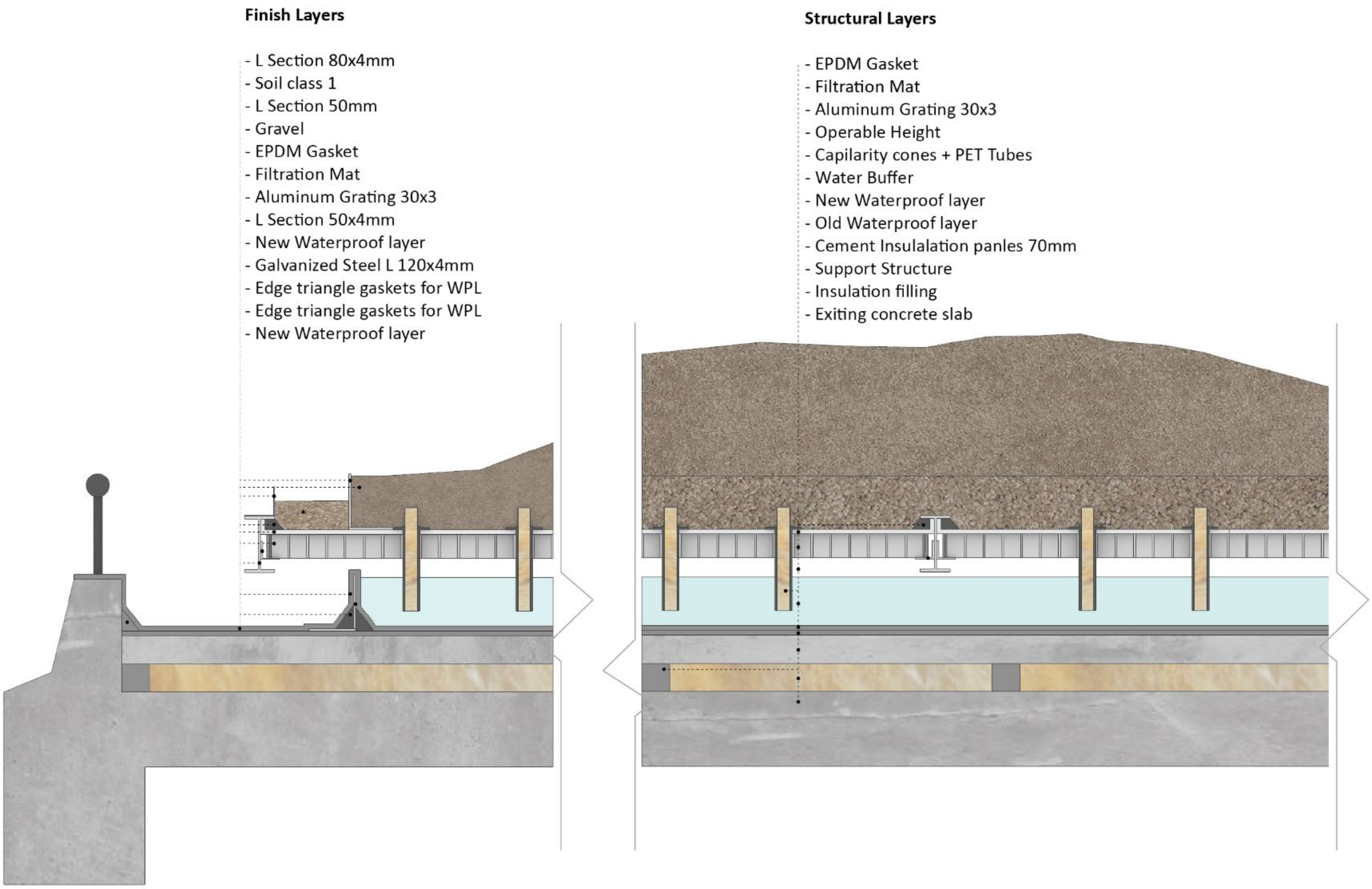


Figure86 - Section C

Figure 86 shows Section C, a transversal section along the middle of the span. Here the detail of the building edge is shown where it is possible to see the offset from the new structure and the water buffer area to the edge beam. The area remains clear for the drainage system. Where is also possible the installation of the capillary cones inside the PET tubes for the passive irrigation of the vegetated areas. Although the system was installed as close as possible to the water surface, the operable height for the structure and the height of the grating increases the length of the cones, which will require to check the feasibility of the system and additional design changes on the PET tube to increase the absorption.

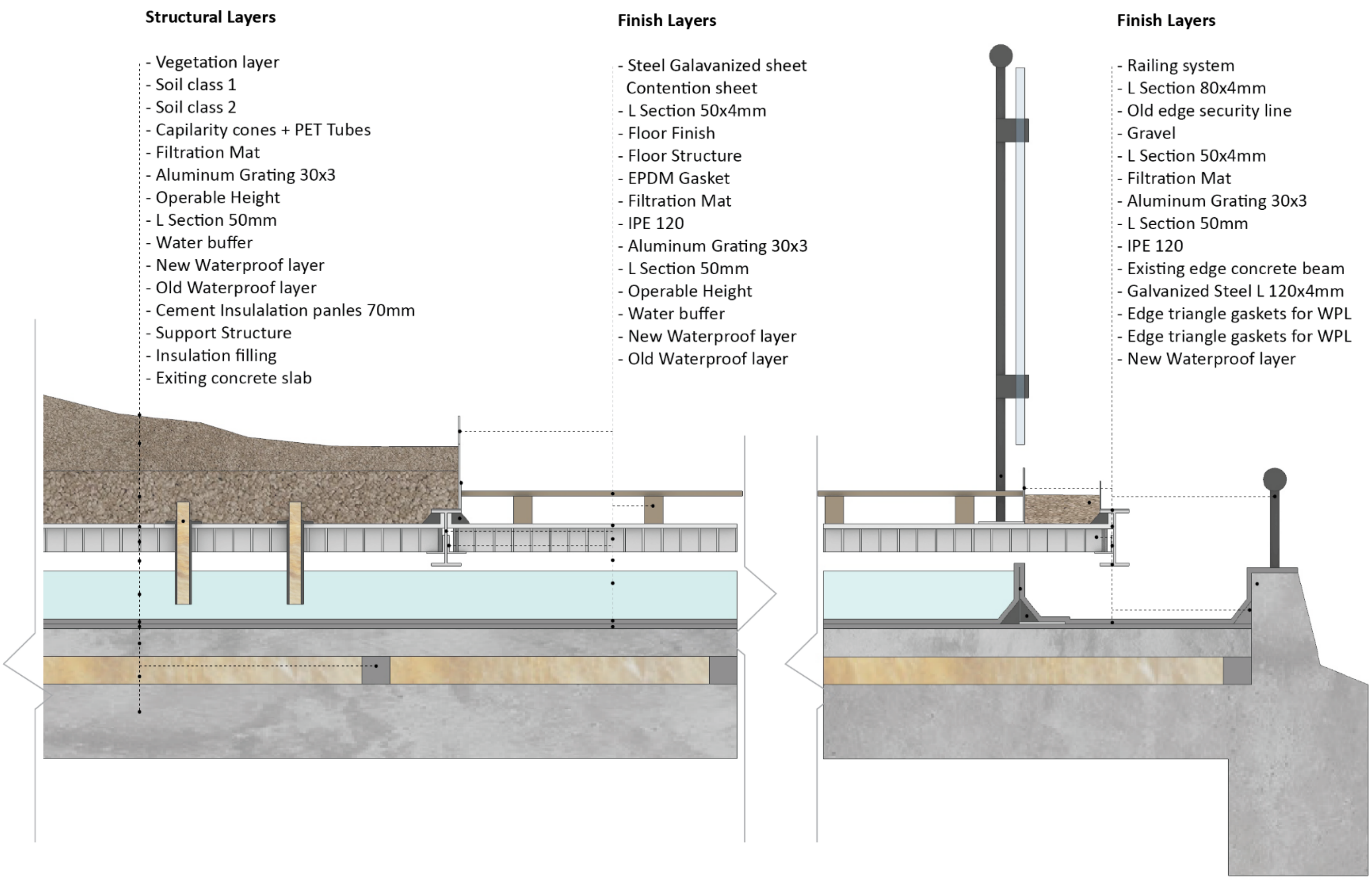


Figure87 - Section D

Figure 87 shows Section D, the other end of the building. Here it is possible to see the detail of the edge railing in case functional areas are proposed. All horizontal sections for the partitioning and contention of the vegetated areas and the flooring structure are fixed to the grating system through shear connection blocks. Inserted on the grid of the grating.

This Section shows the situation of Blocks III and VII from the case sample. Here, insulated concrete panels can be found on top of the slab. The solution shows the design scenario in which these are kept on the roof to avoid its removal and a new waterproof layer is added on top to reinforce the old one for the water buffer system. Different scenarios of interventions are shown in the following graphs.

Edge Details: The edge conditions are presented under 3 different possible scenarios.

Detail 1) Insulated roof: No additional insulation is required, therefore only the new water barrier is installed with the reinforcement system.

Detail 2) The Slab does not have an insulation system, or the insulation system is removed. In this case, the old water barrier is reinforced and reused as a vapor barrier for the new insulation panels and then a new waterproof barrier is installed. Removing the existing insulation system will imply increasing the intervention intensity, which is not desirable.

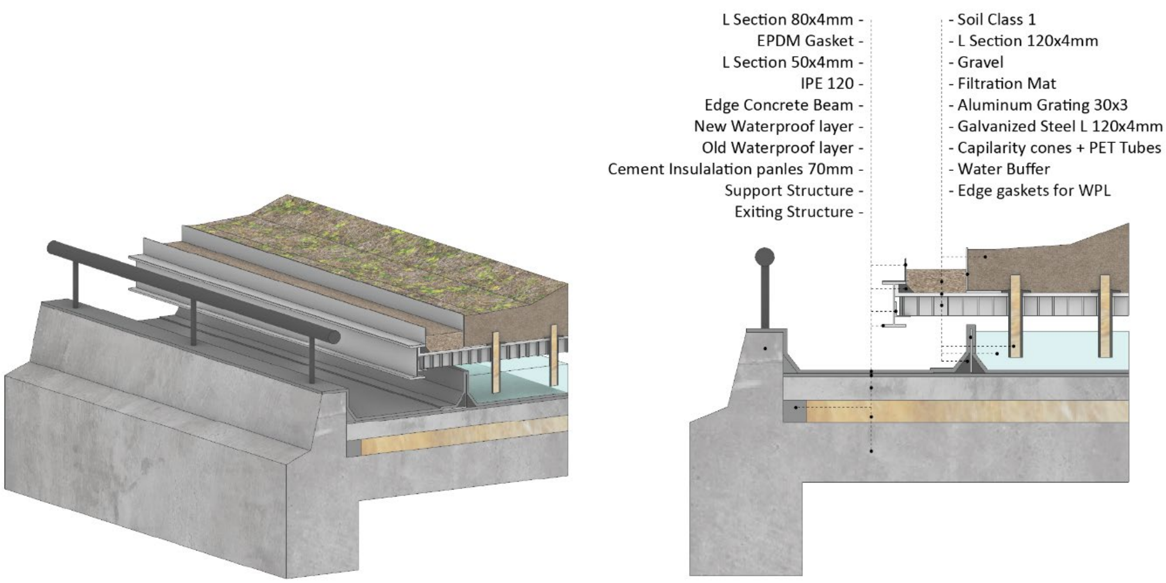


Figure 88 - Edge detail 1

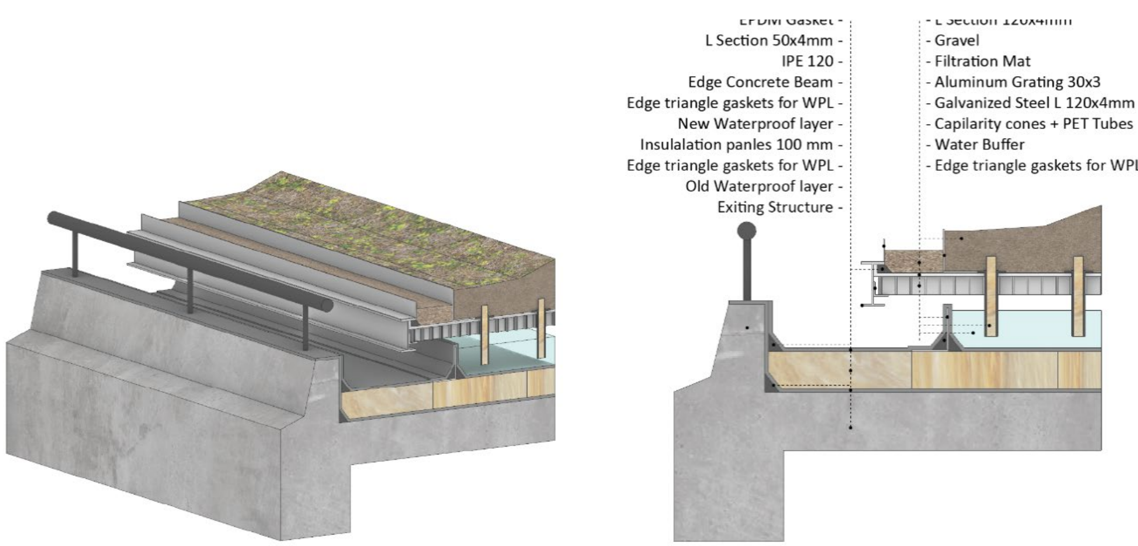


Figure 89- Edge detail 2

Detail 3) The existing insulation system and old waterproof barrier are not removed. A new, thinner insulation layer is installed below the new waterproof barrier. This to prevent removing heavy components like the insulation cement-based panels installed on building cases III and VII.

Detail 4) The best-case scenario. No insulation on the roof, new insulation system installed. The detail shows how the polder roof system would be installed on the edge with an inspection lid to access the component.

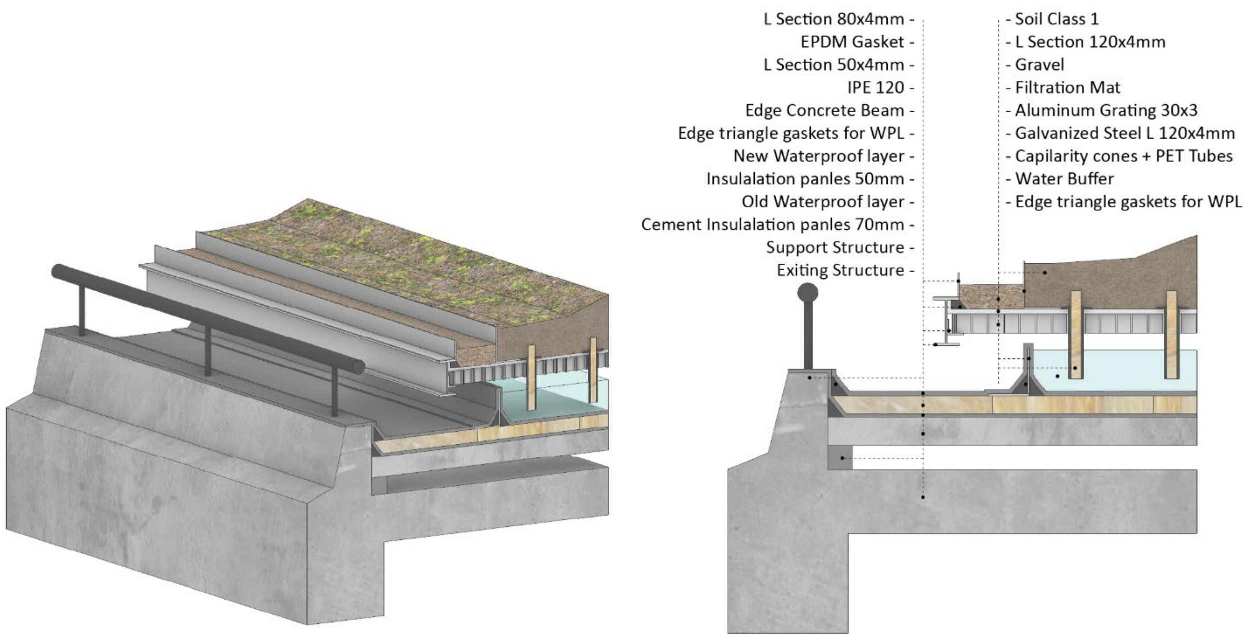


Figure 90 - Edge detail 3

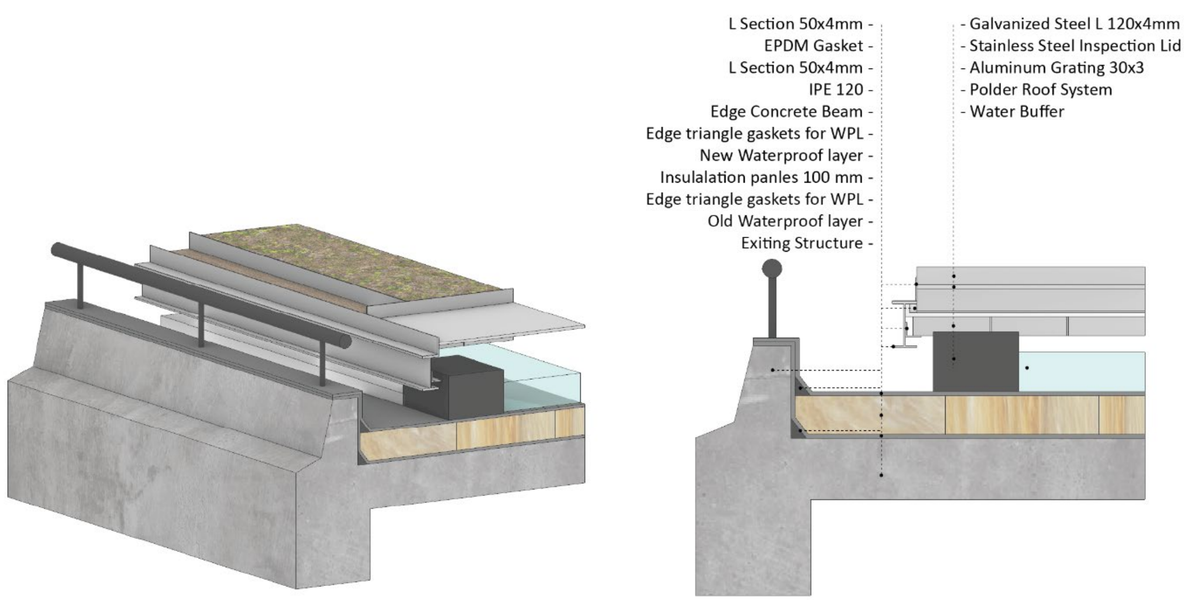


Figure 91- Edge detail 4

Support and Column: For the design of the base support and the column, the possibility of unequal forces applied to the structure need to be considered. This could happen due to design decisions, momentary increment of live loads due to the use of the accessible areas, or during the construction process. If the support is installed on the roof as a fixed connection, uneven tensile forces on the column element could transfer moment forces to the loadbearing wall, which gives another risk factor to be considered. This example is shown on figure 92.

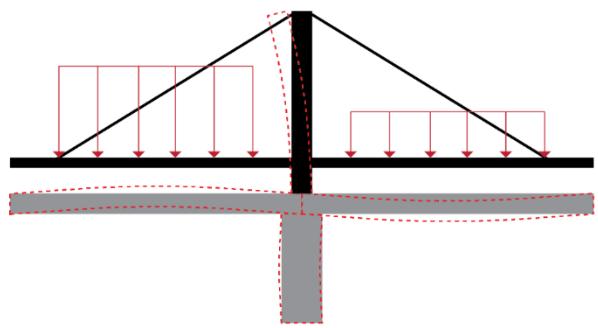


Figure 92 - Deformations on the structure due to unequal loads

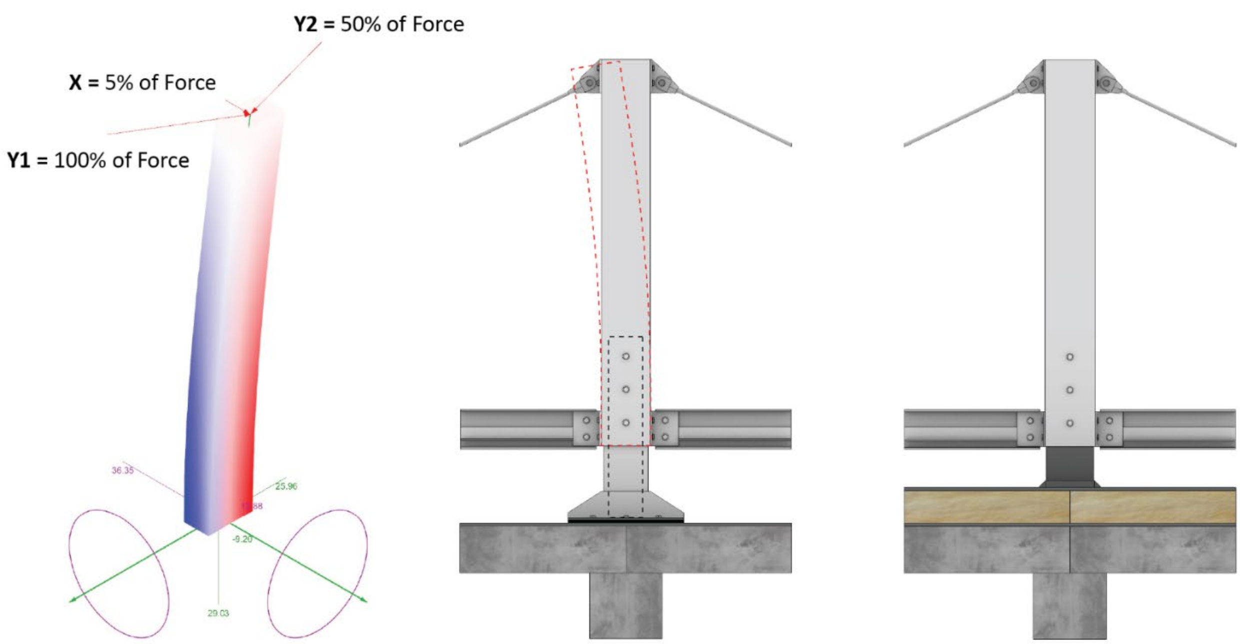
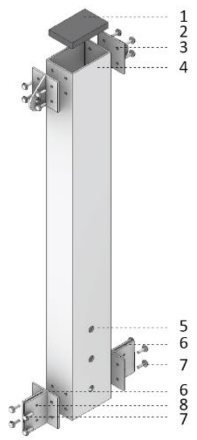


Figure 93 - Base support and column segment design

A quick estimation was calculated with the same FEA software and configuration. A support element with support conditions as a fixed element was analyzed under the applied loads to the main model. 100% of the tensile force was applied on one side, 50% on the opposite side and 5% on the transversal axis (x). The model selected the rectangular cross-section that would be required to fulfill a maximum deflection rate of L/120. The support element was designed as an independent element from the column segment. This will allow to simplify the installation process and to allow the column segment to absorb some of the moment forces caused due to unequal forces and transfer only the vertical forces to the support. Further analysis of this condition should be conducted to determine the maximum moment to be transferred and the performance of this solution to mitigate the problem.



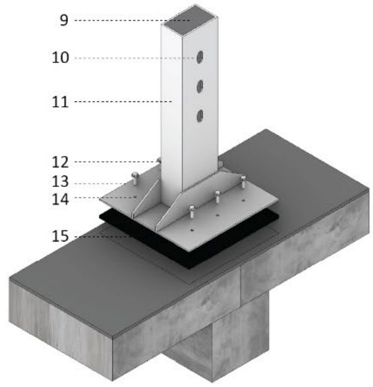
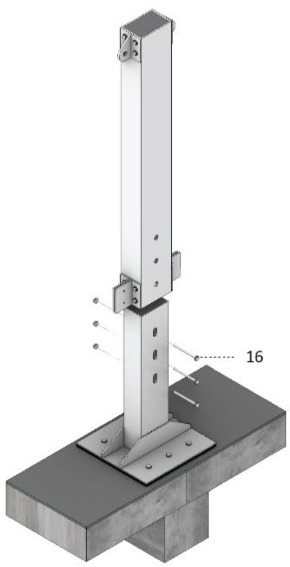
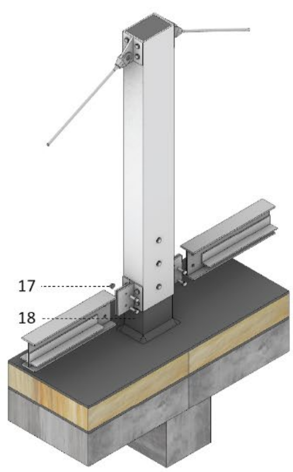
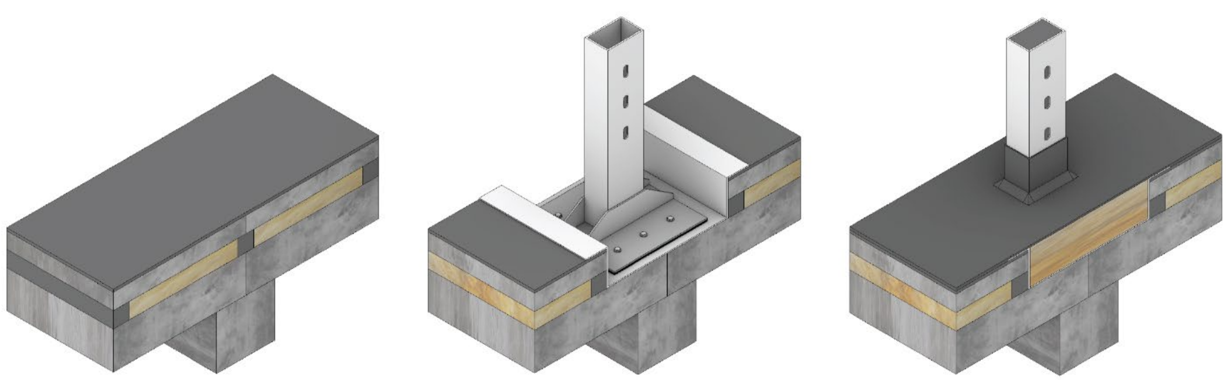


Figure 94 shows the column element, composed of the main rectangular cross-section, in which the brackets to receive the floor beams and the tensile roods are pre-installed through bolted connections. The main support is welded to the bottom plate and reinforcement stiffeners. The holes to receive the column segment are predrilled considering the required tolerance that might be needed to align all the supports. This element is mounted to the existing slab on top of a thermal break plate to reduce thermal losses that a direct connection could cause. After the main support is mounted, the insulation layer is installed and on top, the new water barrier layer. The bottom figures show the condition in which the insulated plates are present, for which the segment where the support goes is removed, followed by the installation of a vapor barrier. Then the support is installed with the new insulation and waterproof layers.





