Roof External Structural Reinforcement Strategy

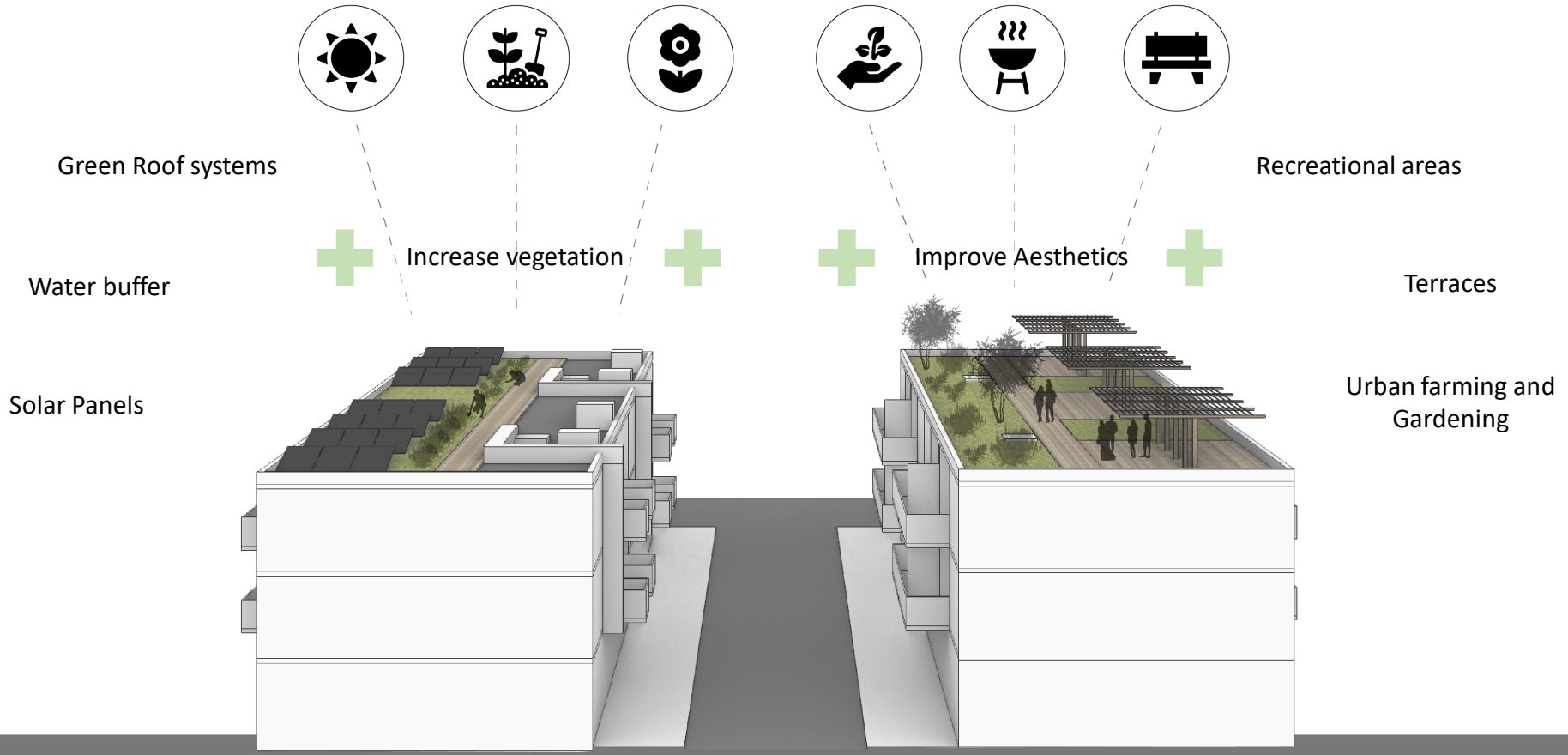
For the Implementation of Multifunctional Roof Interventions on Post-War Typologies