EPDM Cap **2-** Bolted connection for brackets **3-** Pre-mounted brackets for rods **4-** Main column segment **5-** Pre-drilled mounting points for base **6-** Pre-mounted brackets for floor beams **7-** Bolted connections **8-** Pre-drilled mounting points for floor beams **9-** Sealing EPDM cap for base **10-** Pre-drilled holes for main column segment + tolerance for level adjusting **11-** Rectangular section for base + stiffening plates **12-** Bolted connections for slab **13-** Base plate **14-** Pre-drilled mounting points **15-** Thermal beak base plate **16-** Bolted connection for main column beam **17-** Bolted connection for floor beams **18** - Pre-mounted L brackets for grating system



Insulation plates on roof | Cavity for support + vapour barrier | New insulation layer + New Waterproof barrier

Figure 94 - Detail of base support and column segment + installation conditions

5.14. DESIGN TOOL:

The design tool objective is to create the geometric distribution of the strategy for the structural analysis and quantification of covered area, number of elements and the main output for the design stage: the loading floor plan. Figure 95 shows the different parameters considered on the process as inputs and outputs of the 3 processes of the tool:

Process 1: Determining the area of intervention. The area to be covered and the wall segments to be used for the distribution of the reinforcement strategy.

Process 2: Based on the output of phase 1, the configuration of the ideal geometric distribution of the reinforcement system for the structural analysis and the selection of the optimal solution.

Process 3: Based on the solution, the loading areas provided by the system to serve as an aid for the design process of the intervention.

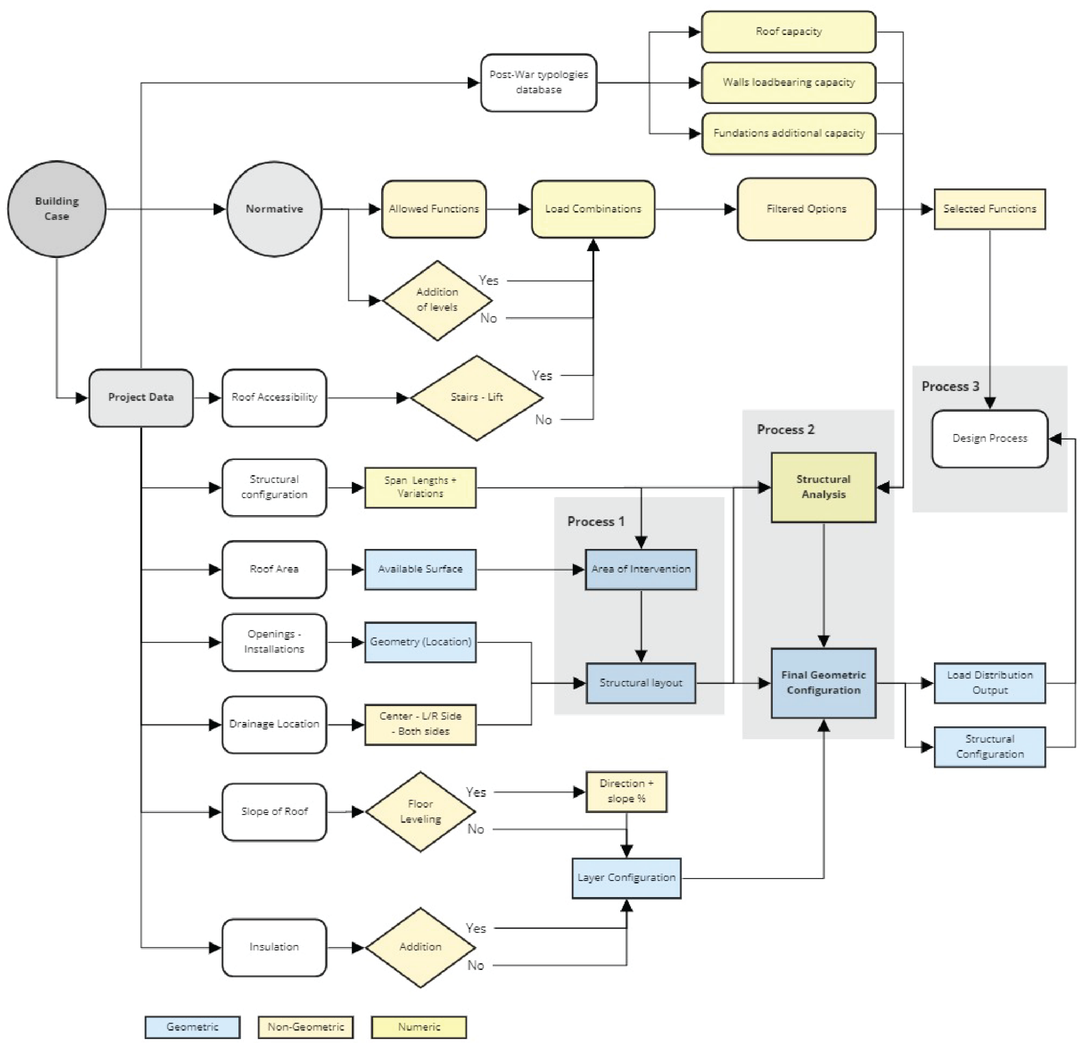
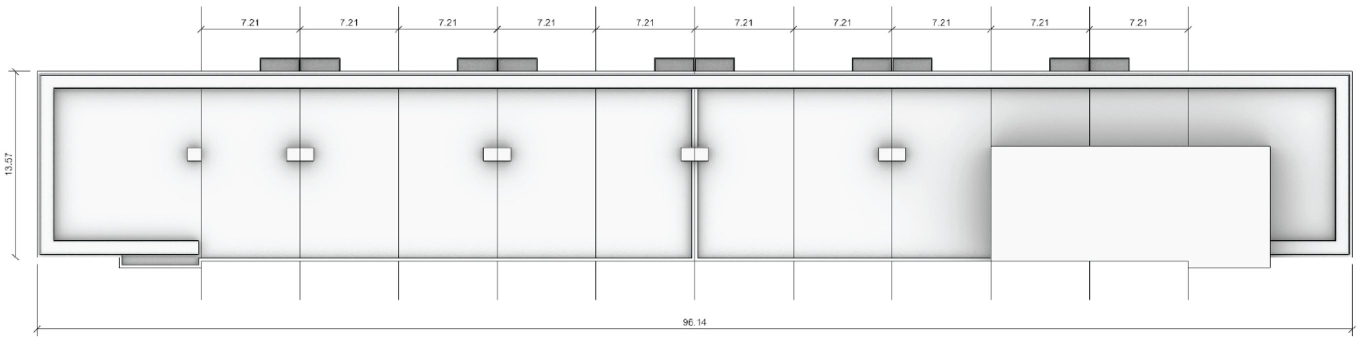
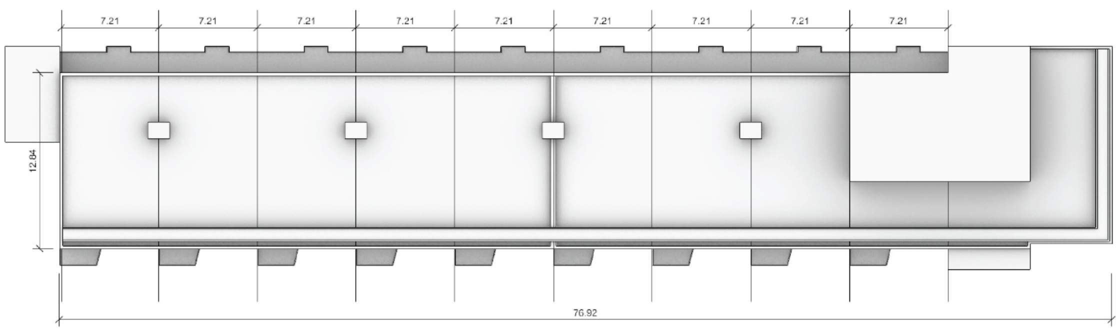


Figure 95 - Design tool flowchart - Process 1, 2 and 3

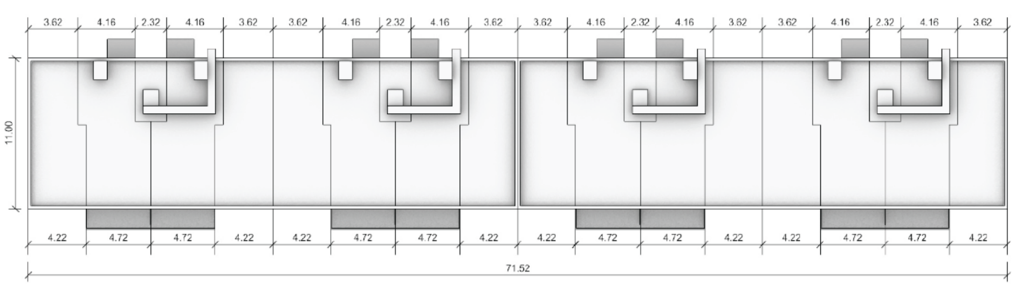
The 3 case studies are used as an example for the Design Tool. Building block IV is used as the main example to show the step-by-step process of Process 1 2 and 3, but the results for blocks III and VII is also shown to show different configurations of the tool.



Block III – Roof Area: **1 335.85 m²** **Available Load Combinations**: **All**



Block VII – Roof Area: **1 018.33 m²** **Available Load Combinations**: **All**



Block IV – Roof Area: 786.72 m² **Available Load Combinations**: **A B D E**

Figure 96Building cases - Roof area and Available Load Combinations

Process 1: The first steps to determine the area of intervention are described on figure 97. For this, the installations, appliances and openings on the roof are considered, as well as the drainage direction and roof accessibility.

1: Identification of elements on the rooftop

2: Demarcation of areas to be avoided due to collision with objects and offset for the drainage system.

3: Final area of intervention and wall segments to be used.

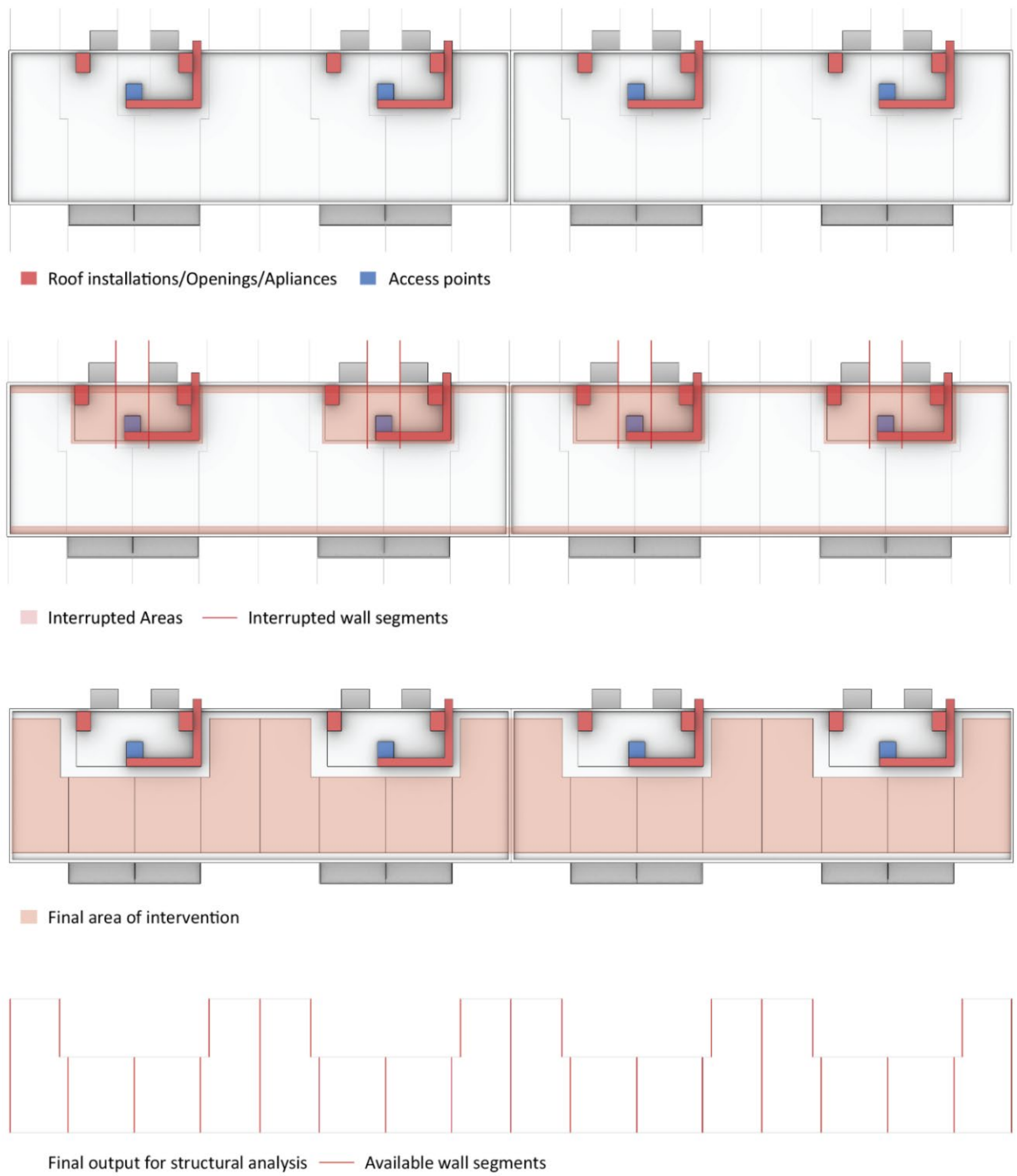


Figure 97 - Process 1 – Part 1

4: Based on the output from the previous stages, the geometry is analyzed to determine the ideal subdivision of segments for the structure based on the available grating spans. The ideal solution would require as little segmentation as possible and as much covered area as possible.

This process and the selected option are shown on figure 98.

Figure 98 - Process 1 - Part 2

Process 2: Based on the geometric output of Process 1, the geometry is used for the structural analysis, where the different configurations shown on figure xx are calculated and the best result is selected based on the number of elements of the solutions. The 3 different options are shown in figure 99. As shown on the results, option 1 and option 3 show the same amount of beam segments. Option 3 shows a reduction of required supports but requires column segments and rod elements for the solution.

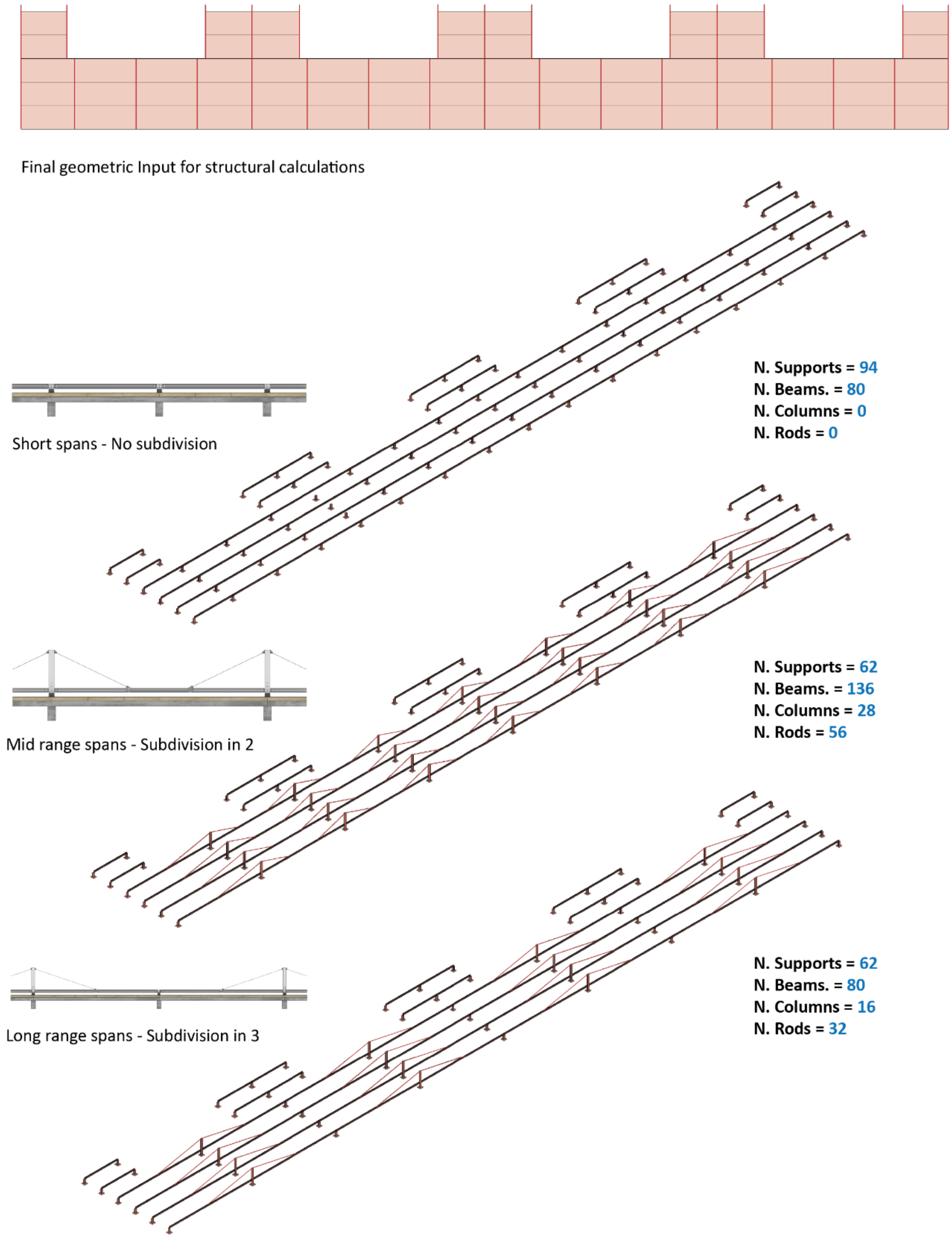


Figure 99 - Process 2 - Selection of the structural configuration

Option 3 would require less intervention on the current structure by decreasing the installation of support elements. Option 1 would provide a higher design freedom degree for the solutions. For this case study, option 3 was selected, described in figure 100, as well as the selected options for blocks III and VII in figures 101 and 102.

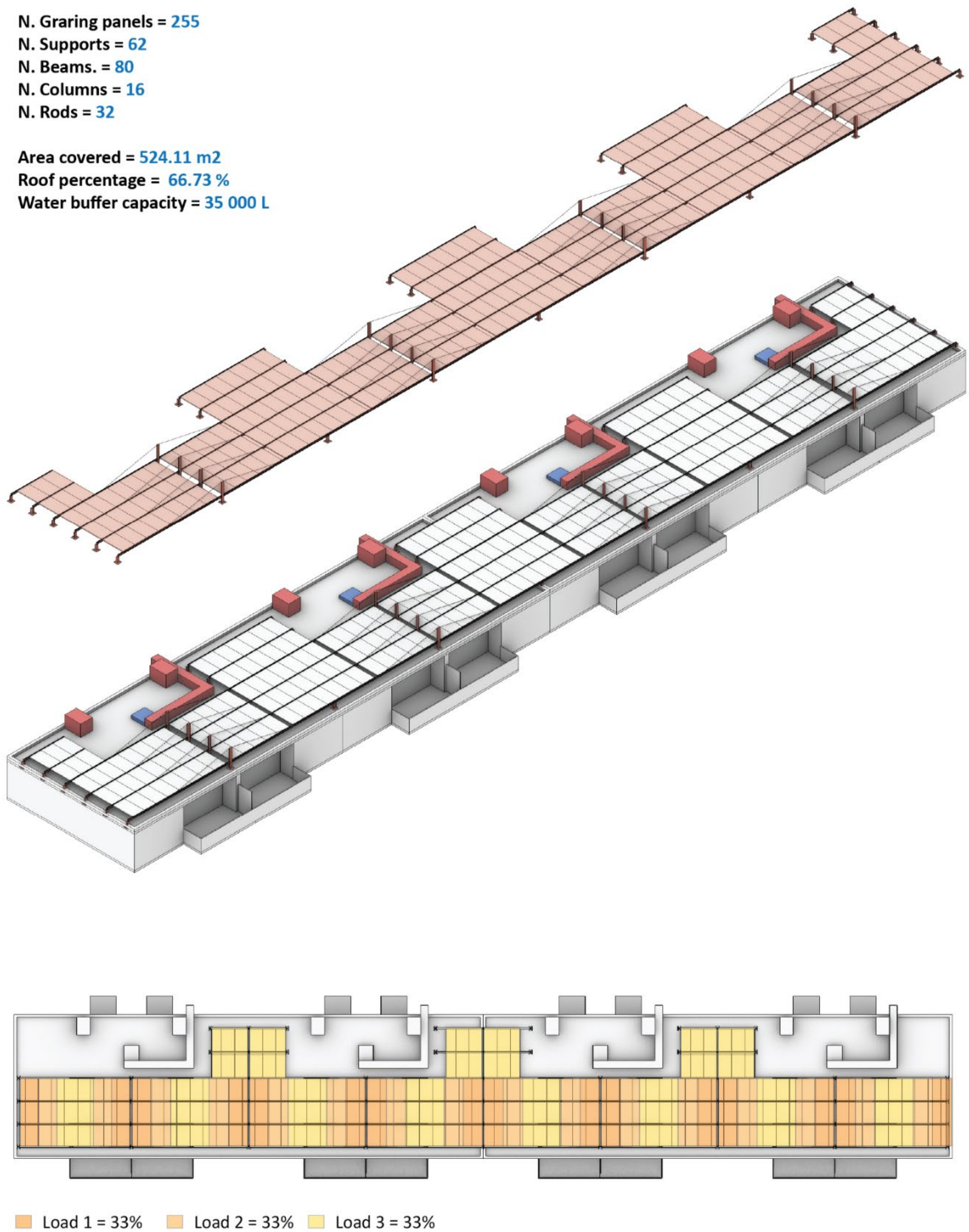


Figure 100 - Results for building case IV

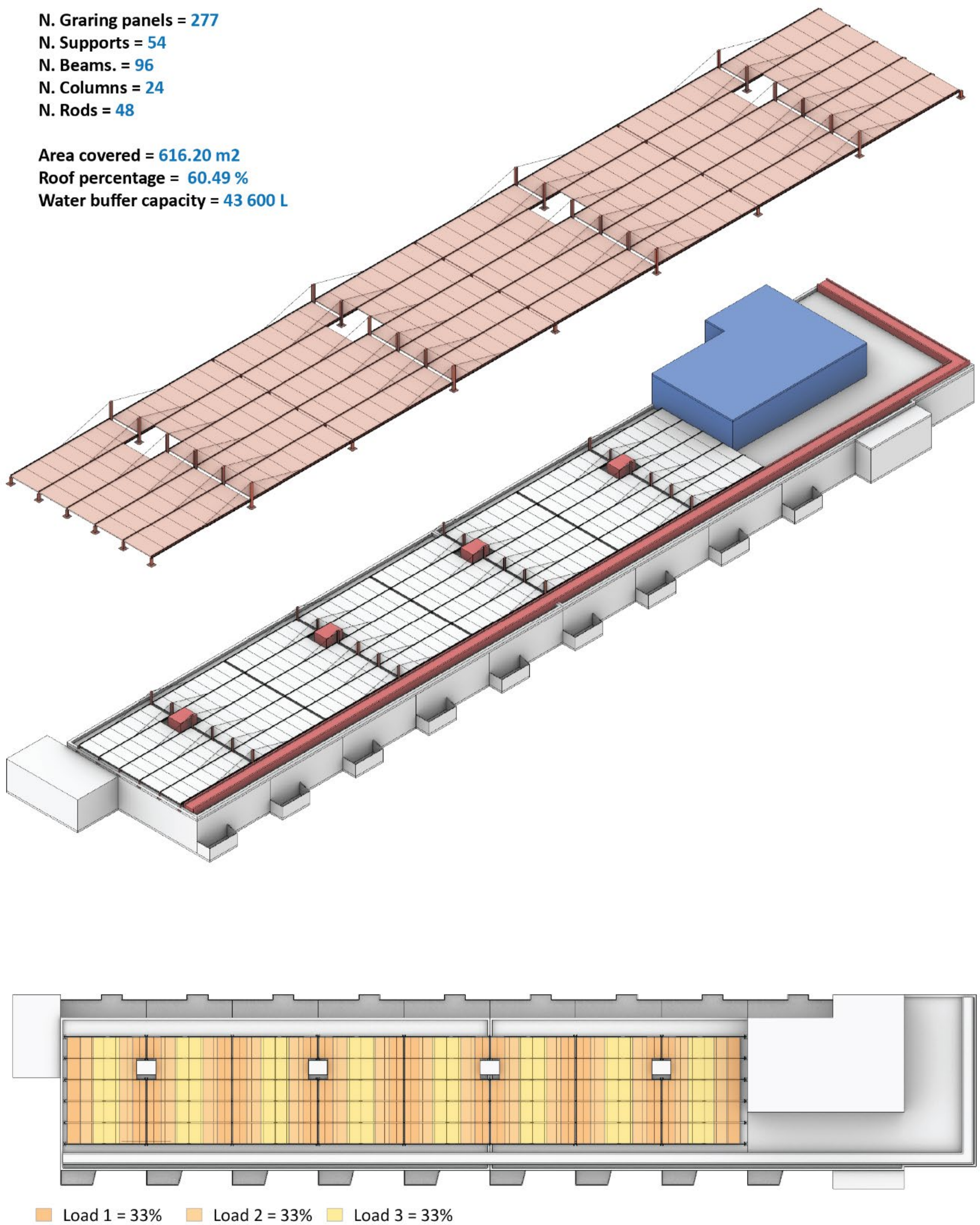
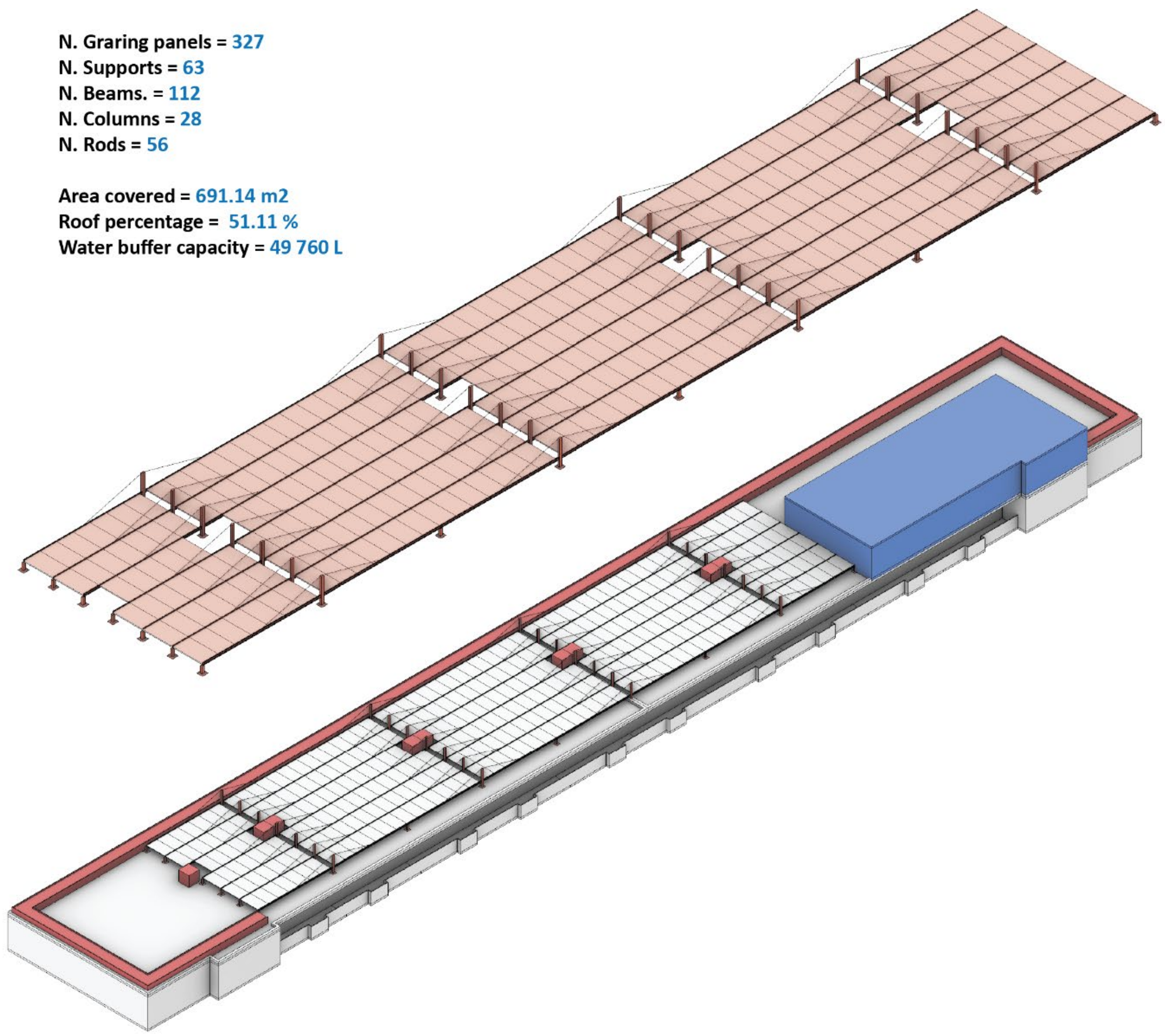


Figure 101 - Results for building case VII



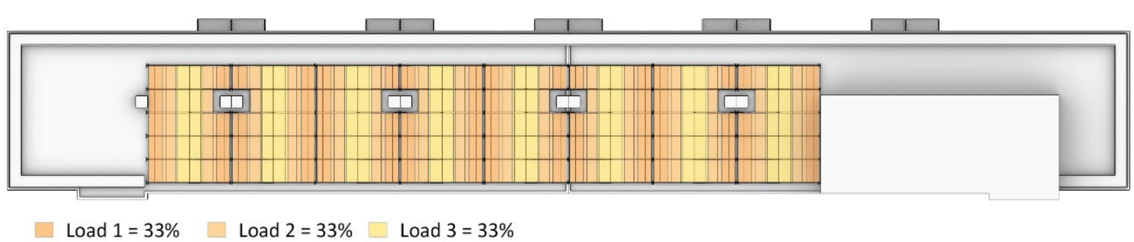


Figure 102 - Results for building case III

As shown on the bottom of figures 100, 101 and 102, the loading areas of the configuration are shown. This is the final output for the design aid tool. The loads for each color grading will depend on the selected functions for the roof. Different scenarios are shown in examples of the following subchapter.

5.15. DESIGN RESULTS

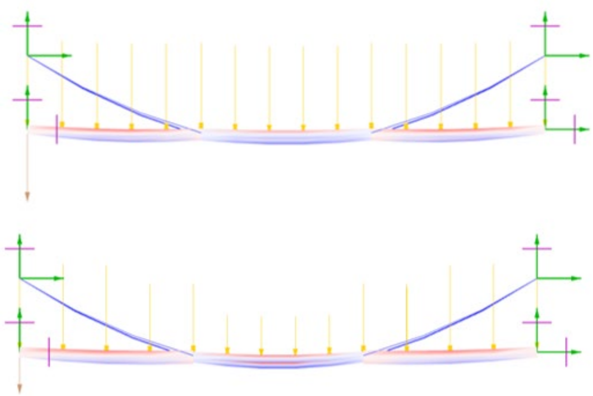
To evaluate the effect of the design aid tool, 3 different cases were evaluated to determine the loads that could be achieved and their effects on the total load applied to the building and the structure weight. For this, the EDL (Equally distributed load) is compared to the UDL (Unequally Distributed load) in subdivisions of 2 and 3. Additionally, UDL 3+ will show the value of the maximum load that could be achieved without decreasing the structural compactness or increasing its weight.

Design Scenario 1 – Building Block III

As shown in table 62, the comparison between an EDL (Equally distributed load) and UDL (Unequally Distributed load) configuration for the typology III shows a minimal decrease in weight for the structure. Although the cross-section of the middle beam decreases, the compactness will not reduce either. A substantial increment of applicable load can be seen in UDL 3+, where an additional 10.31% load increment is reached with a structure of the same weight and a maximum load area of 7.29 kN/m2. Considering that the building is suitable for interventions of up to 12.78 kN/m^2, this would allow to apply any of the heaviest solutions on 33.33 % of the intervened roof surface without increasing the structure height or weight.

Area [70 m2]	EDL	UDL 2	UDL 3	UDL 3 +
Loaded Areas [kN/m2] [%]	5.29 - [100]	5.29 – [66.66] 4.37 [33.33]	5.29 – [33.33] 4.83 – [33.33] 4.37 – [33.33]	7.29 – [33.33] 5.83 – [33.33] 4.37 – [33.33]
Cross Section Height [mm]	120 - 120	120 – 100	120 – 100	140 – 100
Wight of Structure [kg/m2]	0.57	0.56	0.56	0.57
Peak Reaction Force [kN]	37.44	35.30	34.21	41.32
Total Reaction Force [kN]	375.29	353.74	342.93	414.12
Added Load [kN/m2]	5.36	5.04	4.89	5.91

Table 62 - Design Scenario 1



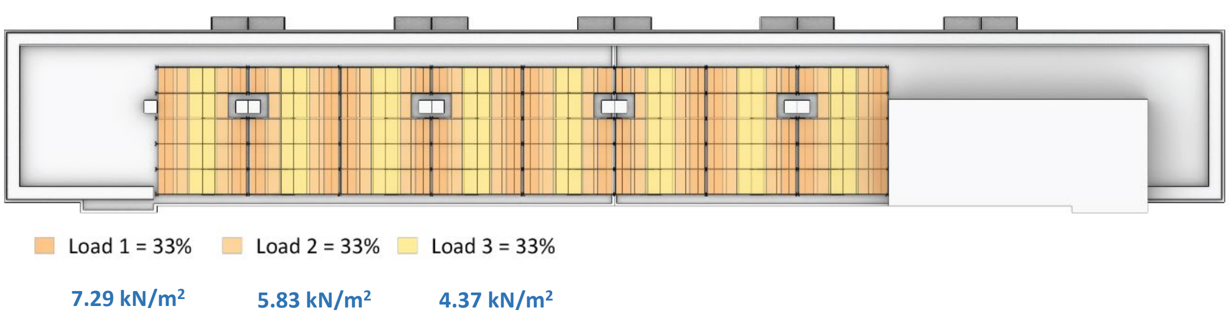


Figure 103 - Design Scenario 1

Design Scenario 2 – Block IV

For this case, the same results were observed. The solution for the EDL and UDL 2 and 3 show a structure of same weight and height. Again, for design scenario UDL 3+, an increase of 10.84 % is reached with a structural configuration of the same characteristics and the same weight as the EDL model, reaching a maximum loaded area of 7.14 kN/m^2.

Building Block IV has a maximum capacity of 5.06 kN/m2, for which only combinations A, B, D and E are available. Nevertheless, with UDL3+, the total applied load is 4.66 while still providing 33.33% of available areas for loads of 7.14 kN/m^2. This makes the building available for all load combinations and for the heaviest intervention loads of the researched samples.

This example shows part of the potential of the load distribution strategy. This example will be used to describe the design assembly sequence of the system and two showcase 2 design examples of the possible uses and design of the roof to assess the feassibility of application of this design aid tool.

Area [50.4m2]	EDL	UDL 2	UDL 3	UDL 3 +
Loaded Areas [kN/m2] [%]	5.14 – [100]	5.14 – [66.66] 4.22 – [33.33]	5.14 – [33.33] 4.68 – [33.33] 4.22 – [33.33]	4.22 – [33.33] 5.68 – [33.33] 7.14 – [33.33]
Cross Section Height [mm]	140	140 – 120	140 – 120	140 – 120
Wight of Structure [kg/m2]	0.45	0.45	0.45	0.45
Peak Reaction Force [kN]	34.20	33.21	32.16	39.01
Total Reaction Force [kN]	212	200.45	194.16	235.20
Added Load [kN/m2]	4.20	3.97	3.85	4.66

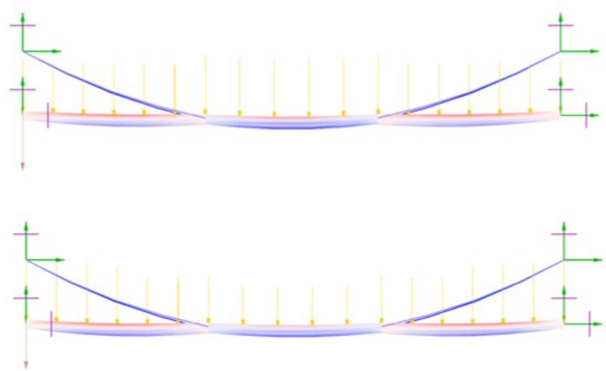
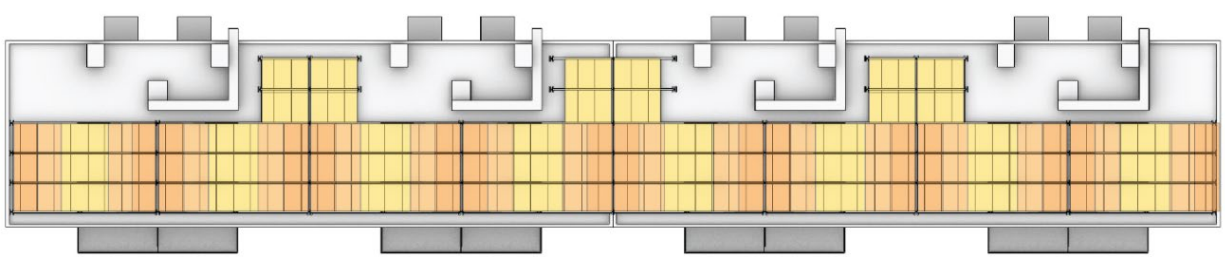


Table 63 - Design Scenario 2



Load 1 = 33% Load 2 = 33% Load 3 = 33%

7.14 kN/m^2 **5.68 kN/m^2** **4.22 kN/m^2**

Figure 104 - Design Scenario 2

Design Scenario 3

This scenario was configured to show the potential of the load distribution strategy for buildings with reduced loadbearing capacity. In this case, study case IV was selected again, but this time, representing a building of 3 stories height with a maximum additional loading capacity of 4.01 kN/m2.

For the EDL, the only compatible function would be load combination A. As seen in the results for scenario UDL 3, the total load is decreased by 7.83 % in comparison to the EDL. Nevertheless, by applying a minimum load of 2.22 kN/m^2 (access only for maintenance), 33.33 % of areas for 5.14 kN/m^2 and 3.68 kN/m^2 loads can be obtained while remaining under the maximum total capacity.

The structure of the same characteristics allows this roof to apply load combinations A, B and C an intensive system without surpassing its maximum capacity.

Area [50.4m2]	EDL	UDL 2	UDL 3
Loaded Areas [kN/m2] [%]	40.1 [100]	5.14 – [66.66] 2.22 – [33.33]	5.14 – [33.33] 3.68 – [33.33] 2.22 – [33.33]
Cross Section Height [mm]	140 – 120	140 -100	120 – 100
Wight of Structure [kg/m2]	0.44	0.43	0.42
Peak Reaction Force [kN]	27.56	28.71	25.41
Total Reaction Force [kN]	166.49	173.91	153.37
Added Load [kN/m2]	3.30	3.45	3.03

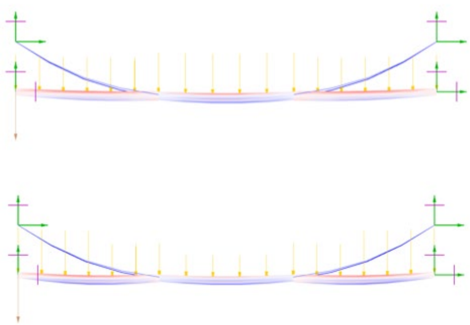


Table 64 - Design Scenario 3

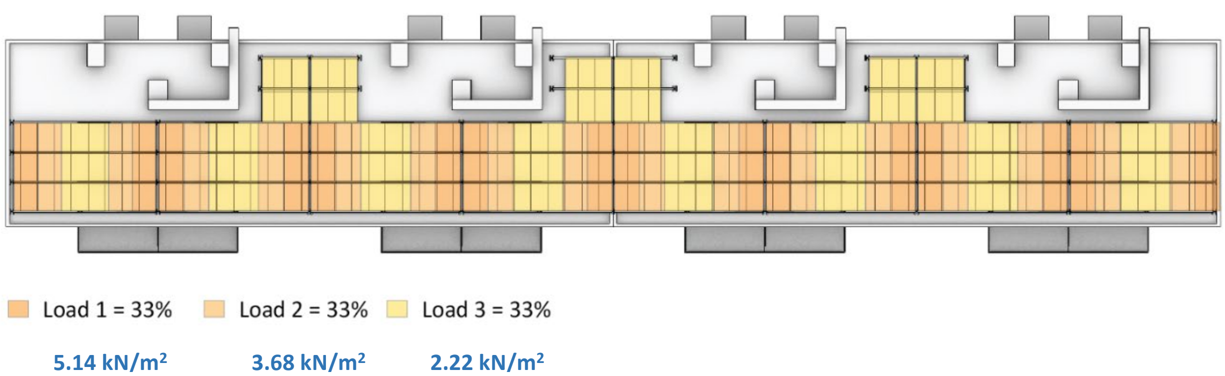


Figure 105 - Design Scenario 3

5.16. ASSEMBLY SEQUENCE

As mentioned before, Design scenario 2 for Block IV will be used to show the assembly process of the reinforcement system and to showcase two different uses that could be given to the roof. Both options are available only for private functions due to the maximum capacity of the roof. One prioritizing green areas for gardening and urban farming and the second one prioritizing access to private terraces for the use of the building users.

1. Preparation of the roof surface and installation of the thermal beak panel. In this case, no removal of insulation panels is required

2. Positioning and mounting of supports to the existing floor slab.

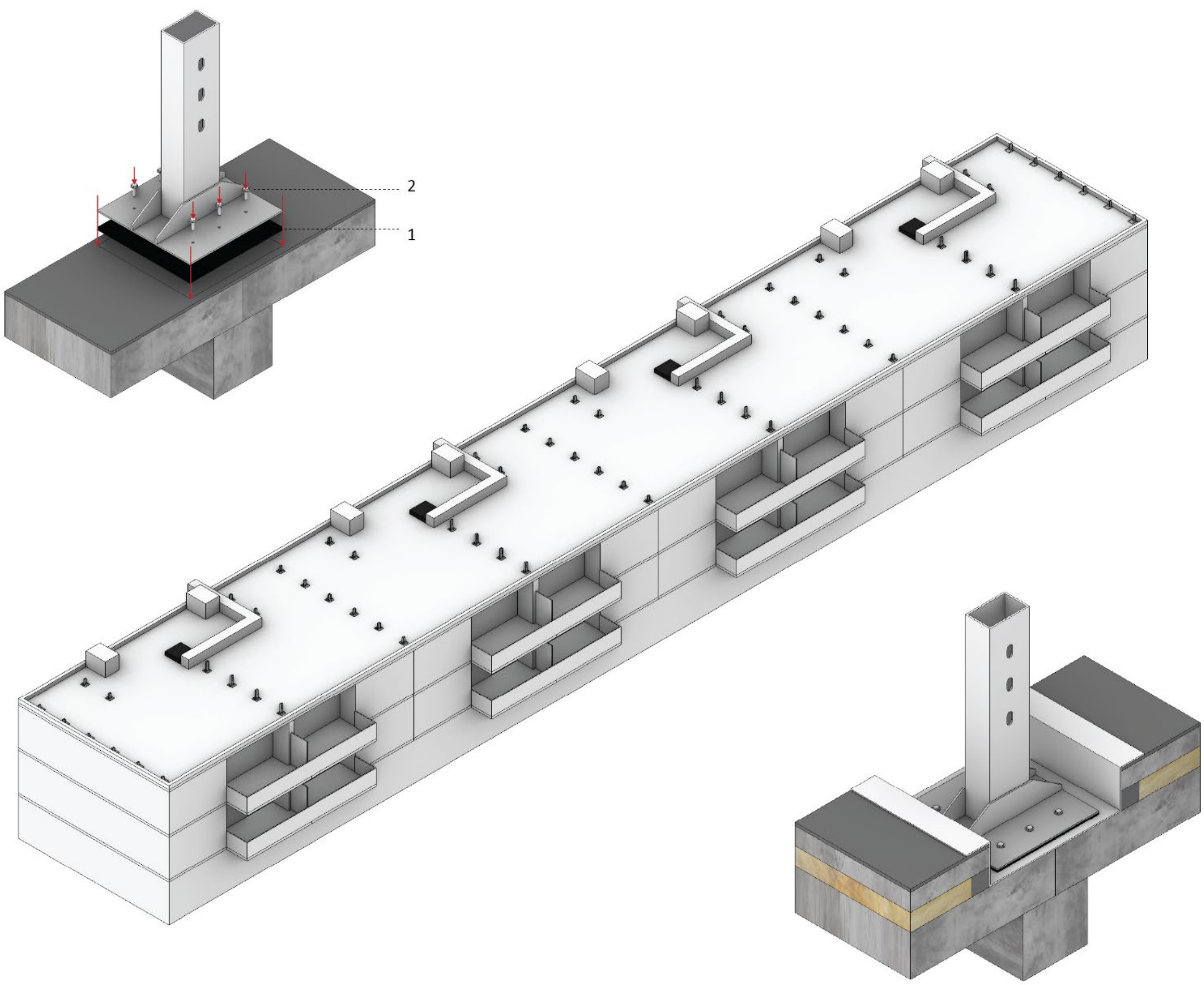


Figure 106 - Assembly sequence - step 1

1. Installation of insulation panels on top of the old waterproof barrier.

2. The L sections for the water buffer boundary and the polder roof drainage control system are installed on top of the insulation panels considering the drainage direction and location.

3. The new waterproof layer is installed on top of the insulation panels, sealing the water buffer area and the joint around the new supports.

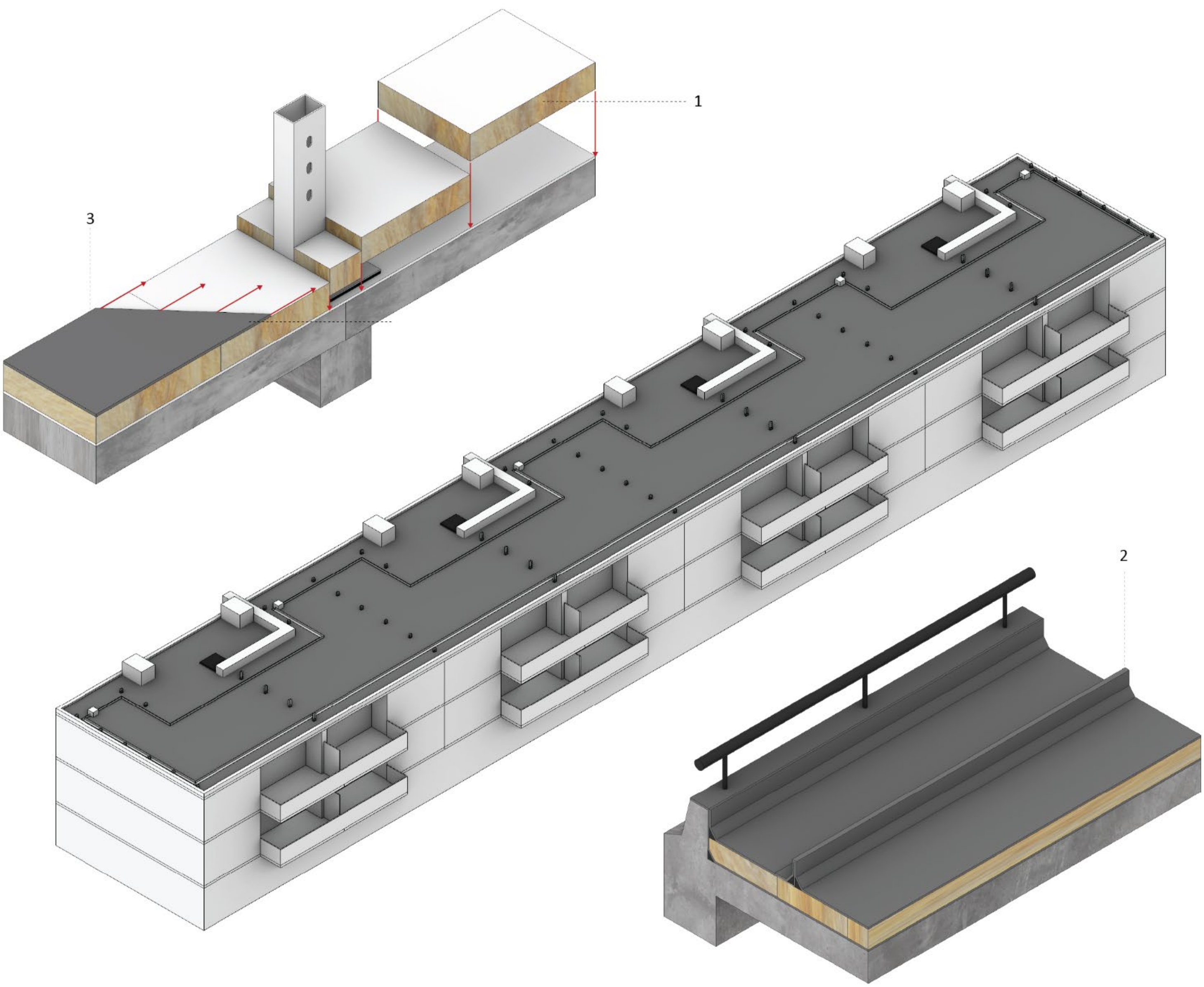


Figure 107 - Assembly sequence - step 2

1.

The column segments, which come with the preinstalled brackets, are placed and fixed on the supports.

2. A set of box segments are placed on the roof to aid the leveling and installation of the beam floor segments.

3. The beams are bolted and fixed to the column segments.

4. The junction plates are installed on the end of the segments, then the rods are installed on both junction points. After this section is finished, the box segments can be removed, and the remaining beams can be installed. Finally, the tensile rods are stressed accordingly for the design requirements.