Final Presentation - Vicente Blanes Carpio – SN:5102219

26 10 2021

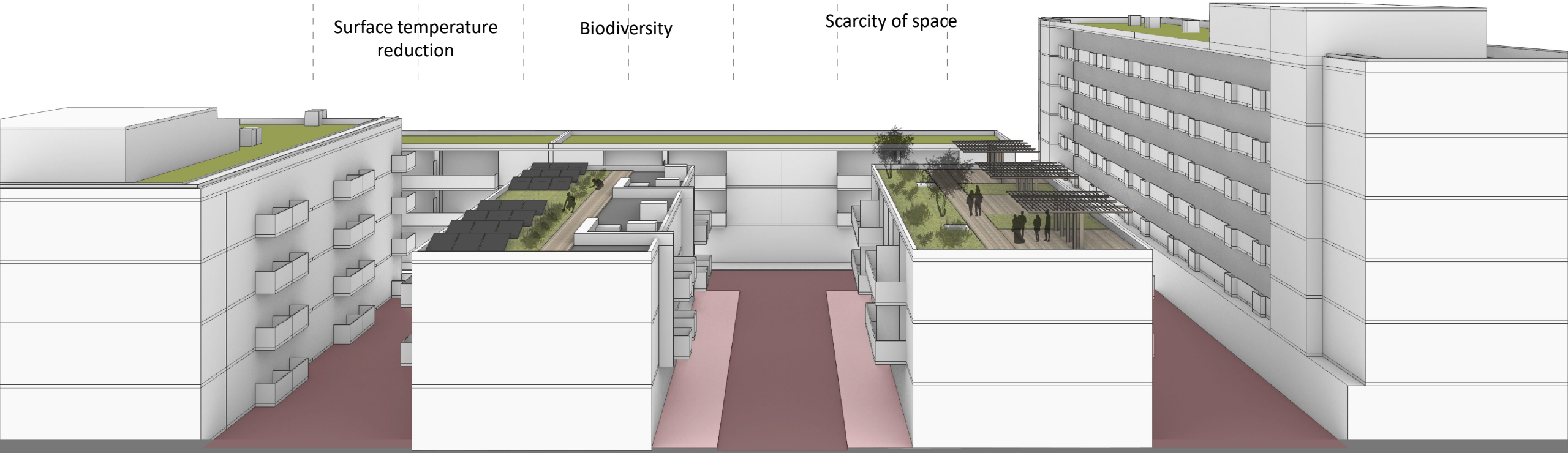
Multifunctional roof interventions

Different functions for private and public use



Urban Environmental Benefits

Up to **40%** of horizontal space in urban areas



"Rotterdam Roofscape Development Program"

Incentives for multifunctional interventions
- Subsidies
- Reduction of levies

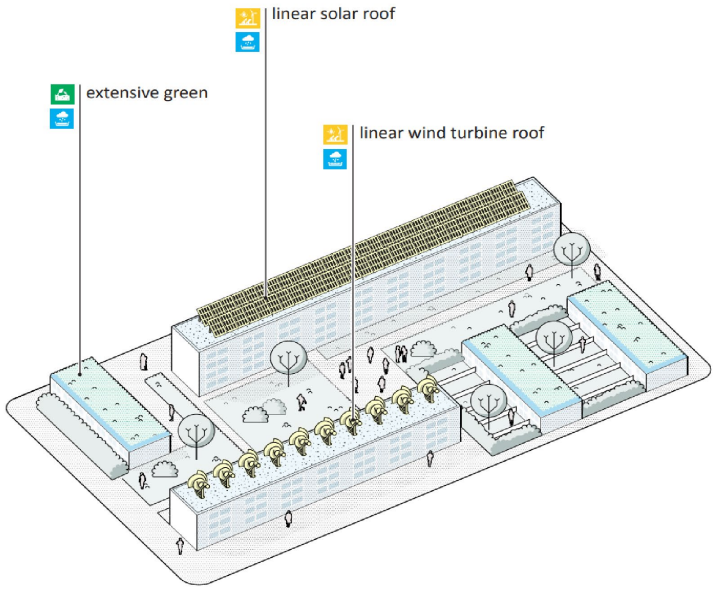
Objective:
Cover 1km^2 of roofs by 2030

Green roofs Vegetative roofs
Blue roofs Rainwater buffer
Yellow roofs Renewable energies
Red roofs Social Functions
Orange roofs Mobility
Purple roofs Residential areas
Gray roofs Infrastructure