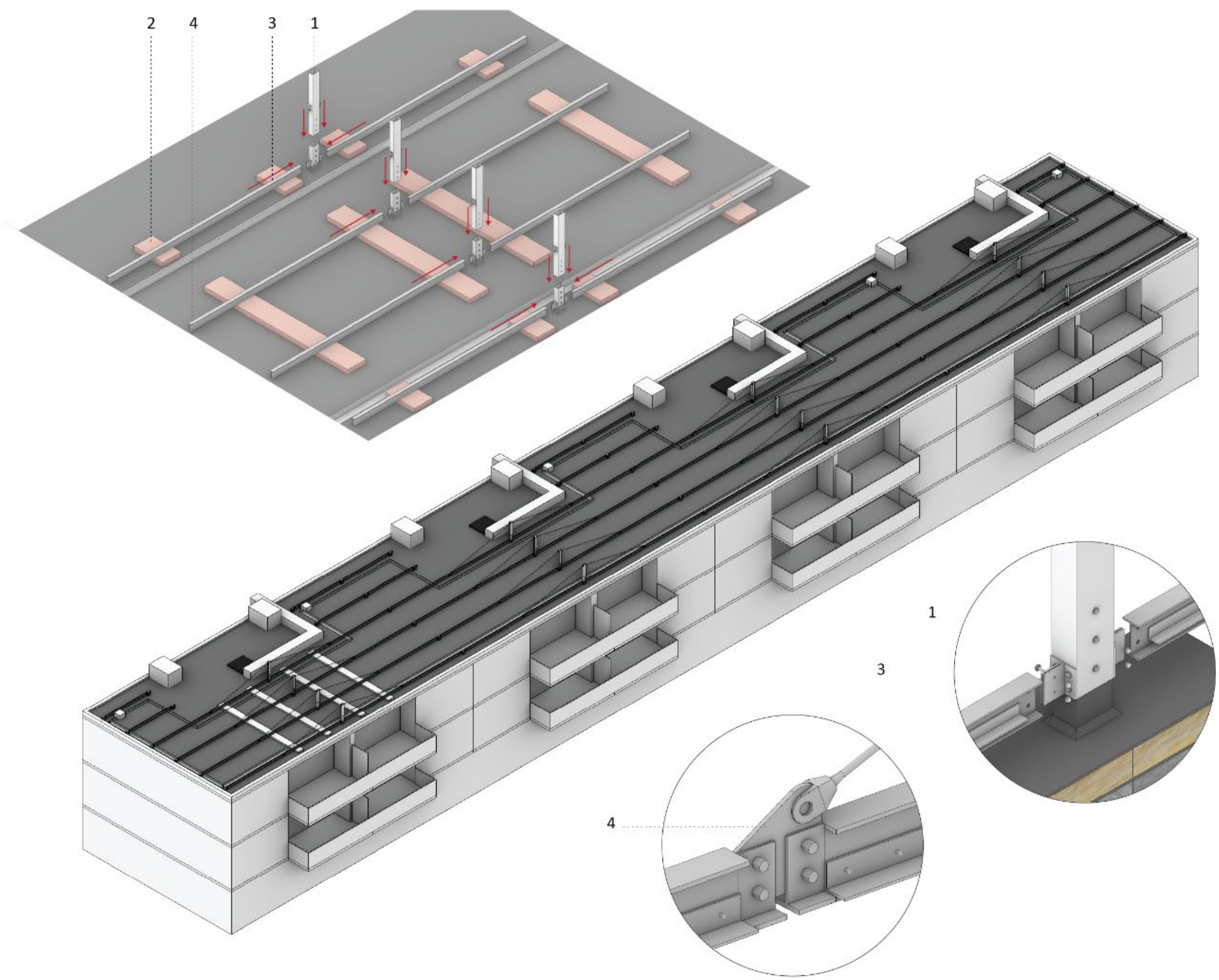


Figure 108 - Assembly sequence - step 3

1. The beam floor segments come with preinstalled L brackets to receive the aluminum grating.
2. The grating is placed and fixed to the L brackets.
3. The filtration matt is installed on top.
4. The FRP spacers are placed on the remaining spaces according to the distribution.
5. The EPDM gaskets are fixed to prevent movement from the filtration mat and the FRP boxes.

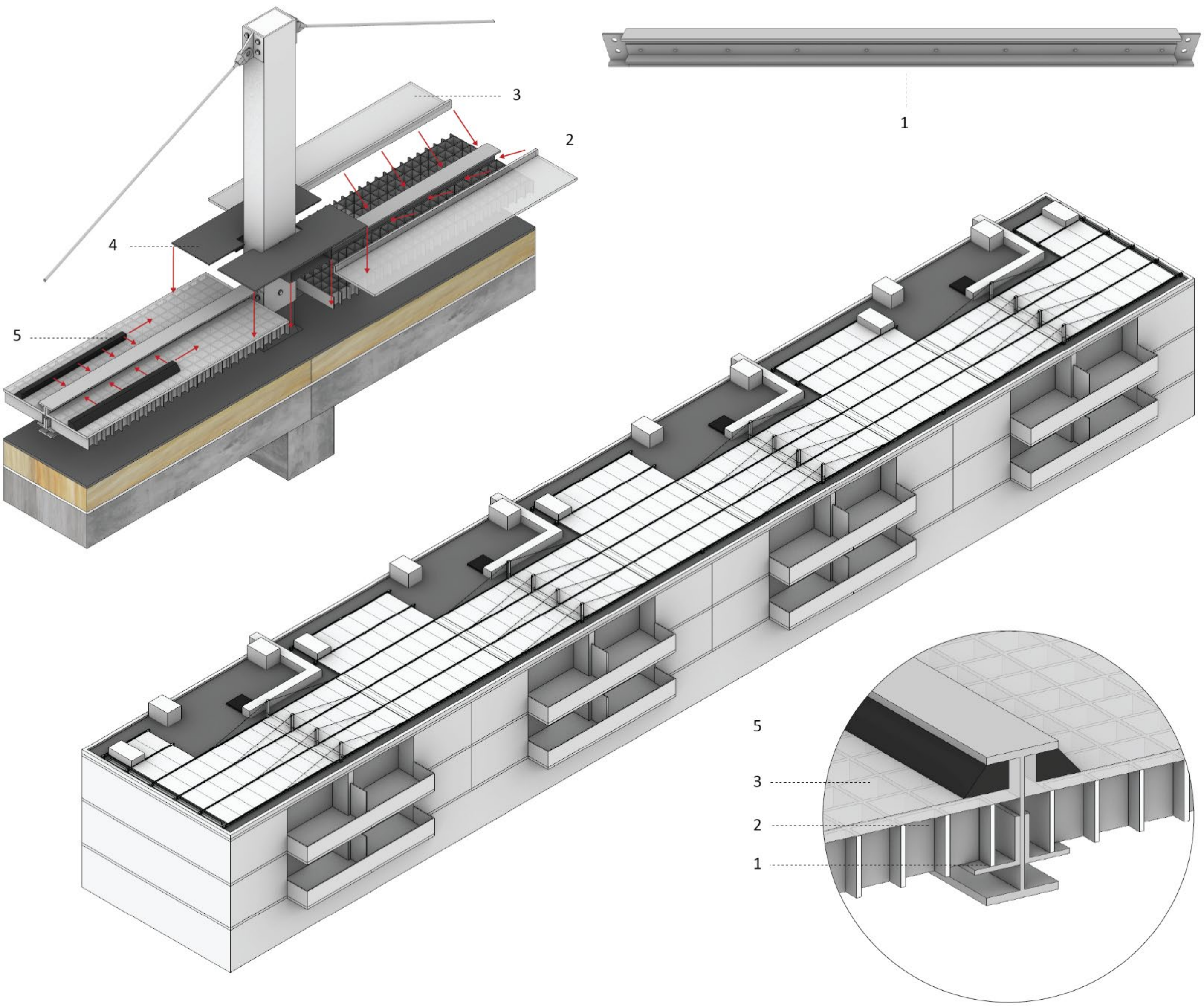


Figure 109 - Assembly sequence - step 4

1. After all the flooring structure is installed, the shear connectors are placed to install the support structure for the flooring finish.

2. The same shear connectors are used to install all the support elements for the partitioning and contention of the vegetated areas.

3. The Steel galvanized plates are installed according to the desired heights for the vegetated areas to create the final contention boundary.

4. The PET cones are installed through the grating system and the capillary cones are inserted.

Finally, the finish layers are installed. For the vegetated areas, the sol is poured homogeneously at both sides around the columns segments to avoid uneven forces on the tensile structure.

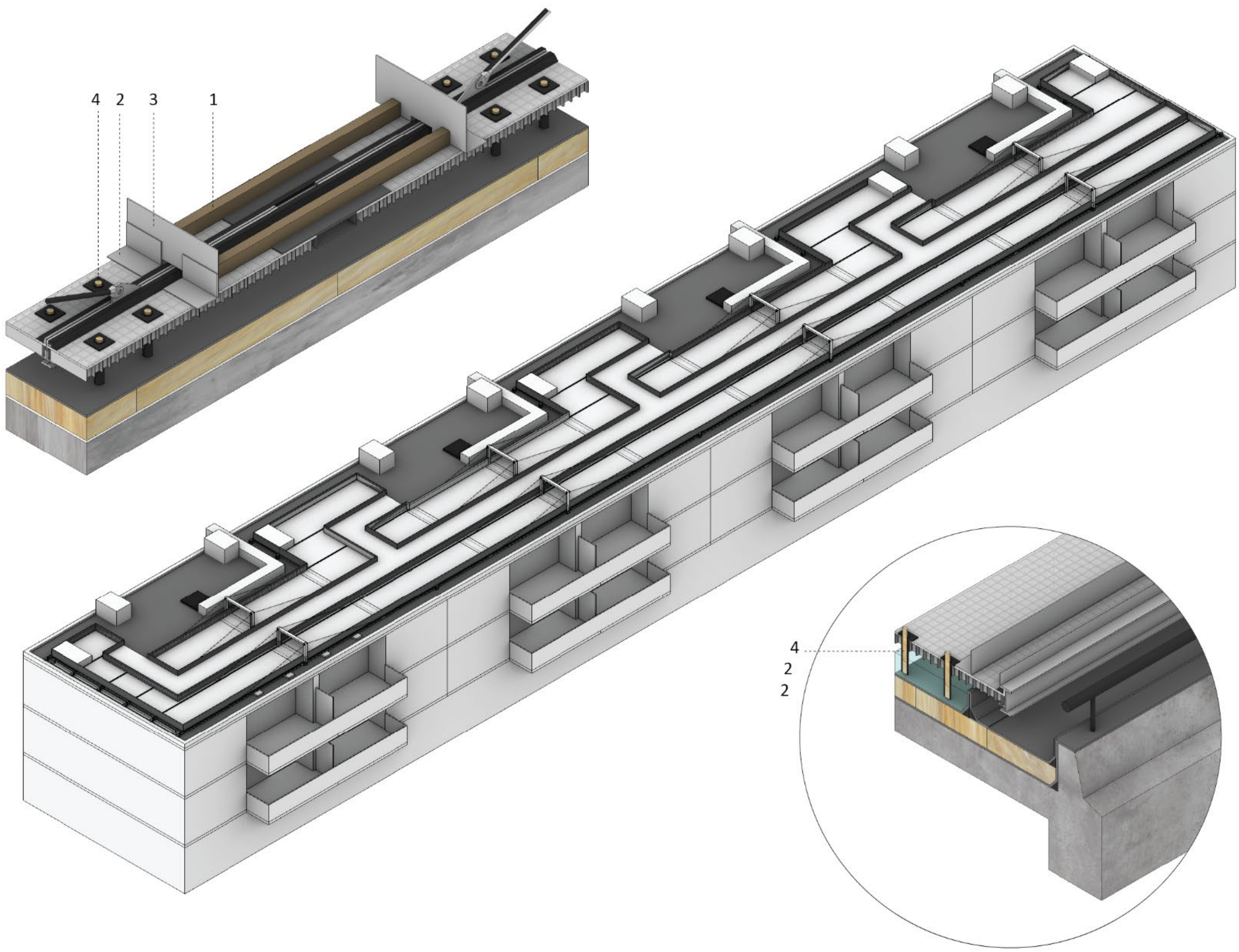
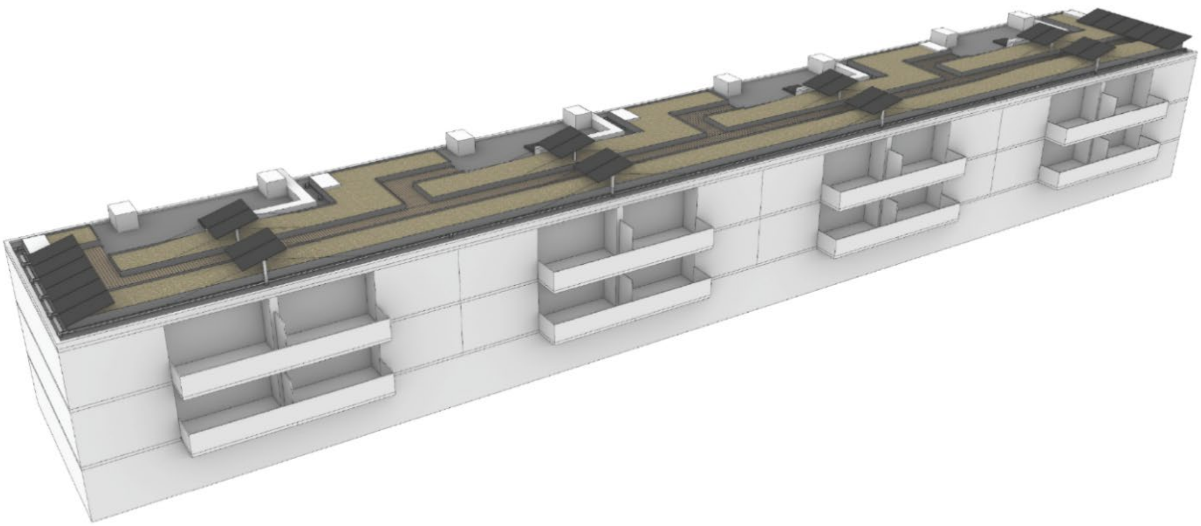
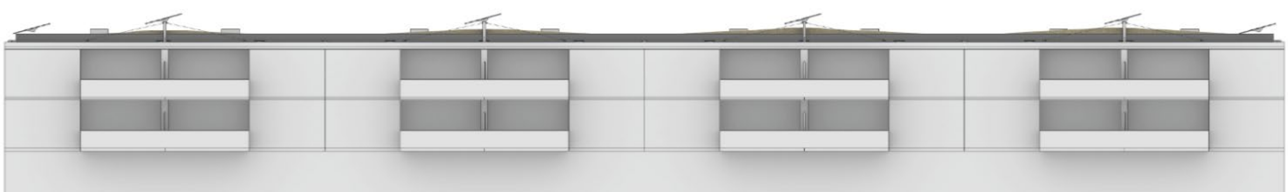
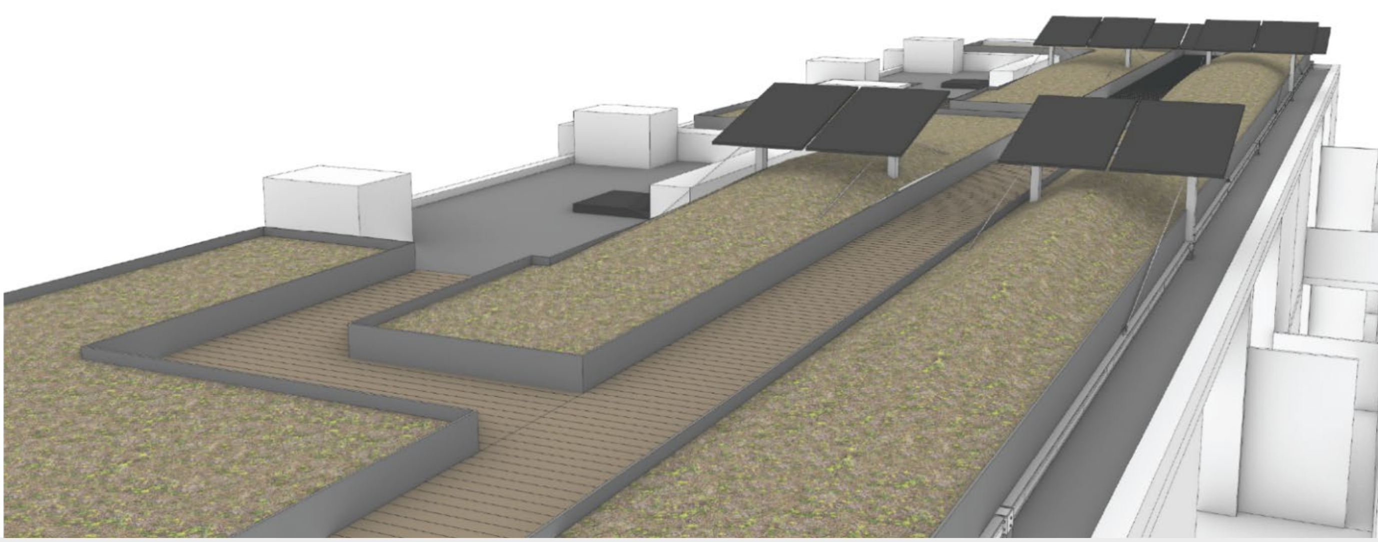


Figure 110 - Assembly sequence - step 5

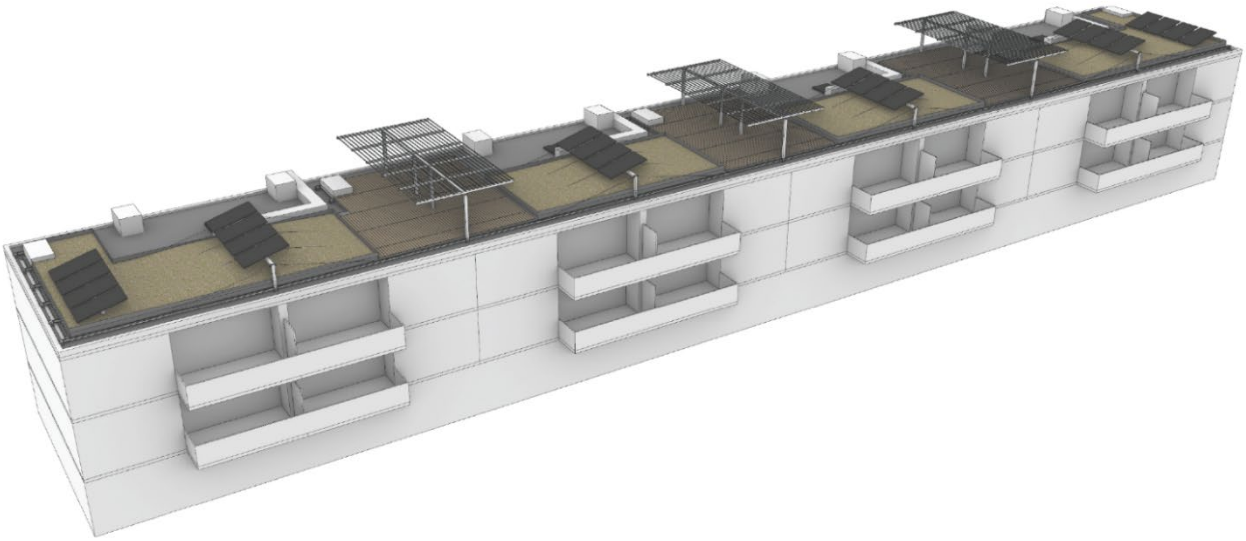
Design Outcome 1 – Gardening and urban farming areas – Private Use

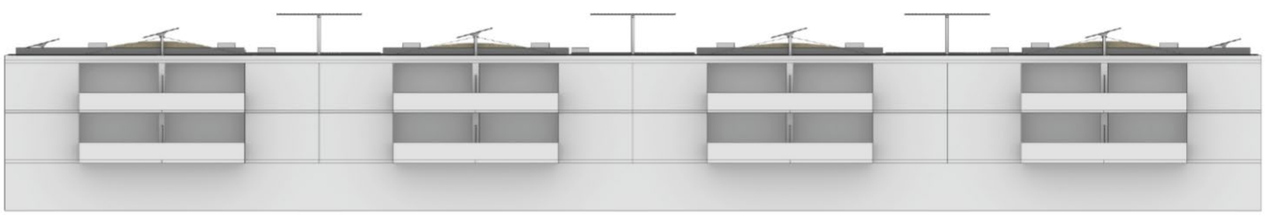


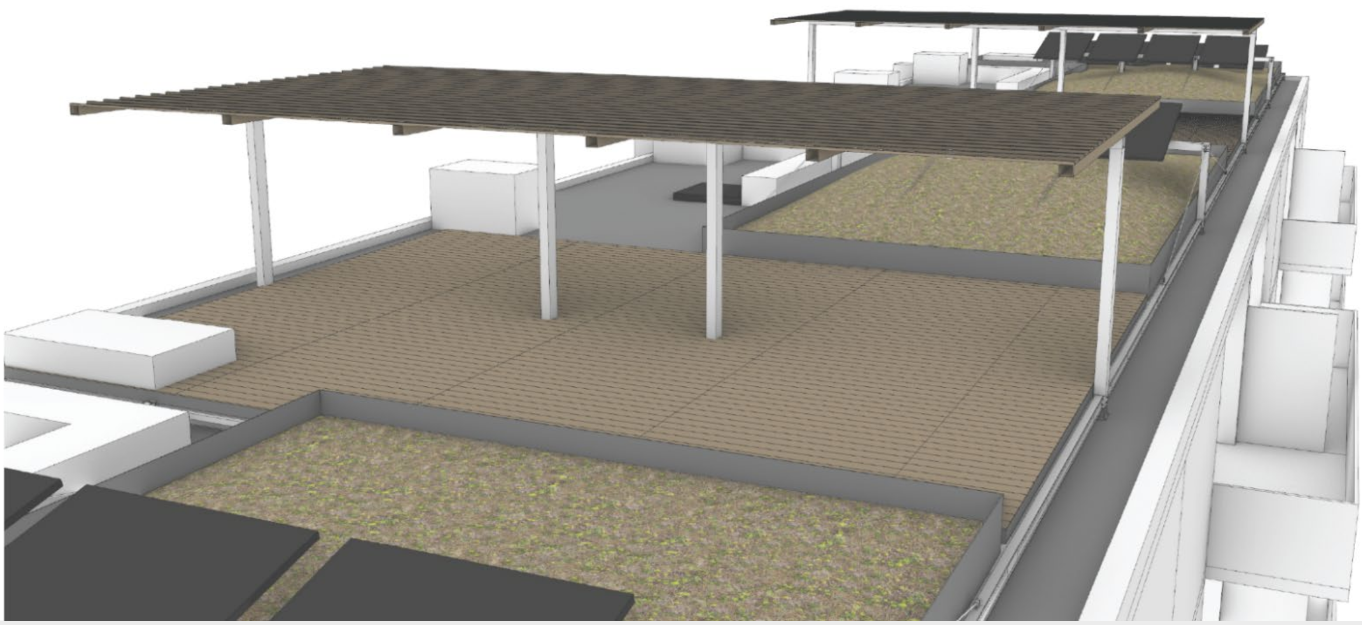




Design Outcome 2 – Terrace spaces and green areas – Private Use







6. EVALUATION AND DISCUSSION

The objective of the research was to propose an alternative reinforcement structural solution to enable the full potential of the available flat roof surfaces of the post-war typologies in the city of Rotterdam. Enabling them for heavier interventions, more beneficial for the user and the urban environment. To fulfill this objective the considerations that were followed were:

- Creating a lighter intervention and more economically accessible by following the design premises of the possible cost-relieving factors that were found throughout the research.
- Considering the structural and constructive limitations of the selected building group to create a system applicable to the best- and worst-case scenarios, lowering the requirements of in-deep analysis and testing of the current structure.
- Creating an external structure to prevent the intervention on finish layers of the building and that can be integrated into other additions to provide more functionality.

The System Scale: Analyzing roof multifunctional interventions, the more relevant and attractive characteristics for all end users (Building owner, user, and city) were found to be: Creating accessible and functional areas, increasing the water retention capacity, maximizing the soil thickness for intensive green roof systems, facilitating the installation of solar panels, and increasing the insulation for energy savings. Moreover, designing a tool to aid the distribution of loads from the start to reduce the structural demands and therefore create a lighter structure.

The Building Scale: Analyzing the selected group of Post-War typologies, the potential of systemic solutions to renovate these typologies was noted. The modular designs and similar construction systems and structural configurations create an opportunity for standard solutions with a wider range of applications. An estimation of the building weight from the selected samples helped to build an overview of the potential additional load that these buildings could carry and the height at which the load requirements become a limitation. Moreover, the potential use of the existing roof structure to carry part of the load of the intervention and therefore reduce the structural demand of the new one.

The Design Process: Combining all the information, the potential of external reinforcement strategies was noted, to apply all the cost-reliving factors and prevent invasive interventions on the building's structure or finish layers. Moreover, all the safety parameters need to be considered for the proposition of a structural system that can be applied to a wider range of buildings under the best- and worst-case scenarios.

All these conclusions conducted the exploration of different design options, which went through an assessment process of constructive and production feasibility and material limitations. The research concluded with the selection and implementation of the proposed strategy.

6.1. EVALUATION OF THE SELECTED STRATEGY

The premises on cost-relieving factors and design factors were used to reflect and evaluate the performance of the presented solution.

Cost-reliving Factors

Assume Building Capacity by Norm and Design Specifications: The proposed system considers all the safety factors derived from the worst-case scenarios, making it suitable for the evaluated building samples as well as for the buildings of the researched groups. Ideally, by visual inspection and revision of the construction drawings, it should be possible to define the maximum applicable capacity and all the boundary conditions to implement the developed system with no additional testing requirements. There are more structural and constructive factors that should also be addressed with further investigation that weren't considered now.

- The maximum moment force that the different construction systems from the analyzed samples could withstand.
- The stability of the building under seismic events in relation to the building height and the additional load on the roof.

Continuing the research on the structural properties of the selected construction systems and the remaining ones could further improve the safe application of the proposed strategy.

Reduce Intervention on Existing Construction: A big advantage of the selected external reinforcement system is, that it operates independently from the insulation system and the building structure. This allows to intervene only in the desired areas of the roof, avoiding areas where the modification or adaptation of installations or appliances on the roof would complicate the process. If insulation is required, the intervention will take place on the whole roof surface, but again, the reinforcement system will only be installed on the desired areas and prevent excessive adaptations of the reinforcement structure or the installations to make them compatible.

Building Cases III and VII showed an insulation system of concrete panels. In this case, the segments where the supports should be installed need to be removed, as these panels are designed for lower loads. Ideally, the supports would be installed without the need of removing any layers other than insulation. Analyzing more case studies could give a broader idea of the additional situations to be found on the existing buildings.

Weight of Structure: The selected design was the lightest solution from the compared options. This, thanks to the use of the roof capacity for the water buffer and insulation layers to reduce the demand on the new structure, and the additional supports along the beams provided by the tensile structure. Both combined, allowed to substantially reduce the cross-section requirements of the structure even for long spans. Comparing the weight per m^2 of the solution to the hypothetical 5.00 cm of additional reinforced concrete, the system represents 1/3 of the weight.