Gold roofs Combination of colors

Post-War Buildings in Rotterdam

18.5 km^2 of concrete flat roof constructions



Green roofs Vegetative roofs
Blue roofs Rainwater buffer
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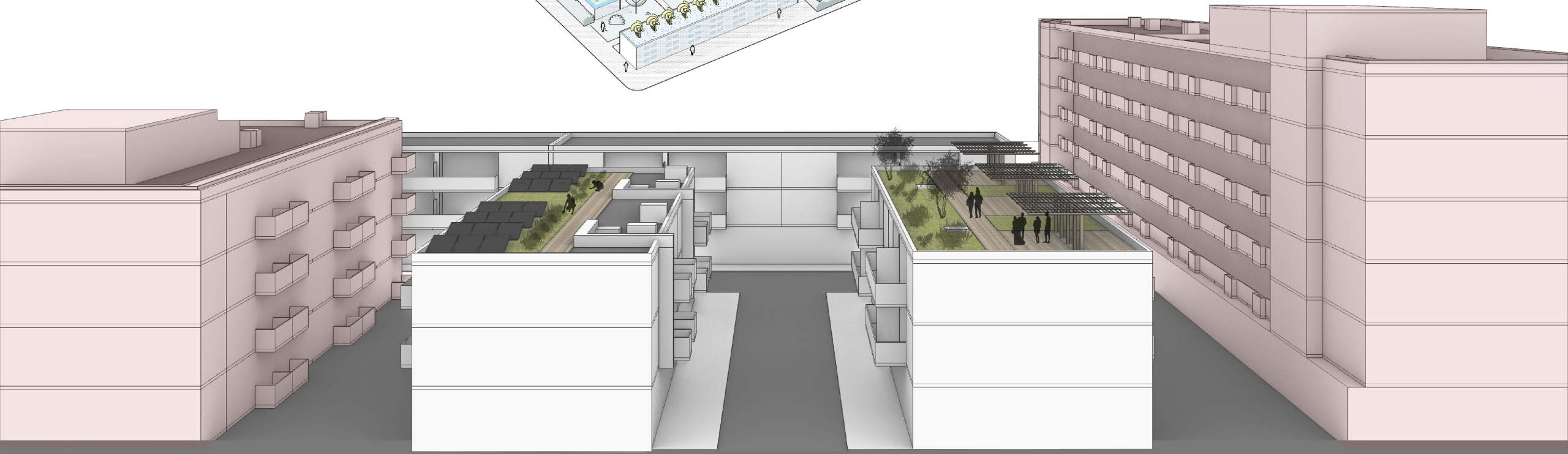


Progress in research and innovation

Large areas of green roof interventions

Measure and evaluation of their effects for the urban environment

Main Holdback: **Economic investment**

- High cost of implementation
- Increased demand of maintenance
- Risk of failure due to water leakages

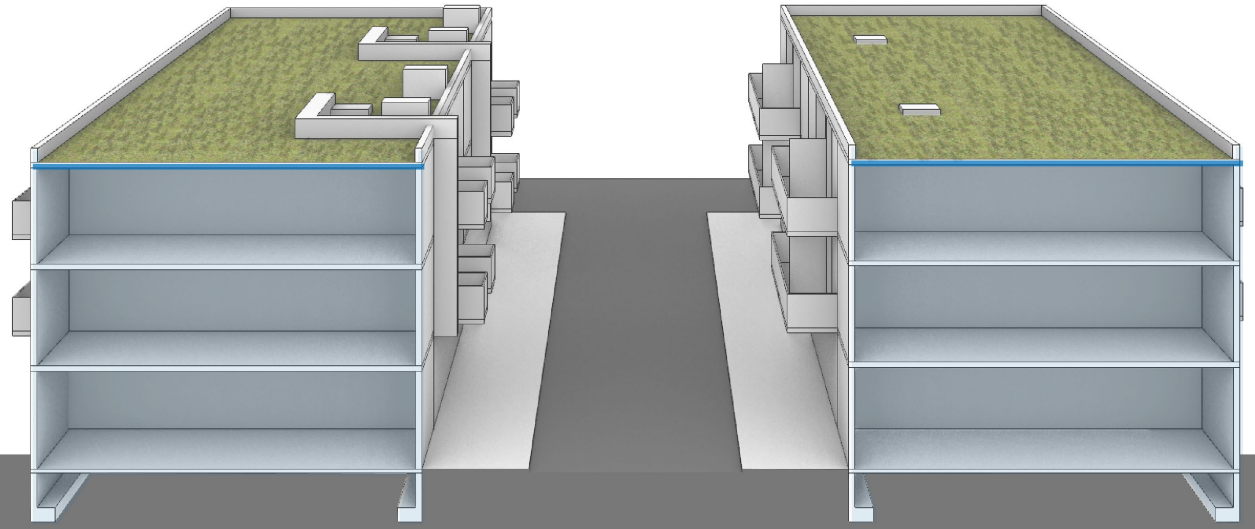
Insufficient Roof Structural Capacity

Vertical structure suitable for higher loads

Reinforcement of roof structure
- Up to **200** Euros/m^2
- **80%** of the intervention cost

Non-Regret Solutions

- Alternative retrofitting strategies of lower weights
- Won't provide the advantages that multifunctional interventions
- Waste the potential capacity of these buildings



“ How to enable and potentiate the implementation of Multifunctional Roofs on Rotterdam Post-War Concrete Structural Typologies with Insufficient Loadbearing Capacity?”

Propose an alternative reinforcement system for the implementation of multifunctional roofs on Post-War buildings in Rotterdam