Number of Elements: The selected strategy increased the segmentation of the beams in order to reduce the weight per element. Doing so, the machinery requirement for transportation and assembly of the pieces is avoided. Based on the selected assembly strategy, this is favorable to make the system suitable for any building regarding its location and urban context. Many of the connections can be preassembled off-site to decrease the time and ease the assembly process on-site. Nevertheless, the increment of segments and the addition of the tensile connections increases work hours and the complexity of the process, for which a more in-depth analysis on cost is required to determine its effect when compared with the current reinforcement strategies.

Adaptability: The system provides 3 different configurations for the different building cases. Different span lengths and their variation will determine the ideal solution for every case. Moreover, the independence of the current structure, the insulation layer, and the external structure, provide a lot of freedom for the adaptability of the system. As shown in Building block IV, the possibility of avoiding complicated areas it's a big point in favor. Building blocks III and VII showed that the versatility of the arrangement of the beams and removal of grating units allow the system to integrate the modular repetitive installations that are normally found on these buildings. The detailing and components of the designs is ruffly changing with the different adaptations. The only substantial changes would be the beam's cross-section height and length, and the column segment's height and cross-section. The components won't change much between different scenarios, which could positively impact the production costs.

Design Factors

Design Freedom: As experienced in the design of the two different use scenarios of building block IV, the design restrictiveness of the tensile structure and the floor plan of loads was less than expected. Different configurations can be achieved through this system depending on the user preferences. Nevertheless, the designs are restricted to orthogonal distributions, following the direction of the structure, and to symmetric and repetitive spaces to make use of the high and low loading areas as much as possible. In the end, the solutions respond to a similar modular configuration to the post war typologies, which does not have a negative impact on the design or the aesthetics, but it doesn't provide complete design freedom as initially proposed either.

Moreover, the building support system allows to mount additional columns and beams for the installation of roofs, solar panels, railings, and other functions that will enhance the functionality of the roof and create a more integrated structural design.

Compactness: The additional L brackets mounted on the main I-beams allow to mount the grating system as low and close as possible to the water buffer area. This allows creating a more compact system that will make efficient use of the structure cross-section height. Nevertheless, the height of the intervention surpasses the height of the edge beam in all cases, making it visible above the roof, especially due to the tensile structure. The visual impact it creates on the building will depend on the final design approach and the visibility of the intervention according to the building height.

Moreover, the irrigation through capillarity requires the development of an additional component to conduct the cones through the grating system and create the absorption coefficient required for the provided distance. This solution requires proper calculations and verifications to test its feasibility and effectiveness.

Accessible Waterproof Layers: The grating panels can be easily removed in case maintenance or repairs on of the waterproof layer is required. Nevertheless, in case a significant portion of the substrate layer is removed, its effect on the balance of forces around the column segments needs to be considered. It might be necessary to attach the column segments to the next line of supports to counteract its effect. For this, additional detailing for this possibility should be considered. Creating such a solution would be very useful prevent the requirement of subtracting the substrate from both sides to maintain the balance, especially for small maintenance or repair interventions.

Compatibility with Polder Roof System: The proposed solution is compatible with the Polder Roof system. The dimension of the water buffer layer is proposed for a capacity of 85mm, which can be distributed on the desired area of the roof. Inspection hatches for the flow-control components of the Polder Roof system are provided on the configuration. As mentioned before, the irrigation through capillarity is still subjected to further analysis and testing to assess its feasibility on this system.

Compatibility with Existing Products: The selected solution proposes a significant modification on the layer configuration of the GR and BGR systems, to make the insulation and water buffer layers independent from the GR components. Doing so, introduce the structural reinforcement system in between, and provide more versatility for the distribution of the system on the roof. This allows to avoid some components, like the water retention boxes. Nevertheless, four new custom components are required for the system.

- The shear connectors for the grating system: To provide fixing points for the substrate contention structure and the finishing layers of the accessible areas.
- The PET tubes for the capillary cones: To maintain the possibility of irrigation through capillarity
- The EPDM fixing gaskets: To fix the position of the filtration mat and seal possible gaps through which the substrate could be drained.
- The FRP box sections: To be used as installation shafts and as spacers to prevent variations on grating sizes.

Ideally, no new custom components were to be proposed, especially for functions for which existing component are already available. Nevertheless, these components are required for the functioning of the proposed system.

Material Durability: Steel was selected as the material for the solution, as it provided the most compact and economic solution from the analysis options. Galvanization of the structural elements would be required to make the system suitable for exposure to water and organic residues. Some of the connections require customized components, like the cutting of a portion of the Falange of the I-beams to receive the plate for the tensile structure. This would require galvanizing all the pieces after all the mounting points and cuts are done. This factor should be considered to analyze if a solution in aluminum would be more appropriate for the system, as the fabrication process of the galvanized components might even the cost of both options.

Sustainability: Another advantage of the system is the possibility to disassemble the whole structure after the lifespan of the building or the new intervention is completed, or in case a new intervention is proposed. The removal of this external reinforcement would leave the concrete structure in its original state. Moreover, the possibility of re-utilization of all the components of the system, as all connections were through for dry assembly. The base support is the only component where welding was selected as the ideal connection for the base plate and the stiffening elements. The rest of the components use standardized products and bolted connections, giving the possibility of reusing them for a different structure or for the same solution on a different building. The system provides a more sustainable and circular approach compared to the use of reinforced concrete or customized panels designed specifically for the span, load and length of the building.

6.2. CONCLUSION

The selected system is a viable solution for the analyzed Post-War building systems. Its adaptability allows to configure the best performing variation for the building's roof and structural characteristics Increasing its loadbearing capacity and enabling it for more impactful and beneficial interventions for the three end benefactors: The building user, the owner, and the surrounding urban environment.

Structural system: The structural solution shows to be lighter compared to the rest of the evaluated options, and significantly lighter than a reinforced concrete solution. After analyzing different design scenarios, it was noted that the strategy will be of most potential for low-rise buildings with reduced loadbearing capacities and foundations capacity restrictions. The design provides an integrated approach to include other functions on the structure that will enhance the possibilities for different uses. Nevertheless, it will partially restrict the design freedom due to the tensile structure.

Design Tool: The design tool allows to configure the structure requirements for the desired load combinations, depending on the preferences of the owner/investor. The design tool developed for the implementation of the strategy allows to analyze the building and determine the maximum area of intervention, the number and sizes of the components that will be required for the intervention, and the load distribution floor plan to maximize the roof capacity.

The following table summarizes all the advantages and disadvantages presented by the proposed solution:

Advantages	Disadvantages
Adaptability: The selected solution fulfills with all the considered risk factors to be suitable for the worst-case scenarios. It is versatile enough to be adapted to any wall loadbearing configuration, selecting the optimal configuration for every case to reduce the number of pieces and complexity of assembly. Moreover, its independency from the existing structure, the insulation and water buffer layers, allows it to cover the maximum amount of roof area as possible, while integrating installations through the configuration process and avoiding areas that would imply intensive interventions.	**Limited Design Freedom**: Although the design process was less restrictive as initially thought, it was possible to see that the solutions will be guided by the two main factors: **- Structural grid:** The solutions will mostly follow orthogonal solutions that follow the distribution of the tensile structure. For short-span buildings, no tensile structure will be required, in which case this parameter doesn't apply. - **Structural balance:** The solutions will likely result in symmetric and repetitive patterns to take full advantage of the different loading capacities. The

Structure Weight: The selected solution had the lowest weight among the analyzed options and shows a substantial reduction of weight in comparison to a concrete reinforcement system. This will be of huge benefit for low-rise buildings, to increase their possibilities for more impactful interventions. **Integrated Structure:** The proposed support system provides the possibility of integrating additional functions to the structure without further modifications. Structural elements to support sun shading systems, roofs, solar panels and more. **Sustainability:** After completing the building or the new structure lifespan, in case of design modifications of the system, or in case of further renovation processes for other functions, the system can be adapted or completely disassembled, leaving the original concrete structure as it was. The use of standard components for the system and the predominant use of dry connections makes it a more circular and sustainable approach in comparison to the use of reinforced concrete, CFRP reinforcement bands and the GFRP box systems. **Design Aid tool**: The use of the load distribution floor plans showed to be of great potential, especially for small buildings with load restrictions. Through the distribution of forces, it is possible to apply loads combinations that where initially out of the range for the smaller building heights. Moreover, the parametric process of the tool to determine the possible area of intervention, total loading areas of different capacities, number of elements of the structure and other data that can be extracted, represents a great potential for other applications as well. As an example, to estimate the potential of a group of buildings, their potential available surfaces of a specific loading capacity or their potential water buffer capacity. These and other factors could be derived from this tool, to allow estimations on the impact that such an intervention could bring at an urban level.	required balance of the structure is important to maintain the safety factors of the building. **Maintenance and Repairs:** In case of reparations or interventions that require to remove heavy components of the roof, like the substrate layer, balance needs to be considered again, where weight needs to be removed from both sides of the tensile structure or develop a system to attach the column segments together to prevent the transmission of excessive moment forces to the building structure. **Custom components:** The system requires the development of 4 custom products, specific for this solution. - The shear connectors for the grating system - PET tubes for capillary cones - FRP box spacers - EPDM gaskets for the filtration mat. **Universal solution:** The safety factor parameters consider the construction systems with the highest risks. The solution will provide a valuable approach for buildings with close characteristics to the ones considered for the safety limits. In case the building has a prefab or casted concrete system, like in buildings VII and III, the loads the system can receive are much higher, which could lead to other potential solutions. The assembly strategy is an additional example. For High rise buildings, the use of tower cranes might be necessary, in which case a different assembly strategy might be more appropriate and would change the selection criteria of the explored options. Determining more concise categories among the listed groups of analyzed buildings might lead to more specific solutions for shorter ranges of buildings, allowing to reach more suited solutions for the different cases.

6.3. LIMITATIONS AND OTHER CONSIDERATIONS:

Economic accessibility assessment: The parameters used to compare the different options are based on the cost relieving factors derived from the analysis of the current reinforcement systems. The economic assessment for the comparison of the different strategies doesn't consider many other factors that could substantially impact on the price of the different solutions, not only on material costs, but also in manufacturing and the assembly strategy.

The prices used for the comparison are based on material price approximations from the information provided by companies and open data sources. Due shortage of time and lack of information, it was difficult to assess if all the obtained prices consider the same parameters to make a fair comparison. Nevertheless, the proximity of results between the prices obtained from company websites and consultations, and the ones obtained from databases was concluded to be enough for the comparison.

Many approximations were taken to assess the possible cost of the different options. The limited amount of information, time, and expertise to assess the economic aspects weren't enough to reach values for a more straightforward comparative analysis. To determine if the presented solution decreases the cost of reinforcement in comparison to the currently implemented strategies, a proper analysis should be conducted considering all the variables that will influence on the final cost. This will allow giving a more accurate answer on whether the proposed system is more economically accessible or not.

Larger roof loadbearing capacities: By consulting the design files of the selected case studies on the Municipality Archive of Rotterdam, it was possible to find the structural calculations of the roof structure and the building foundations. Due to a lack of expertise and language barriers, it was hard to properly assess all the information. Conducting a more systematic analysis of more building cases and with the language expertise and knowledge on structural engineering, more data could be obtained from the files to enrich the information and categorization of the different building typologies.

Nevertheless, it was possible to see that for building blocks III and VII, load bearing capacities of 2.00 and 3.00 kg/m2 were used on the design of specific areas of the roof. By the weight estimations conducted for these typologies, it was derived that interventions above 10 kN/m2 could be possible on these buildings. The implementation of the selected strategy on these buildings for high-capacity interventions could be also categorized as not taking full advantage of the building's capacity, and therefore a non-regret solution. Under this logic, interventions proposing additional floors on these buildings to increase functional areas, like the one proposed by the Solar Decathlon SUM team of TU Delft Solar [36] would be more appropriate solutions for these building cases. Proposing additional floors that are designed from start to allocate green roofs and other functions on the roof areas, as fully integrated systems.

6.4. NEXT STEPS

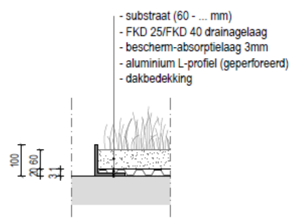
Post-War construction typologies database: Continuing the research on more building cases to obtain more information about the analyzed construction systems. More documentation can be found on the selected construction typologies. Most of the information is written in Dutch. Categorizing this information to create a larger database could be of substantial benefit for any renovation and retrofitting strategy for these post war typologies, which will be crucial for the building industry in the coming years.

Determining ideal group of intervention: By analyzing the implementation of the system on more design cases, and with more information on the loading capacities of the different building groups, the ideal group of application of this strategy could be further defined. For example, solutions like option 6 could be a potential and viable solution for high-rise buildings in which a tower crane will be required anyways due to the building height, and the wall loadbearing peak capacities are higher due to the construction system. In this case, a unitized prefabricated assembly strategy could be more suitable solution. The proposed solution showed to be of great potential for low-rise and mid-rise typologies with construction systems closer to the ones defining the safety factors. Grouping the different construction systems will allow to create specific solutions that can still impact larger groups of buildings, but with more appropriate approaches to prevent non-regret solutions.

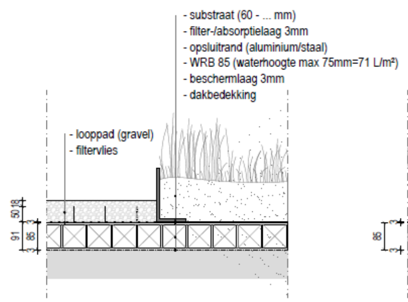
Design Tool: The different sections of the design tool were developed, but some of them require to be finished. Linking all the steps is still necessary to develop the final tool for the evaluation of the buildings. Moreover, the application of design informatics on design strategies and systems provides many potentials, not only to automatize and optimize processes, but to provide valuable information that could be used for other ends as well. An example was given on the advantages of the system, to be able to estimate the possible interventions on buildings and evaluate the possible urban impact these could bring.

Cost analysis of the intervention: conducting a cost analysis of the system to determine if the approach represents a more accessible solution for the investors.

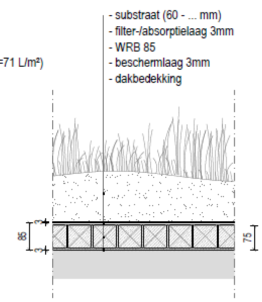
7. ANNEX A – POLDER ROOF SYSTEM DETAILS



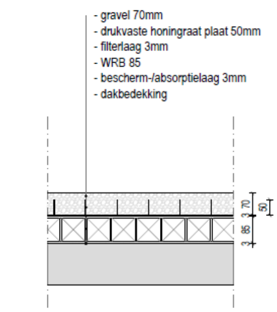
A | basis begroeid dak (FKD 25)



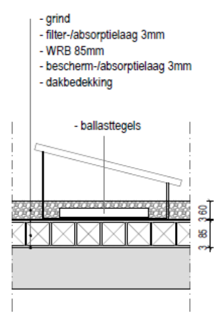
B | Polderdak (WRB85) + begroeid dak/begaanbaar vlak



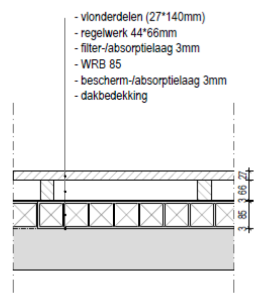
C | Polderdak (WRB85) + begroeid dak



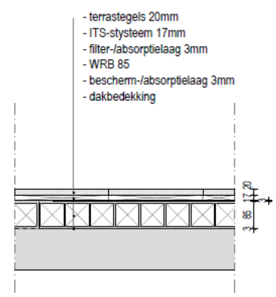
D | Polderdak (WRB85) + gravel pad



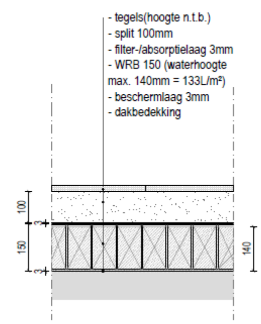
E | Polderdak (WRB85) + zonnepanelen



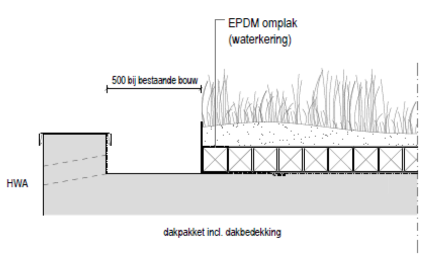
F | Polderdak (WRB85) + vlonderterras



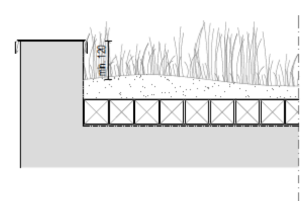
G | Polderdak (WRB85) + keramisch terras



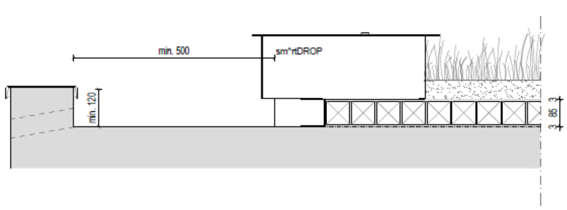
H | Polderdak (WRB 150) + tegelpad/terras



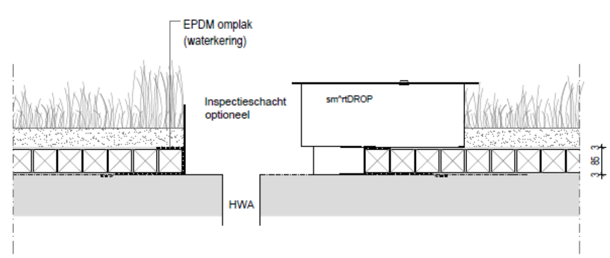
detail 3a | WRB dakpakket met zijuitloop tpv hwa