System Scale

Green roof interventions
Multifunctional interventions

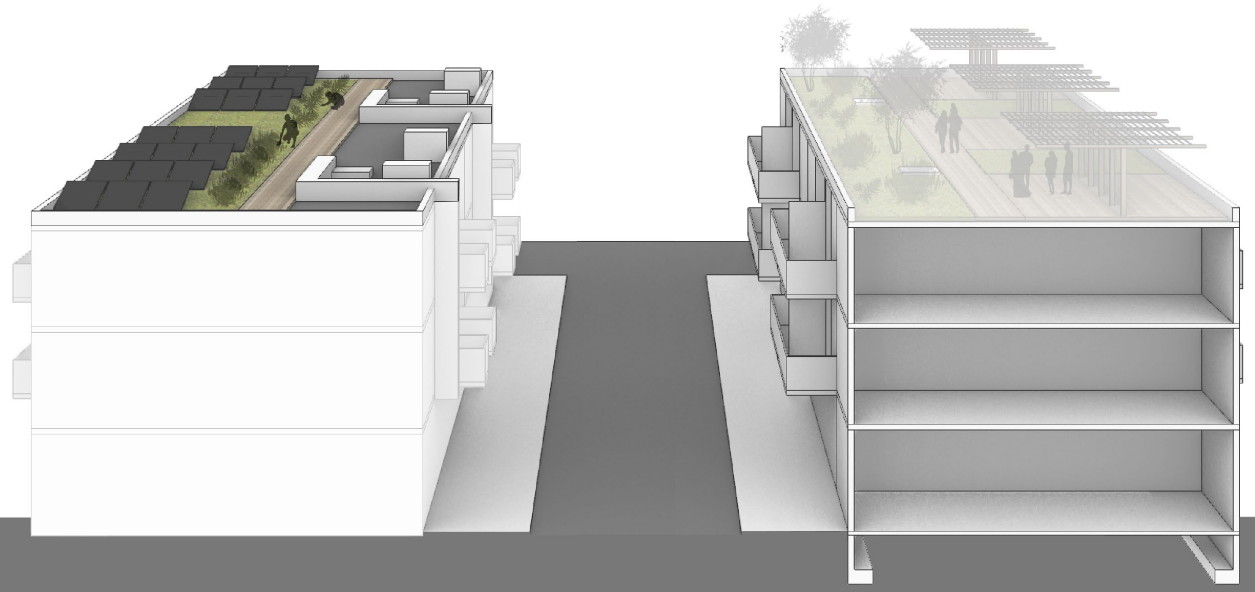
Design stage

Design Premises and Strategies
Exploration of reinforcement solutions

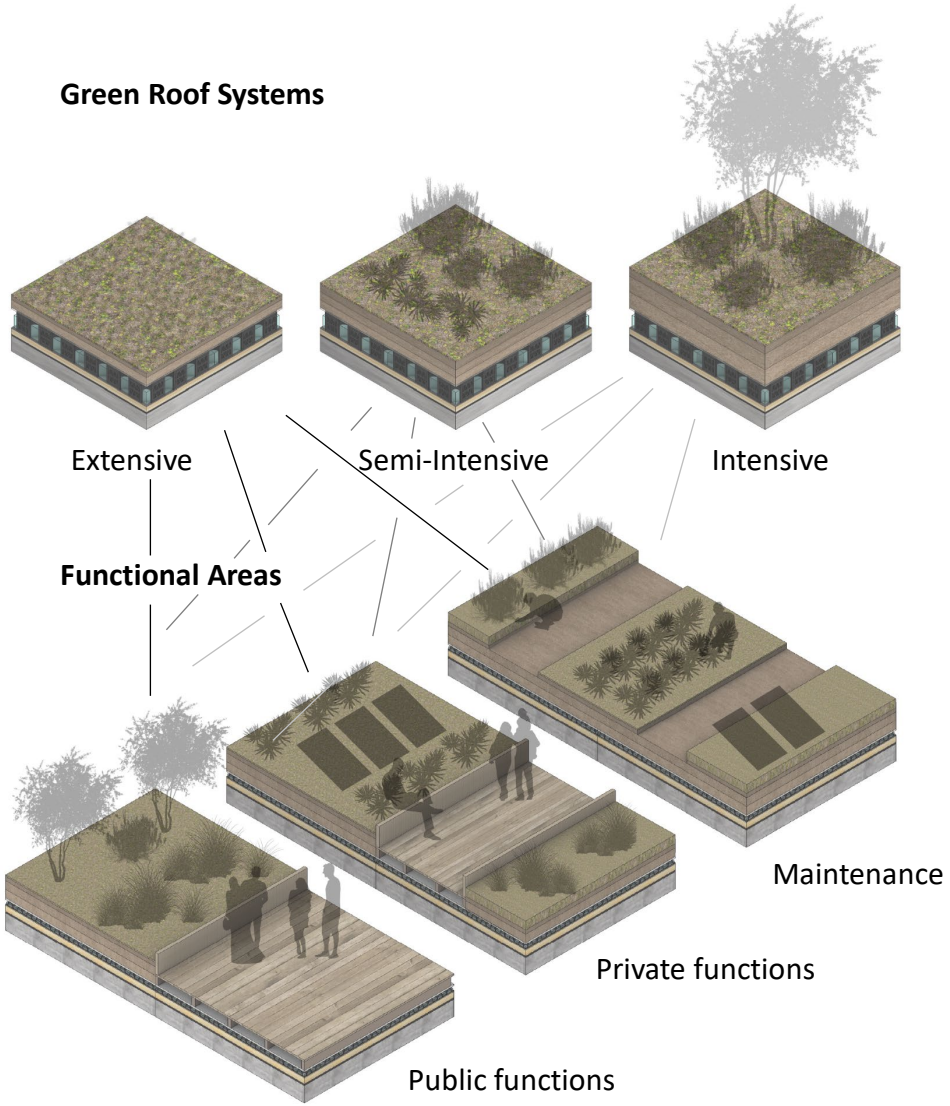
Development of the selected Strategy

Building Scale

Analysis of post-war constructions
Structural systems
Construction typologies



System Scale



- Variety of plant species
- Maximum retention of rainwater
- Increase of insulation
- Implementation of solar panels
- Accessible functional spaces