detail 3b | WRB dakpakket tot dakrand



detail 4a | smartdrop dakrandbij zij-uitloop



detail 4b | smartdorp interne afvoer

8. ANNEX B – BUILDING CASE DOCUMENTATION

8.1. BLOCK III

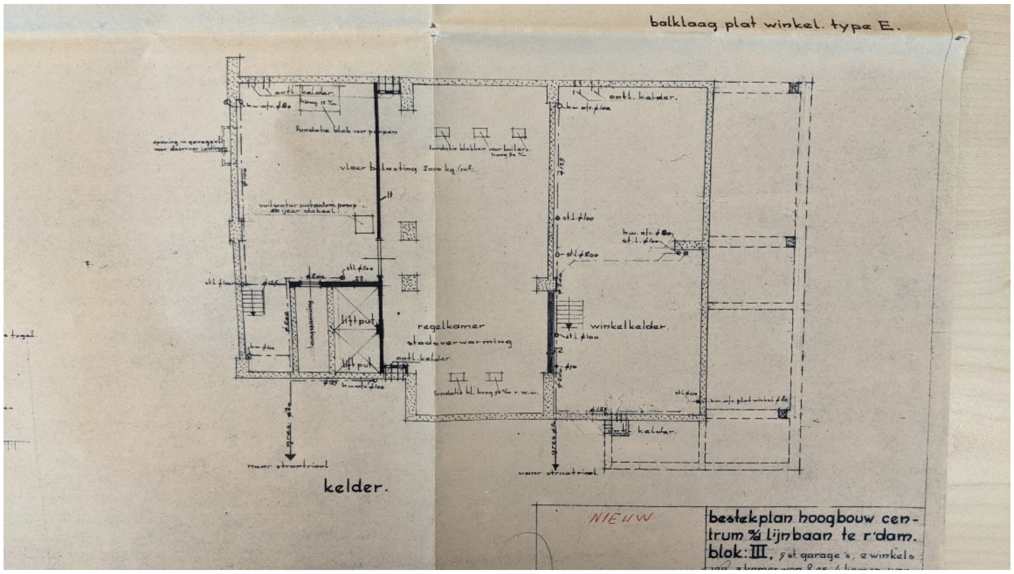


Figure 111 - Basement

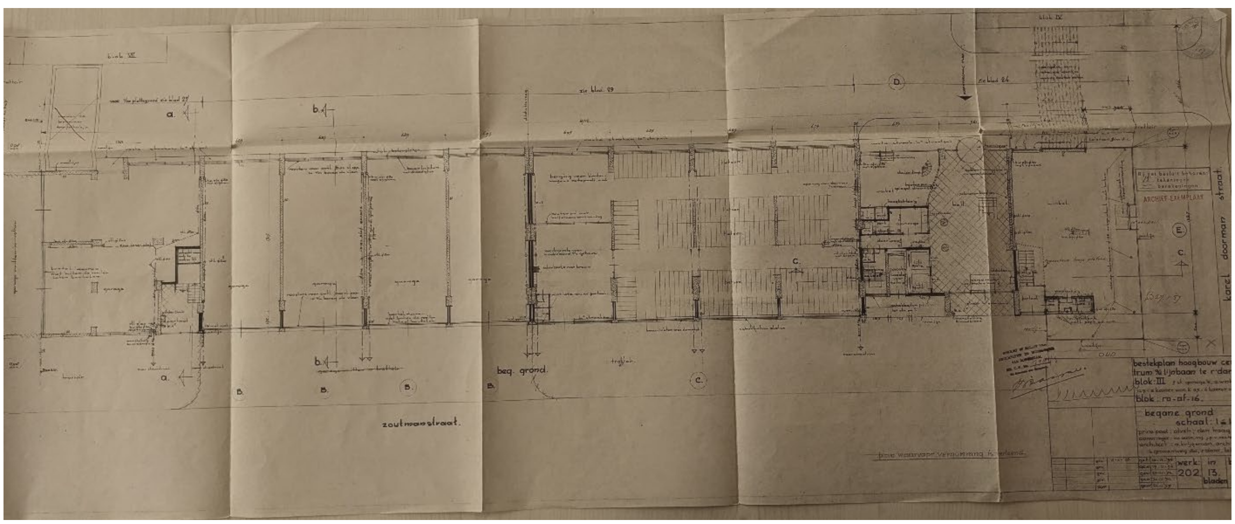


Figure 112 - Ground Floor

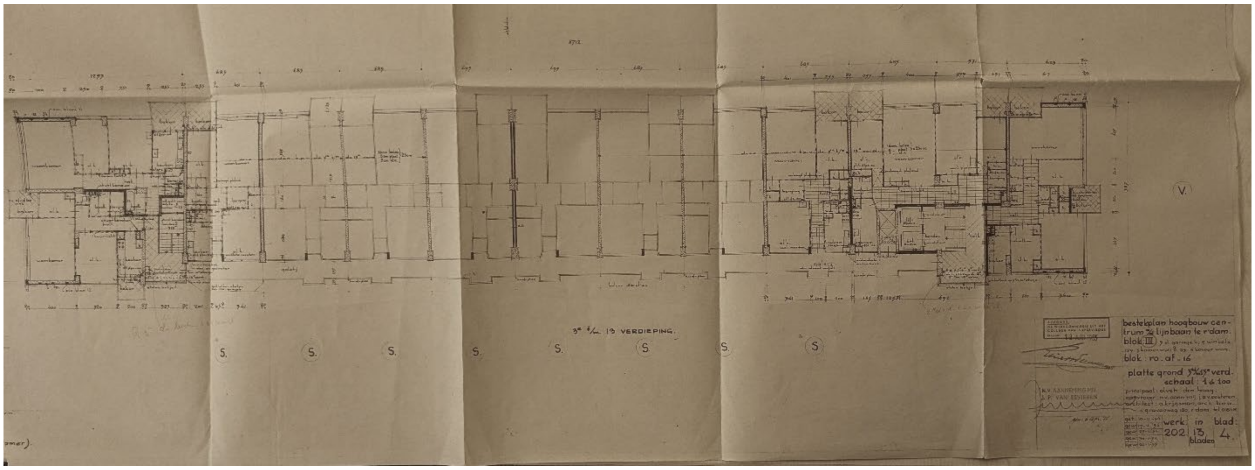


Figure 113 - 3 to 13 Floor

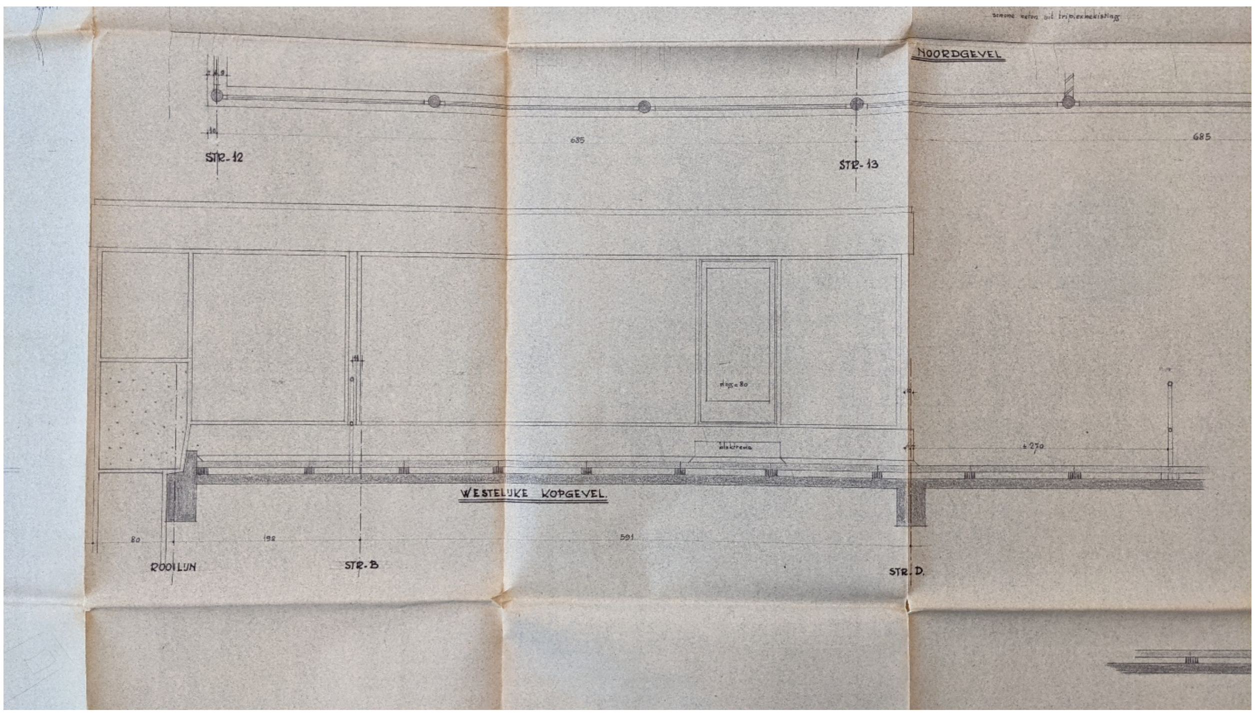


Figure 114 - Roof floor section

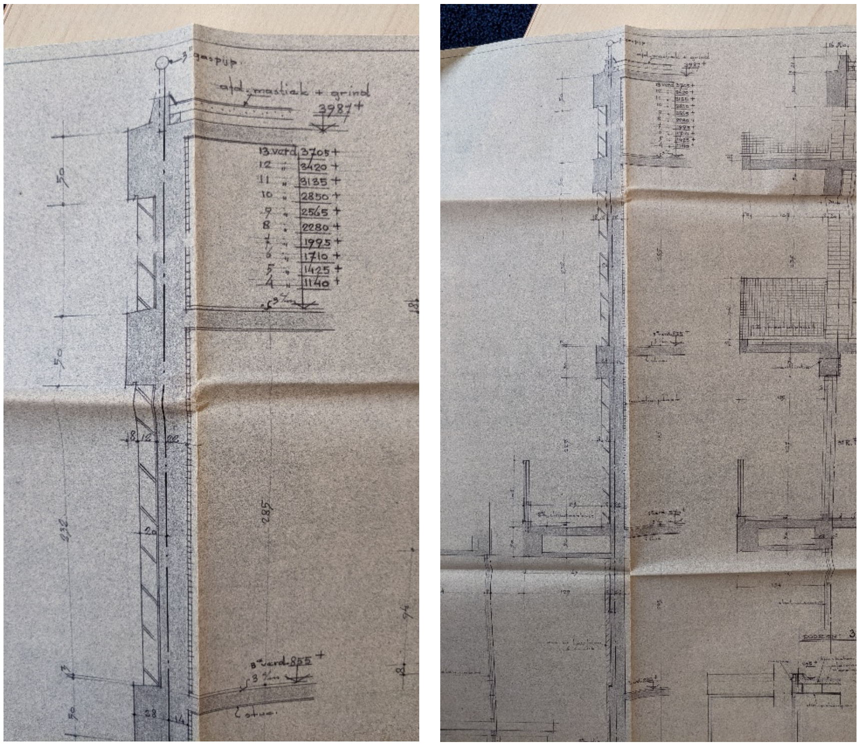


Figure 115 - Building Edge Section

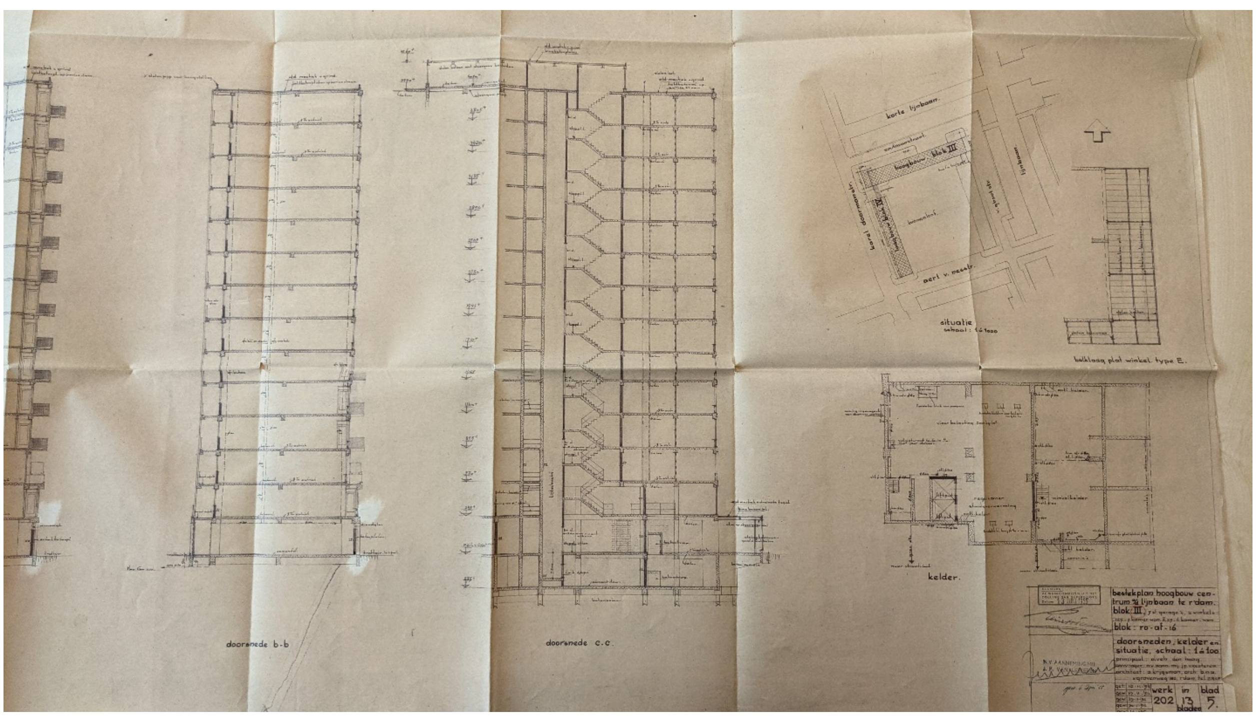
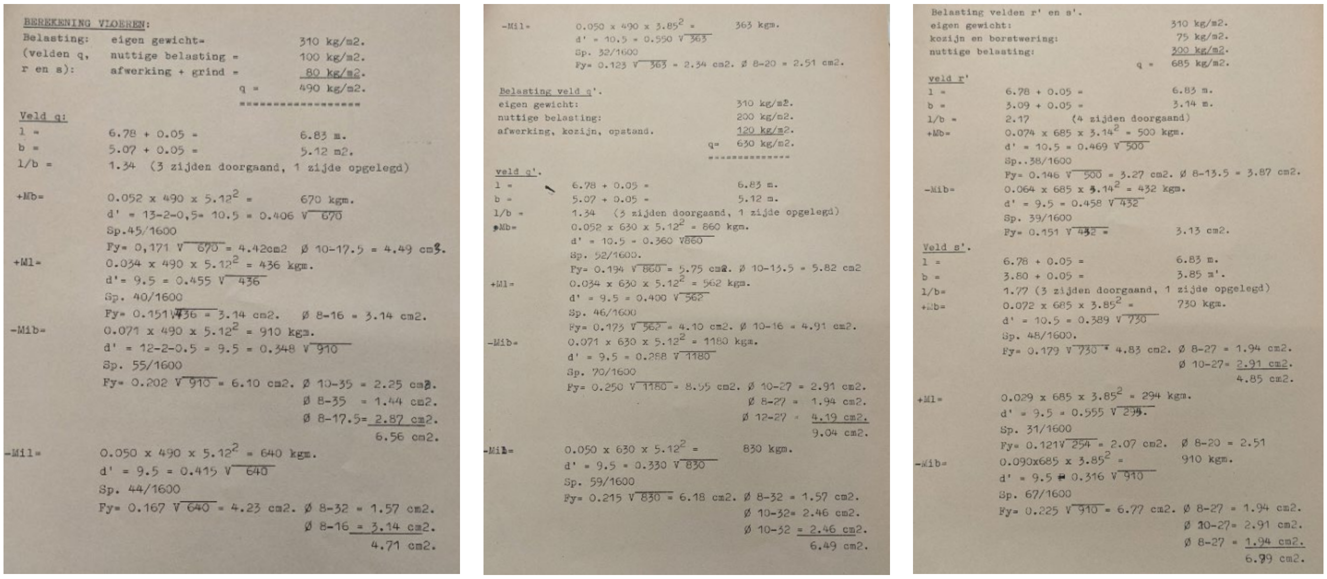


Figure 116 - Building Sections


BEREKENING VLOEREN:
Belasting: eigen gewicht= 310 kg/m2.
(velden q, nuttige belasting = 100 kg/m2.
r en s): afwerking + grind = 80 kg/m2.
q = 490 kg/m2.

Veld q:
l = 6.78 + 0.05 = 6.83 m.
b = 5.07 + 0.05 = 5.12 m2.
l/b = 1.34 (3 zijden doorgaand, 1 zijde opgelegd)
+Mb= $0.052 \times 490 \times 5.12^2$ = 670 kgm.
d' = 13-2-0,5= 10.5 = 0.406 √670
Sp.45/1600
Fy= 0,171 √670 = 4.42cm2 Ø 10-17.5 = 4.49 cm2.
+Ml= $0.034 \times 490 \times 5.12^2$ = 436 kgm.
d'= 9.5 = 0.455 √436
Sp. 40/1600
Fy= 0.151√436 = 3.14 cm2. Ø 8-16 = 3.14 cm2.
-Mib= $0.071 \times 490 \times 5.12^2$ = 910 kgm.
d' = 12-2-0.5 = 9.5 = 0.348 √910
Sp. 55/1600
Fy= 0.202 √910 = 6.10 cm2. Ø 10-35 = 2.25 cm2.
Ø 8-35 = 1.44 cm2.
Ø 8-17.5= 2.87 cm2.
6.56 cm2.
-Mil= $0.050 \times 490 \times 5.12^2$ = 640 kgm.
d' = 9.5 = 0.415 √640
Sp. 44/1600
Fy= 0.167 √640 = 4.23 cm2. Ø 8-32 = 1.57 cm2.
Ø 8-16 = 3.14 cm2.
4.71 cm2.

-Mil= $0.050 \times 490 \times 3.85^2$ = 363 kgm.
d' = 10.5 = 0.550 √363
Sp. 32/1600
Fy= 0.123 √363 = 2.34 cm2. Ø 8-20 = 2.51 cm2.

Belasting veld q'.
eigen gewicht: 310 kg/m2.
nuttige belasting: 200 kg/m2.
afwerking, kozijn, opstand. 120 kg/m2.
q= 630 kg/m2.

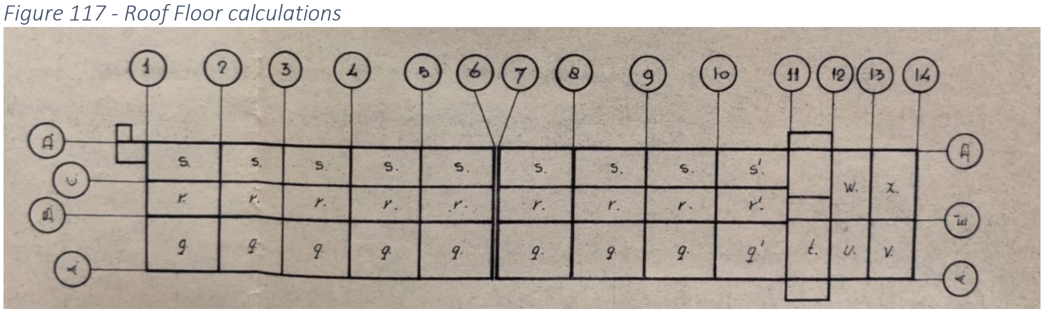
veld q'.
l = 6.78 + 0.05 = 6.83 m.
b = 5.07 + 0.05 = 5.12 m.
l/b = 1.34 (3 zijden doorgaand, 1 zijde opgelegd)
+Mb= $0.052 \times 630 \times 5.12^2$ = 860 kgm.
d' = 10.5 = 0.360 √860
Sp. 52/1600.
Fy= 0.194 √860 = 5.75 cm2. Ø 10-13.5 = 5.82 cm2
+Ml= $0.034 \times 630 \times 5.12^2$ = 562 kgm.
d' = 9.5 = 0.400 √562
Sp. 46/1600
Fy= 0.173 √562 = 4.10 cm2. Ø 10-16 = 4.91 cm2.
-Mib= $0.071 \times 630 \times 5.12^2$ = 1180 kgm.
d' = 9.5 = 0.288 √1180
Sp. 70/1600
Fy= 0.250 √1180 = 8.55 cm2. Ø 10-27 = 2.91 cm2.
Ø 8-27 = 1.94 cm2.
Ø 12-27 = 4.19 cm2.
9.04 cm2.
-Mib= $0.050 \times 630 \times 5.12^2$ = 830 kgm.
d' = 9.5 = 0.330 √830
Sp. 59/1600
Fy= 0.215 √830 = 6.18 cm2. Ø 8-32 = 1.57 cm2.
Ø 10-32= 2.46 cm2.
Ø 10-32 = 2.46 cm2.
6.49 cm2.

Belasting velden r' en s'.
eigen gewicht: 310 kg/m2.
kozijn en borstwering: 75 kg/m2.
nuttige belasting: 300 kg/m2.
q = 685 kg/m2.

veld r'
l = 6.78 + 0.05 = 6.83 m.
b = 3.09 + 0.05 = 3.14 m.
l/b = 2.17 (4 zijden doorgaand)
+Mb= $0.074 \times 685 \times 3.14^2$ = 500 kgm.
d' = 10.5 = 0.469 √500
Sp..38/1600
Fy= 0.146 √500 = 3.27 cm2. Ø 8-13.5 = 3.87 cm2.
-Mib= $0.064 \times 685 \times 3.14^2$ = 432 kgm.
d' = 9.5 = 0.458 √432
Sp. 39/1600
Fy= 0.151 √432 = 3.13 cm2.

Veld s'.
l = 6.78 + 0.05 = 6.83 m.
b = 3.80 + 0.05 = 3.85 m'.
l/b= 1.77 (3 zijden doorgaand, 1 zijde opgelegd)
+Mb= $0.072 \times 685 \times 3.85^2$ = 730 kgm.
d' = 10.5 = 0.389 √730
Sp. 48/1600.
Fy= 0.179 √730 = 4.83 cm2. Ø 8-27 = 1.94 cm2.
Ø 10-27= 2.91 cm2.
4.85 cm2.
+Ml= $0.029 \times 685 \times 3.85^2$ = 294 kgm.
d' = 9.5 = 0.555 √294.
Sp. 31/1600
Fy= 0.121√254 = 2.07 cm2. Ø 8-20 = 2.51
-Mib= $0.090 \times 685 \times 3.85^2$ = 910 kgm.
d' = 9.5 = 0.316 √910
Sp. 67/1600
Fy= 0.225 √910 = 6.77 cm2. Ø 8-27 = 1.94 cm2.
Ø 10-27= 2.91 cm2.
Ø 8-27 = 1.94 cm2.
6.79 cm2.

Figure 117 - Roof Floor calculations



8.2. BLOCK VII

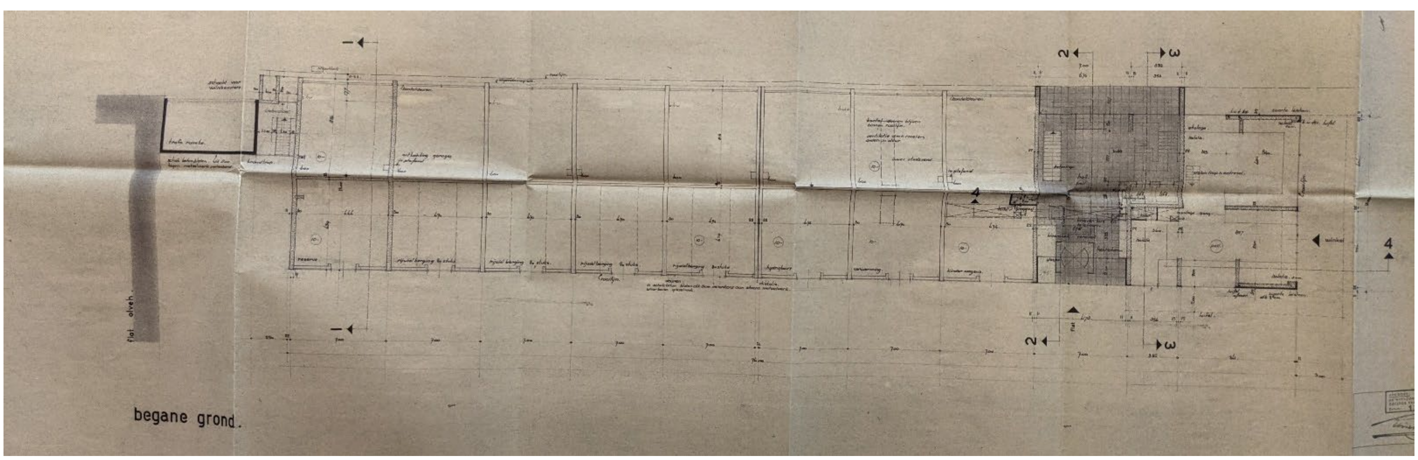


Figure 118 - Ground Floor

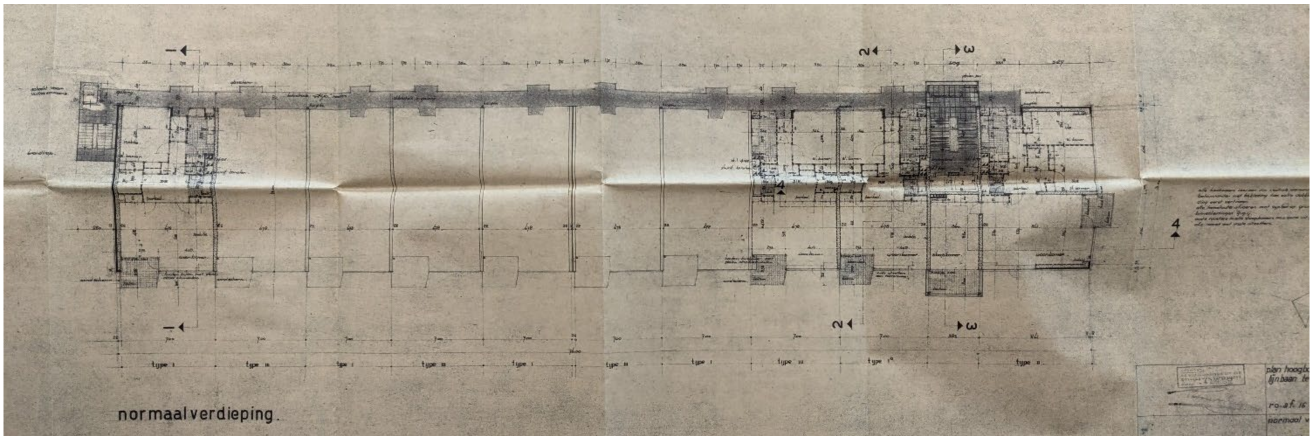


Figure 121 - 2 to 9 Floor

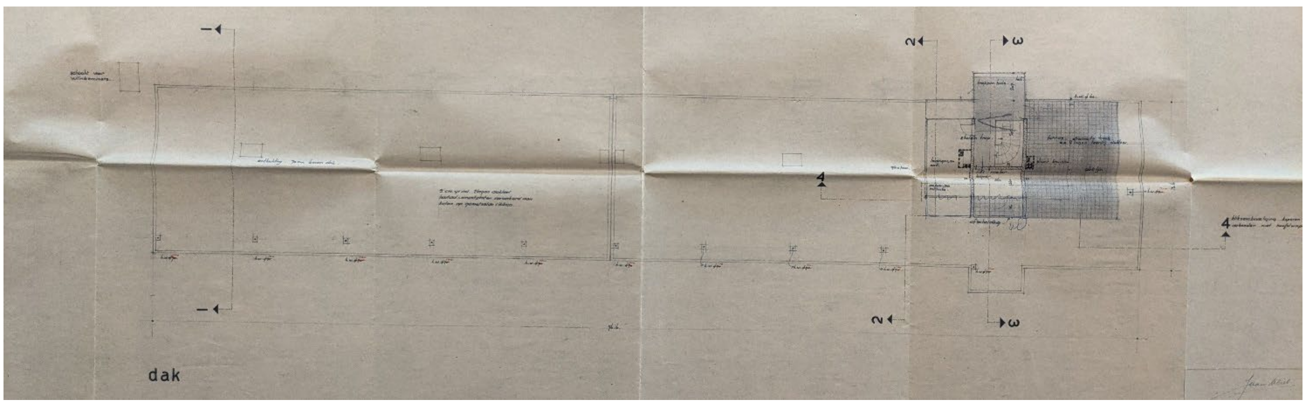


Figure 120 - Roof

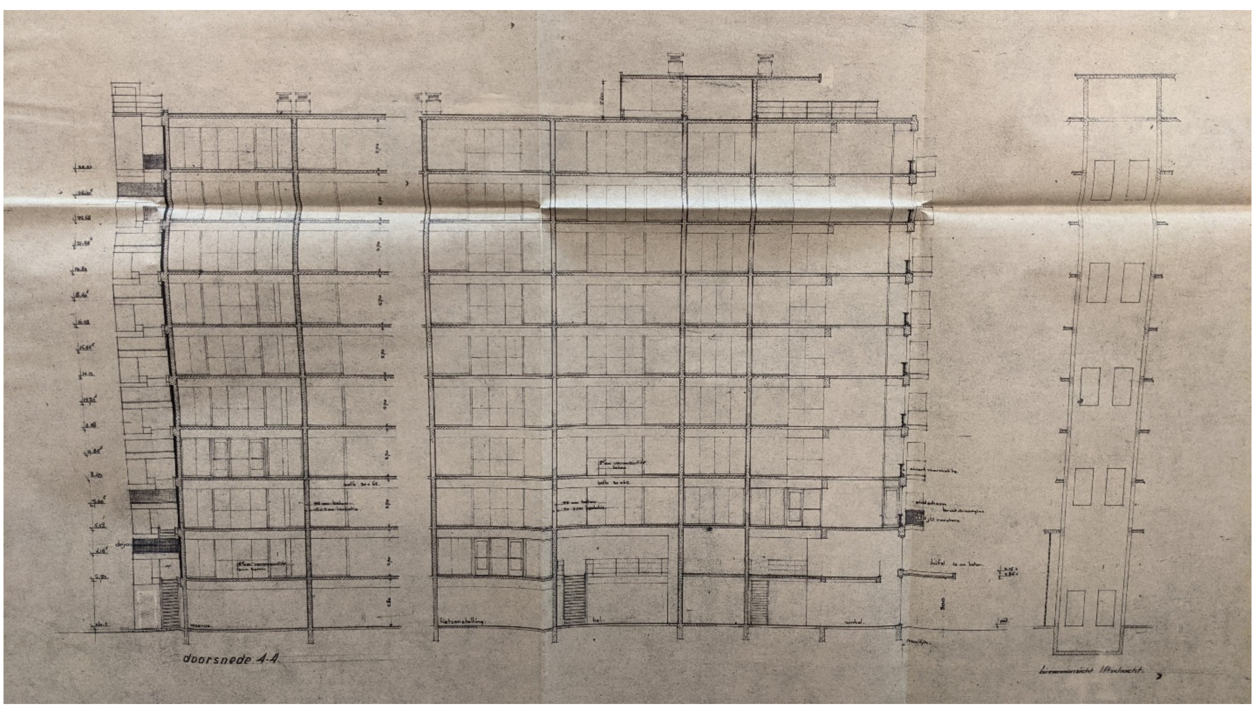
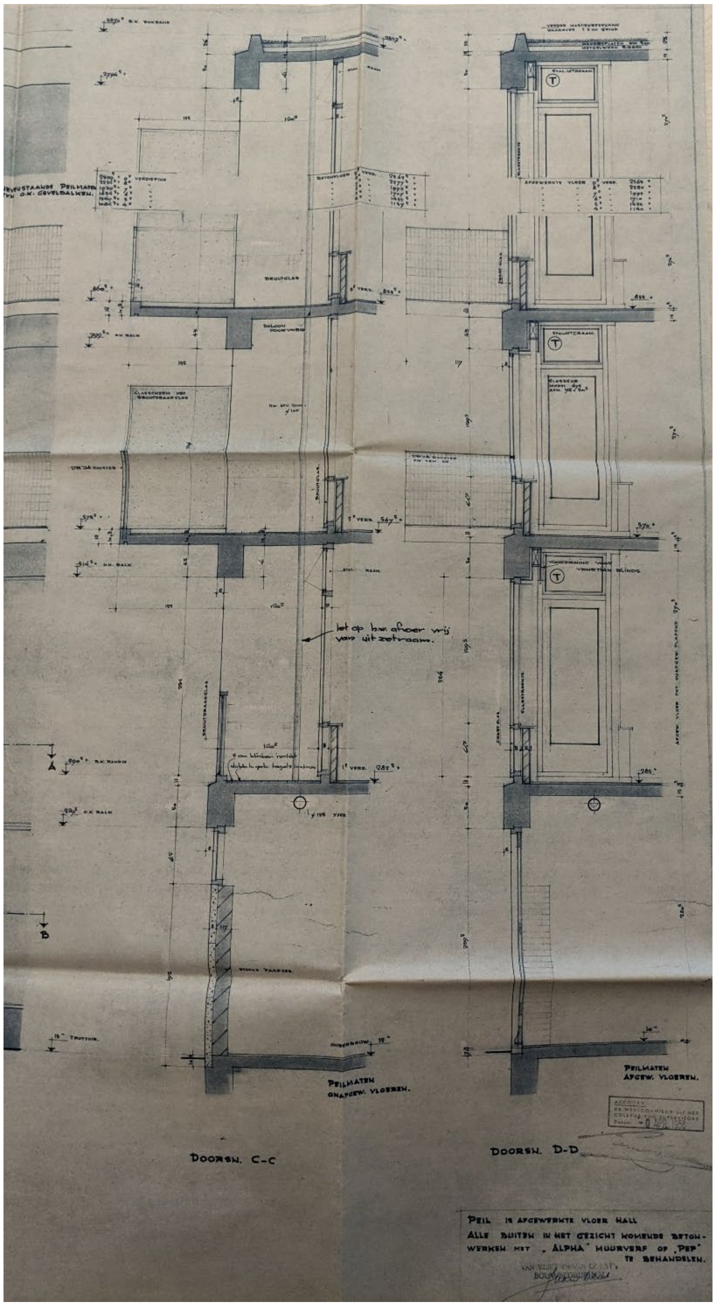


Figure 119 - General Section



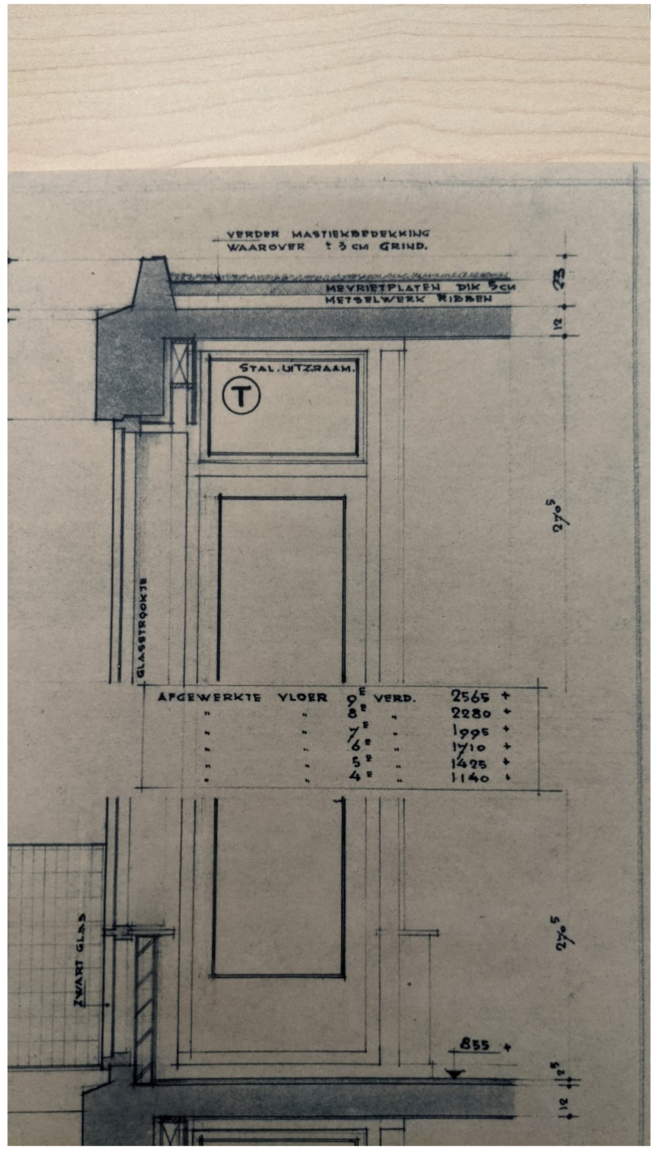


Figure 122 - Building Section

8.3. BLOCK IV

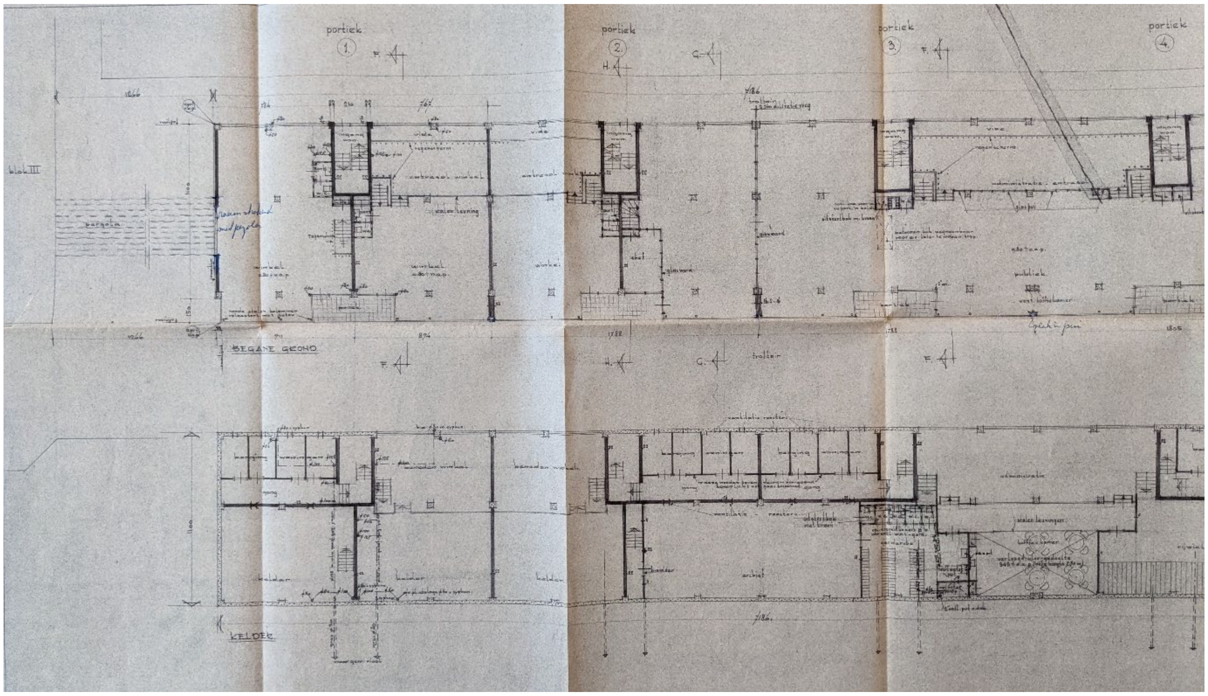


Figure 123 - Ground Floor

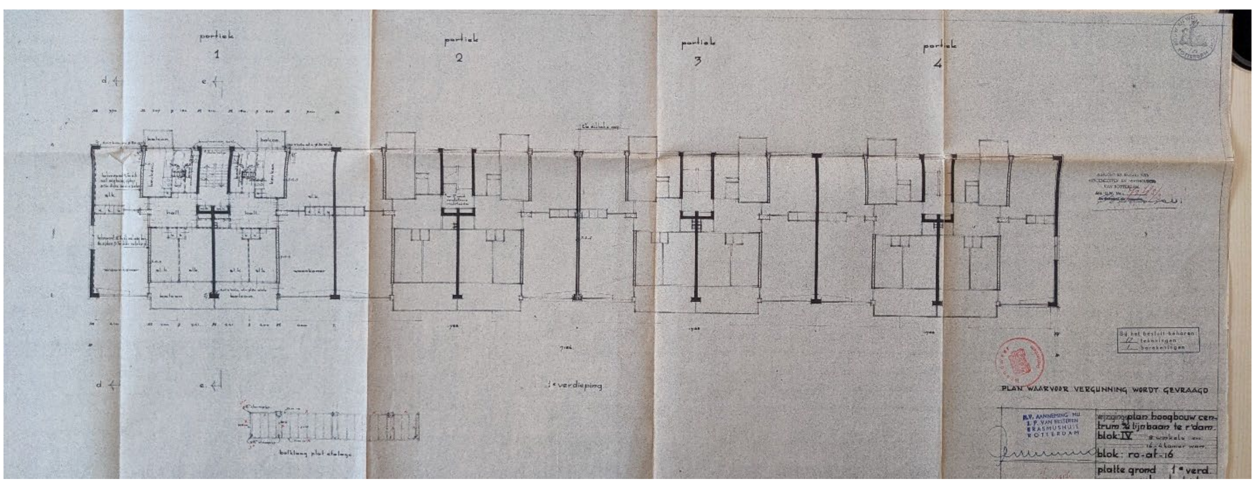


Figure 124 - First and Second Floor

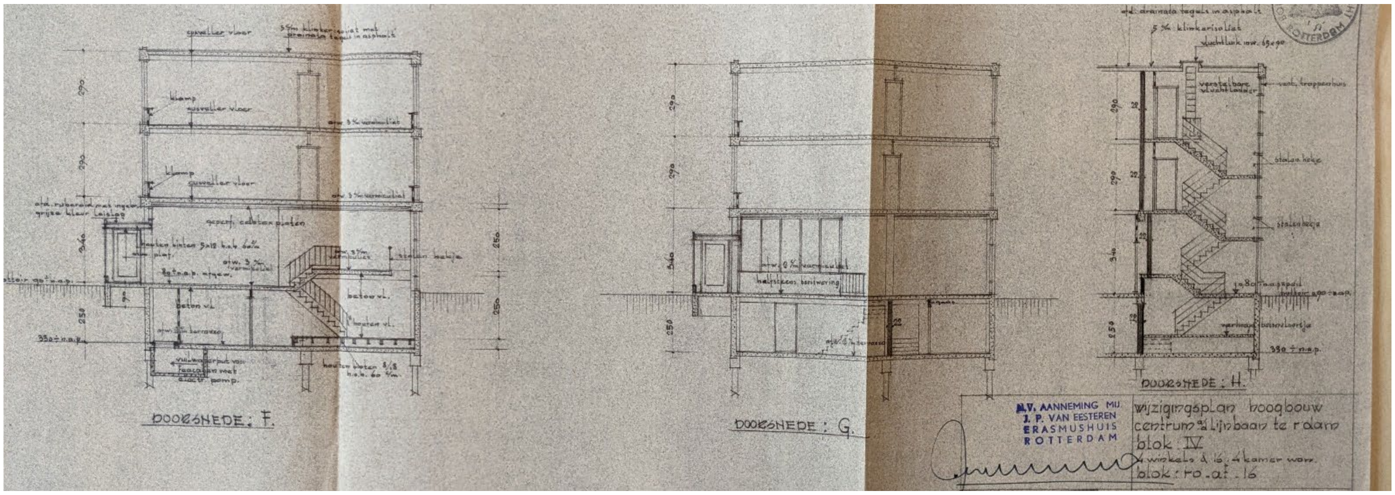


Figure 126 - Building Sections

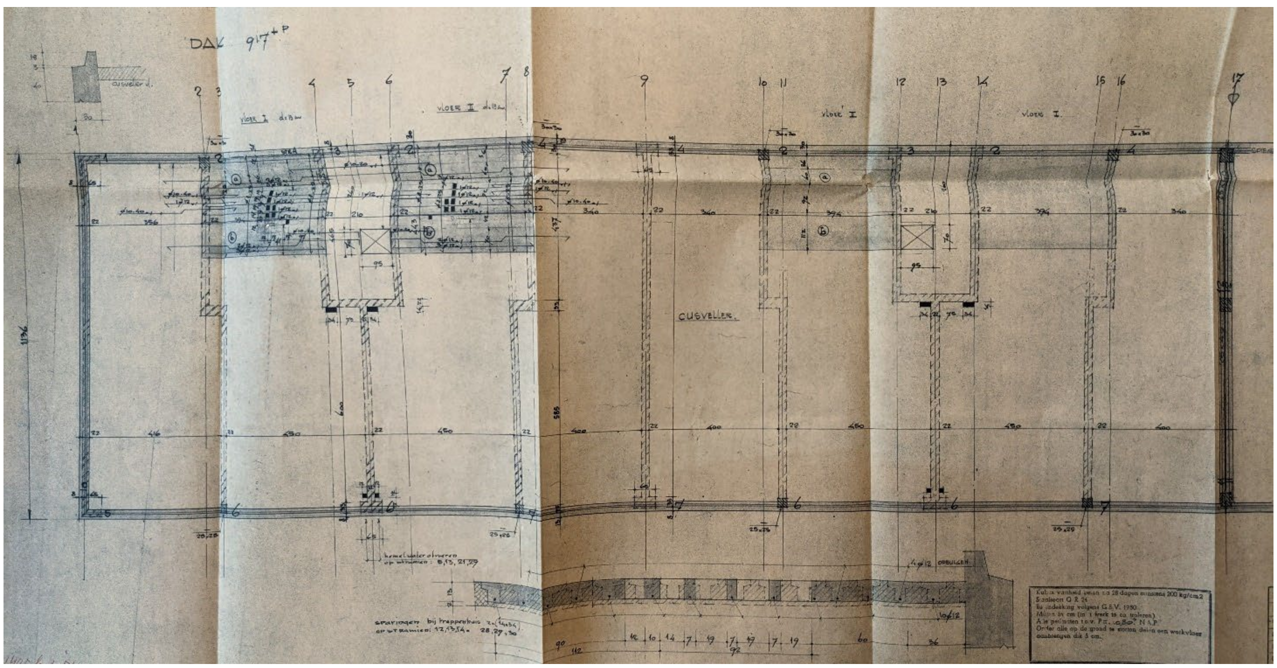
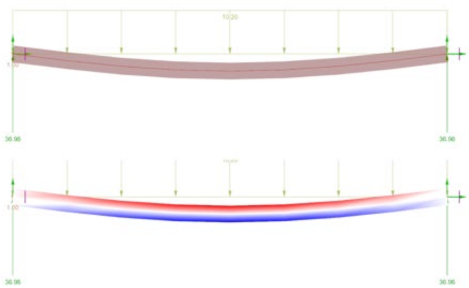


Figure 125 - Roof Structural System

8.4. ANNEX C – ROOF RESIDUAL CAPACITY HYPOTHESIS – CALCULATION RESULTS

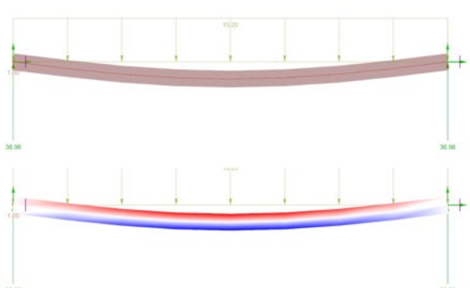
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	270	240
- Max Height [mm]	270.00	240.00
- Max Width [mm]	135.00	120.00
Max Displacement [mm]	20.29	19.02
Allowed Displacement	20.58	20.58
Utilization Max	+/- 55.70	+/- 64.80
Weight	252.22	214.85
Weight Reduction [%]	- 14.81	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

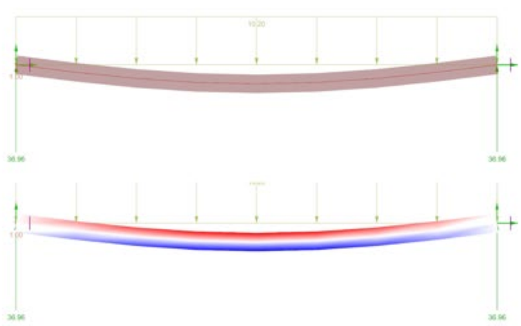
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	300	270
- Max Height [mm]	300.00	270.00
- Max Width [mm]	150.00	135.00
Max Displacement [mm]	18.37	19.20
Allowed Displacement	20.58	20.58
Utilization Max	+/- 64.50	+/- 61.30
Weight	295.63	252.22
Weight Reduction [%]	- 14.68	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

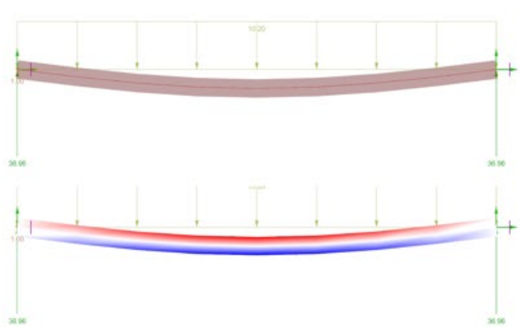
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	300	330
- Max Height [mm]	300.00	330.00
- Max Width [mm]	150.00	160.00
Max Displacement [mm]	18.19	15.65
Allowed Displacement	20.58	20.58
Utilization Max	+/- 60.00	+/- 63.80
Weight	343.98	295.63
Weight Reduction [%]	- 14.05	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

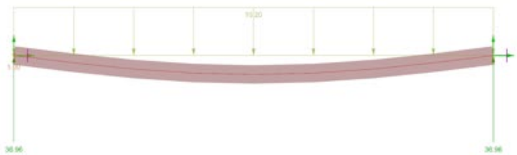
Configuration	A

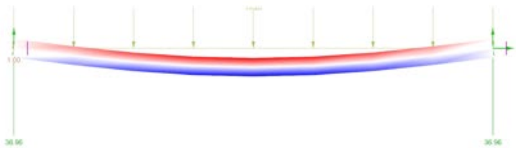


	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	270	270
- Max Height [mm]	270.00	270.00
- Max Width [mm]	135.00	135.00
Max Displacement [mm]	20.40	15.95
Allowed Displacement	20.58	20.58
Utilization Max	+/- 67.30	+/- 53.50
Weight	252.22	252.22
Weight Reduction [%]	0	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

Configuration	A

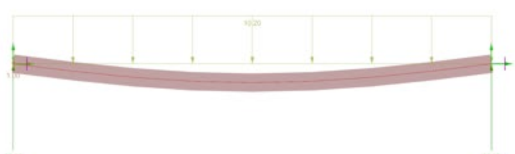


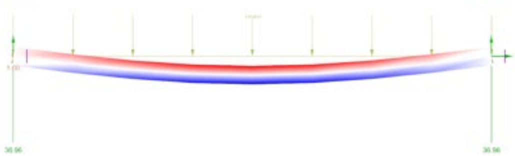


	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	300	270
- Max Height [mm]	300.00	270.00
- Max Width [mm]	150.00	135.00
Max Displacement [mm]	18.37	19.19
Allowed Displacement	20.58	20.58
Utilization Max	+/- 64.50	+/- 61.30
Weight	295.63	252.22
Weight Reduction [%]	- 14.68	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

Configuration	A

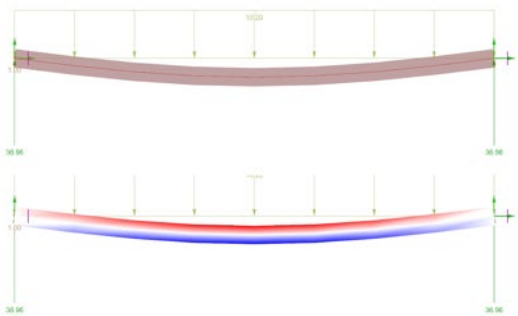




	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	330	300
- Max Height [mm]	330.00	300.00
- Max Width [mm]	160.00	150.00
Max Displacement [mm]	15.65	18.19
Allowed Displacement	20.58	20.58
Utilization Max	+/- 60.00	+/- 63.80
Weight	343.98	295.63
Weight Reduction [%]	- 14.05	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

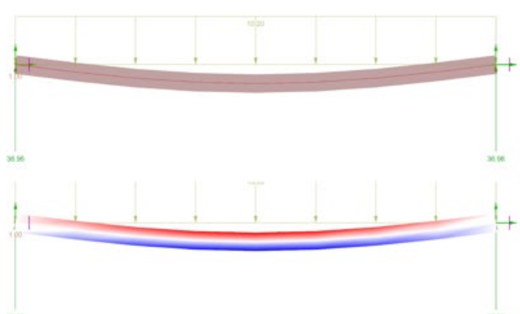
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	300	300
- Max Height [mm]	300.00	300.00
- Max Width [mm]	150.00	150.00
Max Displacement [mm]	17.93	14.84
Allowed Displacement	20.58	20.58
Utilization Max	+/- 66.20	+/- 55.50
Weight	295.63	295.63
Weight Reduction [%]	0	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

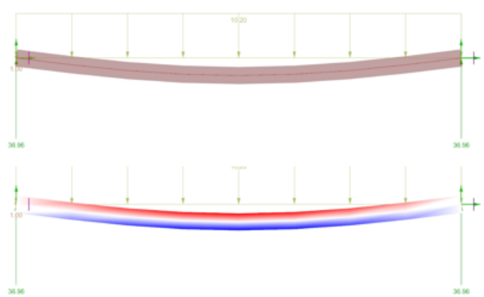
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	300	300
- Max Height [mm]	300.00	300.00
- Max Width [mm]	150.00	150.00
Max Displacement [mm]	18.37	14.84
Allowed Displacement	20.58	20.58
Utilization Max	+/- 66.20	+/- 55.50
Weight	295.63	295.63
Weight Reduction [%]	0	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

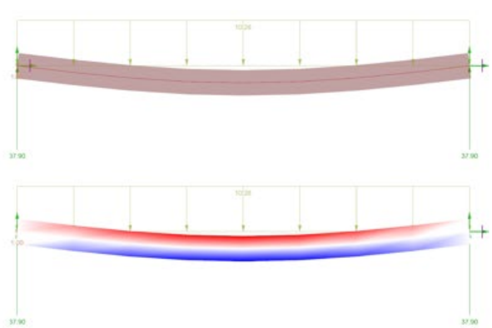
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	IPE	IPE
- Type	330	300
- Max Height [mm]	330.00	300.00
- Max Width [mm]	160.00	150.00
Max Displacement [mm]	15.65	18.19
Allowed Displacement	20.58	20.58
Utilization Max	+/- 60.00	+/- 63.80
Weight	343.98	295.63
Weight Reduction [%]	- 14.05	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

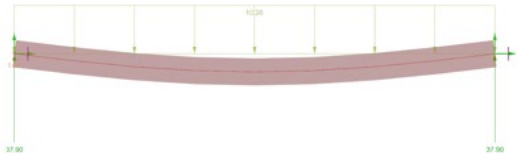
Configuration	A

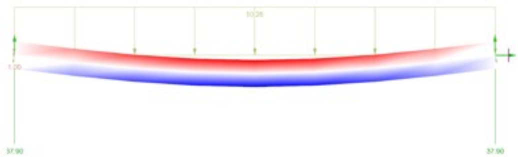


	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	21	12
- Max Height [mm]	394	394
- Max Width [mm]	241	140
Max Displacement [mm]	19.21	20.67
Allowed Displacement	20.58	20.58
Utilization Max	-81.80 / +81.80	-90.40 / +90.40
Weight	385.51	223.94
Weight Reduction [%]	- 41.91	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

Configuration	A

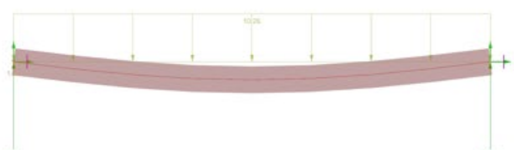


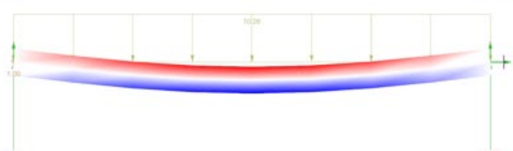


	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	26	21
- Max Height [mm]	394	394
- Max Width [mm]	343	241
Max Displacement [mm]	17.95	18.39
Allowed Displacement	20.58	20.58
Utilization Max	-75.20 / +72.50	-77.80 / +77.80
Weight	548.67	385.51
Weight Reduction [%]	- 29.74	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

Configuration	A

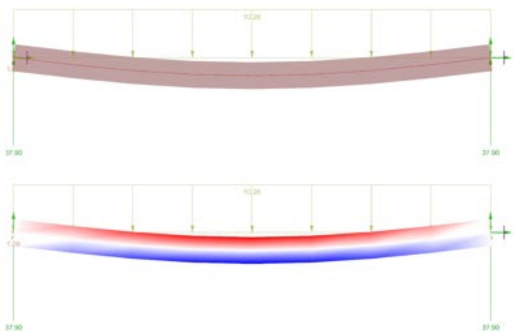




	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	27	24
- Max Height [mm]	394	394
- Max Width [mm]	343	292
Max Displacement [mm]	21.21	20.65
Allowed Displacement	20.58	20.58
Utilization Max	-88.80 / +88.80	-86.80 / +86.80
Weight	548.67	467.09
Weight Reduction [%]	- 14.87	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

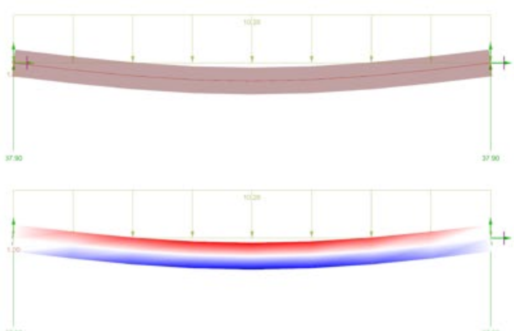
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	21	17
- Max Height [mm]	394	394
- Max Width [mm]	241	191
Max Displacement [mm]	19.51	19.03
Allowed Displacement	20.58	20.58
Utilization Max	-85.30 / +81.8	-84.80 / +84.80
Weight	385.51	305.53
Weight Reduction [%]	- 20.74	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

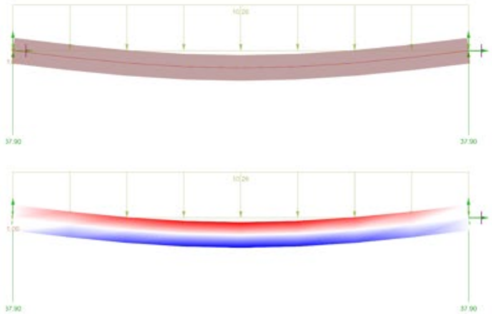
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	26	21
- Max Height [mm]	394	394
- Max Width [mm]	343	241
Max Displacement [mm]	17.95	18.39
Allowed Displacement	20.58	20.58
Utilization Max	-75.20 / +75.20	-77.80 / +77.80
Weight	548.68	385.51
Weight Reduction [%]	- 29.73	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	**4.84**	6.68	**3.49**	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

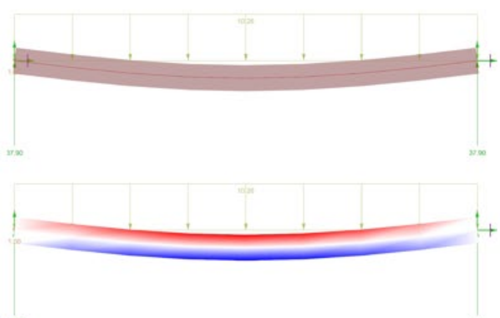
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	27	24
- Max Height [mm]	384	394
- Max Width [mm]	343	292
Max Displacement [mm]	21.21	20.65
Allowed Displacement	20.58	20.58
Utilization Max	-88.80 / +88.80	-86.80 / +86.80
Weight	548.67	467.09
Weight Reduction [%]	- 14.86	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

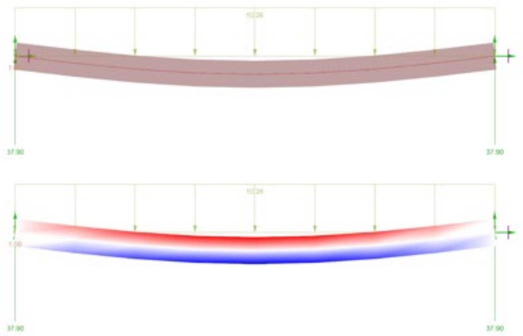
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	24	21
- Max Height [mm]	394	394
- Max Width [mm]	292	241
Max Displacement [mm]	20.37	20.24
Allowed Displacement	20.58	20.58
Utilization Max	-89.90 / +89.90	-90.70 / +90.70
Weight	467.10	385.51
Weight Reduction [%]	- 17.46	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	Governing Load SLS (kN/m^2)	Governing Load ULS (kN/m^2)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

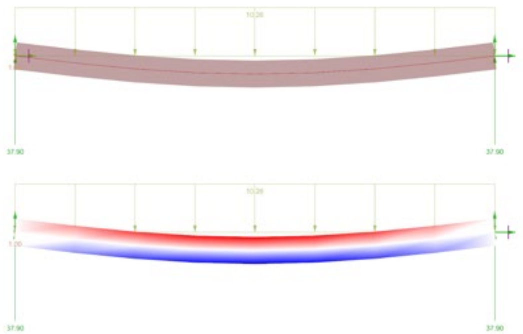
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	26	21
- Max Height [mm]	394	394
- Max Width [mm]	343	241
Max Displacement [mm]	17.95	20.24
Allowed Displacement	20.58	20.58
Utilization Max	-77.10 / +77.10	-90.70 / +90.70
Weight	548.67	385.51
Weight Reduction [%]	- 29.74	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

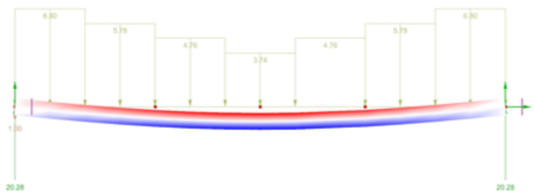
Configuration	A



	With WB + PVP	Without WB + PVP
Cs	SAWN L	SAWN L
- Type	27	24
- Max Height [mm]	384	394
- Max Width [mm]	343	292
Max Displacement [mm]	21.21	20.65
Allowed Displacement	20.58	20.58
Utilization Max	-88.80 / +88.80	-86.80 / +86.80
Weight	548.67	467.09
Weight Reduction [%]	- 14.86	

Comb.	With WB + PVP		Without WB + PVP		Weight Reduction (%)
	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	
A	3.66	5.13	2.31	3.31	- 36.88
B	4.84	6.68	3.49	4.86	- 27.89
C	5.79	7.96	4.79	6.61	- 17.27
D	3.72	5.36	2.87	4.22	- 22.84
E	4.84	6.68	3.49	4.86	- 27.89
F	5.79	7.96	4.79	6.61	- 17.27
G	4.72	6.86	3.87	5.72	- 18.00
H	4.84	6.86	3.87	5.72	- 20.04
I	5.79	7.96	4.79	6.61	- 17.27

9. Annex D – LOAD DISTRIBUTION HYPOTHESIS – CALCULATION RESULTS

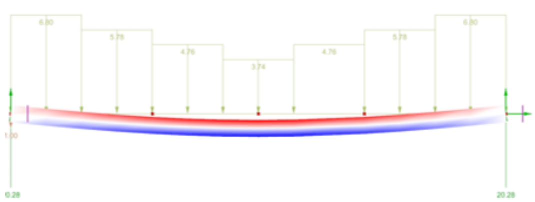


Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	240			
- Max Height [mm]	240.00			
- Max Width [mm]	120.00			
Max Displacement [mm]	20.81	20.59	20.53	20.40
Allowed Displacement	20.58			
Utilization Max (%)	+/- 50.70	+/- 58.30	+/- 58.00	+/- 56.70
Total Reaction Force (kN)	37.57	40.56	40.34	39.80
Weight Increment [%]	0	9.20	8.59	7.16

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

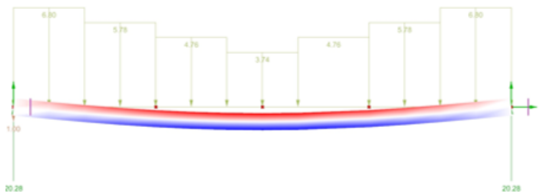


Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	270			
- Max Height [mm]	270.00			
- Max Width [mm]	135.00			
Max Displacement [mm]	20.61	20.51	20.53	20.60
Allowed Displacement	20.58			
Utilization Max (%)	+/- 56.90	+/- 63.50	+/- 63.60	+/- 62.60
Total Reaction Force (kN)	37.57	64.94	65.07	64.45
Weight Increment [%]	0	17.73	17.97	16.83

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

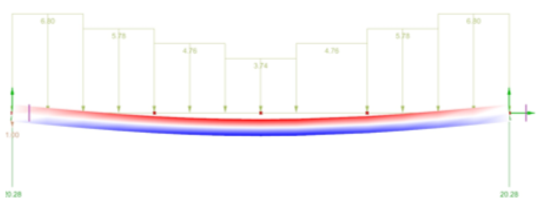


Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	300			
- Max Height [mm]	300.00			
- Max Width [mm]	150.00			
Max Displacement [mm]	19.64	20.61	20.61	20.52
Allowed Displacement	20.58			
Utilization Max (%)	+/- 59.90	+/- 69.40	+/- 69.40	+/- 68.00
Total Reaction Force (kN)	75.62	98.18	98.27	96.61
Weight Increment [%]	0	29.83	29.95	27.77

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

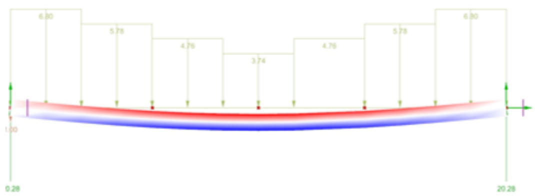


Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	270			
- Max Height [mm]	270.00			
- Max Width [mm]	135.00			
Max Displacement [mm]	20.61	20.55	20.58	20.41
Allowed Displacement	20.58			
Utilization Max (%)	+/- 49.10	+/- 65.90	+/- 65.80	+/- 64.30
Total Reaction Force (kN)	55.16	59.74	59.75	58.85
Weight Increment [%]	0	8.30	8.32	6.68

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

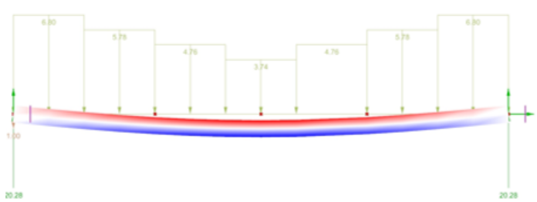


Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	270			
- Max Height [mm]	270.00			
- Max Width [mm]	135.00			
Max Displacement [mm]	20.81	20.55	20.41	20.41
Allowed Displacement	20.58			
Utilization Max (%)	+/- 50.70	+/- 65.90	+/- 65.80	+/- 64.30
Total Reaction Force (kN)	37.57	59.74	59.75	59.84
Weight Increment [%]	0	8.30	8.32	6.68

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

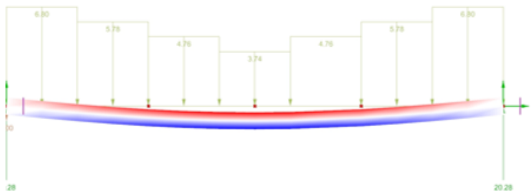


Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	300			
- Max Height [mm]	300.00			
- Max Width [mm]	150.00			
Max Displacement [mm]	19.64	20.56	20.60	20.58
Allowed Displacement	20.58			
Utilization Max (%)	+/- 59.10	+/- 71.20	+/- 71.10	+/- 69.90
Total Reaction Force (kN)	75.62	92.98	92.95	91.95
Weight Increment [%]	0	22.96	22.92	21.60

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

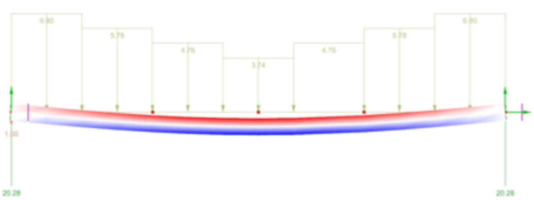


Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	300			
- Max Height [mm]	300.00			
- Max Width [mm]	150.00			
Max Displacement [mm]	19.65	20.59	20.59	20.63
Allowed Displacement	20.58			
Utilization Max (%)	+/- 51.50	+/- 73.00	+/- 72.80	+/- 71.80
Total Reaction Force (kN)	75.62	87.78	87.63	87.28
Weight Increment [%]	0	16.08	15.88	15.43

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

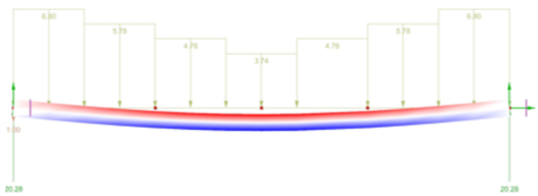


Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	300			
- Max Height [mm]	300.00			
- Max Width [mm]	150.00			
Max Displacement [mm]	19.64	20.59	20.59	20.63
Allowed Displacement	20.58			
Utilization Max (%)	+/- 51.50	+/- 73.00	+/- 72.80	+/- 71.80
Total Reaction Force (kN)	75.62	87.78	87.63	87.28
Weight Increment [%]	0	16.08	15.89	15.43

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43



Subdivisión in 7 - Utilization

	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Segment Length (m)	7.00	1	1.4	2.33

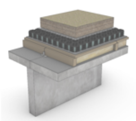
	Uniform Load	Sub. - 7	Sub. - 5	Sub. - 3
Cs	IPE			
- Type	330			
- Max Height [mm]	330.00			
- Max Width [mm]	150.00			
Max Displacement [mm]	19.64	20.59	20.59	20.63
Allowed Displacement	20.58			
Utilization Max (%)	+/- 59.90	+/- 73.00	+/- 72.80	+/- 71.80
Total Reaction Force (kN)	75.62	87.78	87.62	87.28
Weight Increment [%]	0	16.08	15.88	15.43

Comb.	Governing Load SLS (kN/m²)	Governing Load ULS (kN/m²)	Load Increase			
			Minimum (Functional)	Partition in 7 (Variable)	Partition in 5 (Variable)	Partition in 3 (Variable)
A	2.31	3.31	Maintenance 1.87 kN/m2	+ 9.20	+ 8.59	+ 7.16
B	3.49	4.86	Maintenance 1.87 kN/m2	+ 17.73	+ 17.97	+ 16.83
C	4.79	6.61	Maintenance 1.87 kN/m2	+ 29.83	+ 29.95	+ 27.77
D	2.87	4.22	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
E	3.49	4.86	Private 2.87 kN/m2	+ 8.30	+ 8.32	+ 6.68
F	4.79	6.61	Private 2.87 kN/m2	+ 22.92	+ 22.92	+ 21.60
G	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
H	3.87	5.72	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43
I	4.79	6.61	Public 3.87 kN/m2	+ 16.08	+ 15.89	+ 15.43

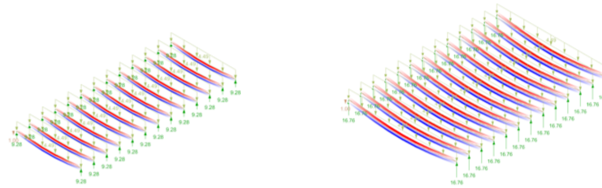
9.1. ANNEX E – DESIGN COMPARISON – CALCULATION RESULTS

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientati on
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System



Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Full Load

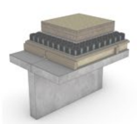
Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

Aluminum	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	203	0.39	116.06	13	34.44	383	Y	Y
Longest Spann	355	0.60	148.37	13	455	535	Y	Y

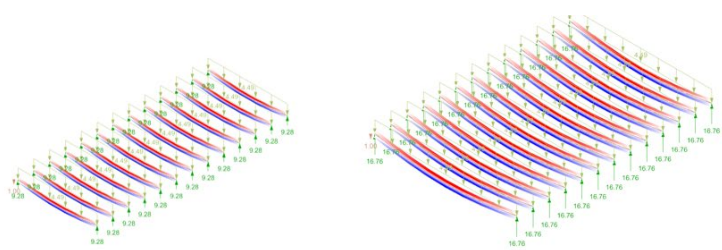
4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.40	11	203	0.45	11	228	0.48	11	254	0.50	11	304	A
+32.8		-32.8	+36.3		-36.3	+38.6		38.6-	+38.3		-38.3	Utilization
0.41	11	203	0.45	11	254	0.51	11	304	0.56	13	304	B
+42.4		-42.5	+40.9		-40.9	+35.6		-35.6	+35.7		-35.7	Utilization
0.39	13	203	0.44	13	254	0.51	13	304	0.60	13	355	C
+40.8		-40.8	+39.3		-39.3	+34.2		-34.2	+32.1		-32.1	Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientati on
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System



Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Full Load

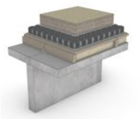
Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

GFRP	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	200	0.52	207.41	13	68.35	420	Y	Y
Longest Spann	300	0.60	232.06	13	158.95	480	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.40	13	150	0.51	11	200	0.52	13	200	0.59	11	300	A
+7.3		-7.3	+5.8		-5.8	+6.6		-6.6	+5.4		-5.4	Utilization
0.51	11	200	0.51	11	200	0.58	11	300	0.59	11	300	B
+4.6		-4.6	+7.4		-7.4	+5.0		-5.0	+7.0		-7.0	Utilization
0.52	13	200	0.52	13	200	0.61	13	300	0.60	13	300	C
+4.4		-4.4	+7.1		-7.1	+4.8		-4.8	+6.7		-6.7	Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

Support A

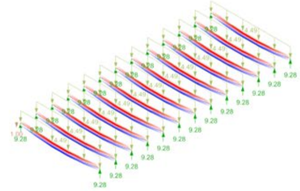
Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

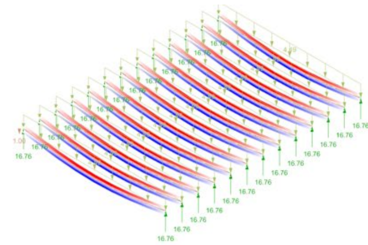
Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Full Load

Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5



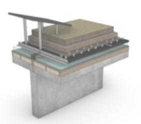


Steel	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	160	0.50	86.01	13	63.11	340	Y	Y
Longest Spann	240	0.73	100.27	13	214.84	420	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.46	11	140	0.50	13	160	0.58	11	200	0.63	11	220	A
+25.7		-25.7	+24.5		-24.5	+24.1		-24.1	+26.1		-26.1	Utilization
0.46	13	140	0.54	11	180	0.60	13	200	0.69	11	240	B
+27.0		-27.0	+28.9		-28.9	+25.3		-25.3	+26.2		-26.2	Utilization
0.50	13	160	0.55	13	180	0.66	13	220	0.73	13	240	C
+22.9		-22.9	+27.8		-27.8	+23.2		-23.2	+25.3		-25.2	Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

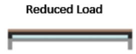
Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load



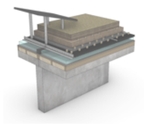
Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

Aluminum	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	228	0.46	104.79	9	46.66	280	Y	Y
Longest Spann	355	0.57	122.20	9	156.69	280	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.55	7	203	0.61	7	228	0.54	7	254	0.56	7	304	A
+34.7		-34.7	+38.3		-38.3	+37.3		-37.3	+37.1		-37.1	Utilization
0.42	8	203	0.45	8	254	0.49	8	304	0.49	9	304	B
+42.5		-42.5	+40.9		-40.9	35.6+		-35.6	+37.9		-37.9	Utilization
0.46	9	228	0.49	9	254	0.51	9	304	0.57	9	355	C
+33.6		-33.6	+41.2		-41.2	+41.1		-41.1	+38.8		-38.8	Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load

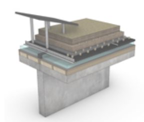
Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

GFRP	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	200	0.52	184.45	9	68.35	280	Y	Y
Longest Spann	300	0.57	194.72	11	158.95	275	Y	Y

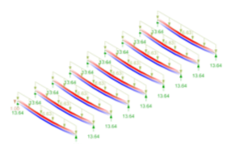
4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.43	9	150	0.57	7	200	0.63	8	300	0.67	6	300	A
+7.1		-7.1	+5.6		-5.6	+3.6		-3.6	+6.2		-6.2	Utilization
0.50	8	200	0.46	9	200	0.55	8	300	0.52	9	300	B
+4.6		-4.6	+6.4		-6.4	+5.0		-5.0	+6.0		-6.0	Utilization
0.52	9	200	0.57	9	300	0.57	9	300	0.57	11	300	C
+5.3		-5.3	+4.1		-4.1	+5.8		-5.8	+6.9		-6.9	Utilization

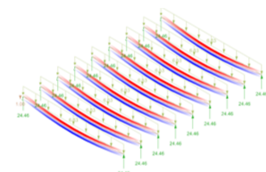
Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



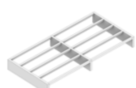
Uni Directional System





Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X



Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load

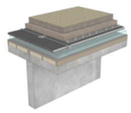
Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

Steel	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	160	0.66	90.31	8	63.11	280	Y	Y
Longest Spann	240	0.67	69.84	11	214.84	275	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.53	7	140	0.57	8	160	0.53	9	180	0.67	8	220	A
+24.9		-24.9	+27.7		-27.7	+25.1		-25.1	+24.1		-24.1	Utilization
0.64	7	160	0.69	7	200	0..58	8	220	0.62	8	240	B
+27.5		-27.5	+25.3		-25.3	+24.1		-24.1	+26.2		-26.2	Utilization
0.66	8	160	0.57	9	200	0.61	9	220	0.67	11	240	C
+32.6		-32.6	+25.5		-25.5	+27.9		-27.9	+25.9		-25.9	Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load

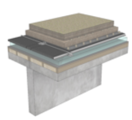
Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

Aluminum	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	304 203	0.48	102.03	4 15	65.74 27.55	275	Y	Y
Longest Spann	355 101	0.60	126.73	9 48	156.69 3.66	280	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.47	4 - 15	254 – 152	0.48	4 - 15	304 – 152	0.60	4 - 15	355 - 177	0.55	4 - 18	355 – 228	A
+35.9		-35.9	+36.5		-36.5	+40.0		-40.0	+59.1		-59.1	Utilization
0.45	4 - 12	304 – 203	0.48	4 – 15	355 – 203	0.55	4 - 15	355 – 228	0.55	6 - 30	355 – 152	B
+33.4		-33.4	+37.1		-37.1	+56.2		-56.2	+43.6		-43.6	Utilization
0.48	4 - 15	304 - 203	0.57	4 - 15	355 – 228	0.55	6 - 30	355 – 127	0.60	9 - 48	355 – 101	C
+44.8		-44.8	+50.2		-50.2	+42.6		-42.6	+42.4		-42.4	Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load

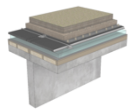
Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

GFRP	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	300 200	0.63	218.55	4 12	90.83 54.68	280	Y	Y
Longest Spann	500 150	0.58	193.07	6 40	182.57 15.46	275	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.54	4 - 15	200 – 150	0.63	4 - 15	300 - 200	0.69	4 - 15	300 - 200	0.68	4 - 15	500 - 200	A
+7.0		-7.0	+5.6		-5.6	+7.8		-7.8	+8.1		-8.1	Utilization
0.65	4 - 12	300 - 200	0.58	4 - 15	300 – 200	0.59	4 - 18	500 – 200	0.51	5 - 24	500 – 150	B
+4.8		-4.8	+7.9		-7.9	+6.8		-6.8	+8.3		-8.3	Utilization
0.63	4 - 12	300 – 200	0.61	4 - 21	500 – 200	0.50	5 - 32	500 – 150	0.58	6 - 40	500 – 150	C
+6.4		-6.4	+7.1		-7.1	+7.8		-7.8	+8.2		-8.2	Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

Support A

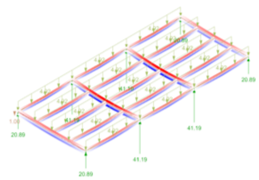
Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

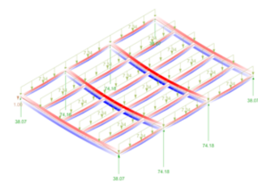
Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load

Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5



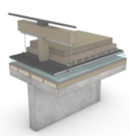


Steel	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	220 160	0.63	72.87	4 16	104.87 50.48	280	Y	Y
Longest Spann	360 180	0.78	82.16	4 18	399.46 60.03	280	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.57	4 - 12	180 – 140	0.66	4 - 12	220 – 140	0.71	4 - 15	240 – 160	0.66	4 - 18	300 – 140	A
+27.5	-27.5		+28.1	-28.1		+29.2	-29.2		+27.3	-27.3		Utilization
0.59	4 – 9	220 - 160	0.62	4 - 12	240 – 160	0.68	4 - 15	300 – 160	0.68	4 - 18	300 – 160	B
+30.3	-30.3		+30.6	-30.6		+26.0	-26.0		+32.3	-32.3		Utilization
0.63	4 - 12	220 - 160	0.68	4 - 15	270 – 160	0.71	4 - 18	300 – 160	0.78	4 - 18	360 – 180	C
+30.5	-30.5		+29.9	-29.9		+31.4	-31.4		+32.1	-32.1		Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load

Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
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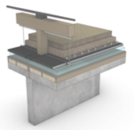
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

Aluminum	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	304 203	0.48	102.03	4 15 + 20	65.74 27.55	275	Y	Y
Longest Spann	355 101	0.60	126.73	9 48 + 54	156.69 3.66	280	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.47	4 - 15	254 – 152	0.48	4 - 15	304 – 152	0.60	4 - 15	355 - 177	0.55	4 - 18	355 – 228	A
+35.9	-35.9		+36.5	-36.5		+40.0	-40.0		+59.1	-59.1		Utilization
0.45	4 - 12	304 – 203	0.48	4 – 15	355 – 203	0.55	4 - 15	355 – 228	0.55	6 - 30	355 – 152	B
+33.4	-33.4		+37.1	-37.1		+56.2	-56.2		+43.6	-43.6		Utilization
0.48	4 - 15	304 - 203	0.57	4 - 15	355 – 228	0.55	6 - 30	355 – 127	0.60	9 - 48	355 – 101	C
+44.8	-44.8		+50.2	-50.2		+42.6	-42.6		+42.4	-42.4		Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

Support A

Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load

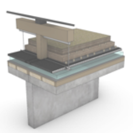
Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5

GFRP	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	300 200	0.63	218.55	4 12 + 16	90.83 54.68	280	Y	Y
Longest Spann	500 150	0.58	193.07	6 40 + 48	182.57 15.46	275	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.54	4 - 15	200 – 150	0.63	4 - 15	300 - 200	0.69	4 - 15	300 - 200	0.68	4 - 15	500 - 200	A
+7.0		-7.0	+5.6		-5.6	+7.8		-7.8	+8.1		-8.1	Utilization
0.65	4 - 12	300 - 200	0.58	4 - 15	300 – 200	0.59	4 - 18	500 – 200	0.51	5 - 24	500 – 150	B
+4.8		-4.8	+7.9		-7.9	+6.8		-6.8	+8.3		-8.3	Utilization
0.63	4 - 12	300 – 200	0.61	4 - 21	500 – 200	0.50	5 - 32	500 – 150	0.58	6 - 40	500 – 150	C
+6.4		-6.4	+7.1		-7.1	+7.8		-7.8	+8.2		-8.2	Utilization

Loads

Uniform Line Load = (Q1 x Qa x Qb)/a		
Load	[kN/m]	Orientation
Gravity	0.98 [N]	Z-Global
Self Weight	Automatic (Assigned CS)	Z-Global
Imposed Load	According to Table	Z-Global



Uni Directional System

Support A

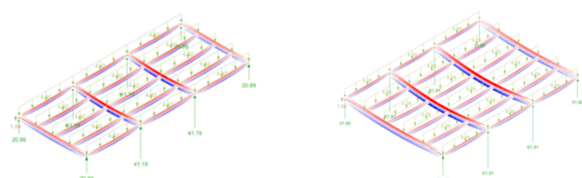
Tx	Ty	Tz	Rx	Ry	Rz
X	X	X	X		X

Support B

Tx	Ty	Tz	Rx	Ry	Rz
	X	X	X		X

Reduced Load

Material Properties	Youngs Modulus [N/mm2]	In Plane Shear Modulus [N/mm2]	Trans. Shear Modulus [N/mm2]	Specific Weight [kN/m3]	Yield Strength [N/mm2]
Sawn Wood	1050	434	434	5.80	1.30
Glulam	1300	434	434	6.22	1.2
Aluminum	7070	2727	2727	26.50	11
GFRP	4000	1340	1340	19.6	35
Steel	21000	8076	8076	76.98	35.5



Steel	Quantitative						Qualitative	
	Cross Section Height [mm]	Wight [kg/m2]	Price [€/m2]	N of Pieces [units]	Weight of Pieces [kg]	Compactness [mm]	Access to Layers [Y/N]	Adaptability [Y/N]
Shortest Spann	220 160	0.63	72.87	4 16 + 24	104.87 50.48	280	Y	Y
Longest Spann	360 180	0.78	82.16	4 18 +24	399.46 60.03	280	Y	Y

4			5			6			7			Load
Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	Weight [kN/m2]	N of Beams	CS Height [mm]	
0.57	4 - 12	180 – 140	0.66	4 - 12	220 – 140	0.71	4 - 15	240 – 160	0.66	4 - 18	300 – 140	A
+27.5		-27.5	+28.1		-28.1	+29.2		-29.2	+27.3		-27.3	Utilization
0.59	4 – 9	220 - 160	0.62	4 - 12	240 – 160	0.68	4 - 15	300 – 160	0.68	4 - 18	300 – 160	B
+30.3		-30.3	+30.6		-30.6	+26.0		-26.0	+32.3		-32.3	Utilization
0.63	4 - 12	220 - 160	0.68	4 - 15	270 – 160	0.71	4 - 18	300 – 160	0.78	4 - 18	360 – 180	C
+30.5		-30.5	+29.9		-29.9	+31.4		-31.4	+32.1		-32.1	Utilization

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