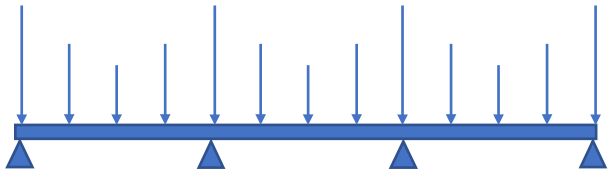
9 Load Combinations

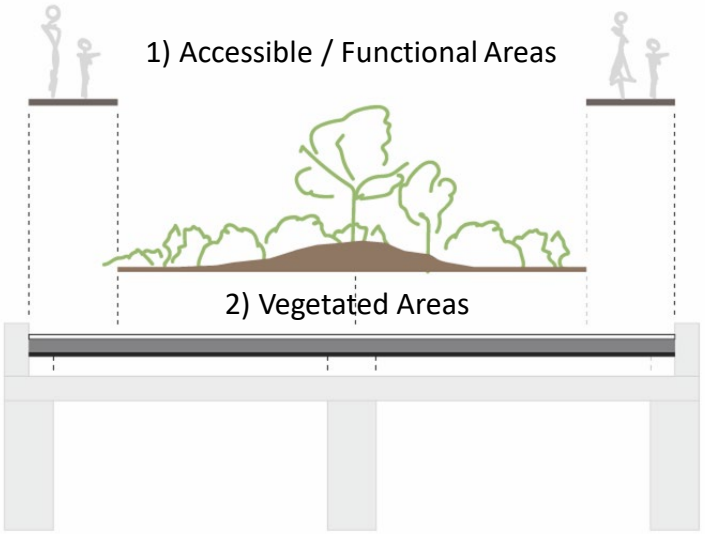
Load Combinations	Maintenance		Private Functions		Public Functions	
Extensive	3.66	2.72	3.66	3.72	3.66	4.72
Semi-Intensive	**4.84**	**2.72**	**4.84**	**3.72**	**4.84**	**4.72**
Intensive	5.79	**2.72**	5.79	3.72	5.79	4.72

Weight Distribution

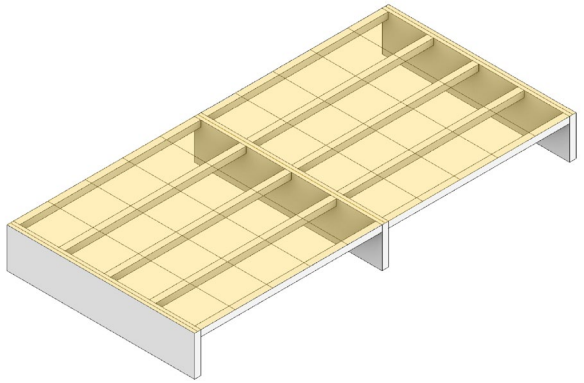
Heavier loads close to loadbearing structure

Based on rules of thumb

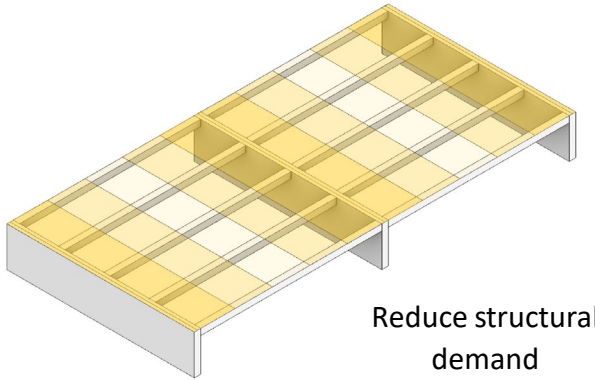




Design Aid Tool



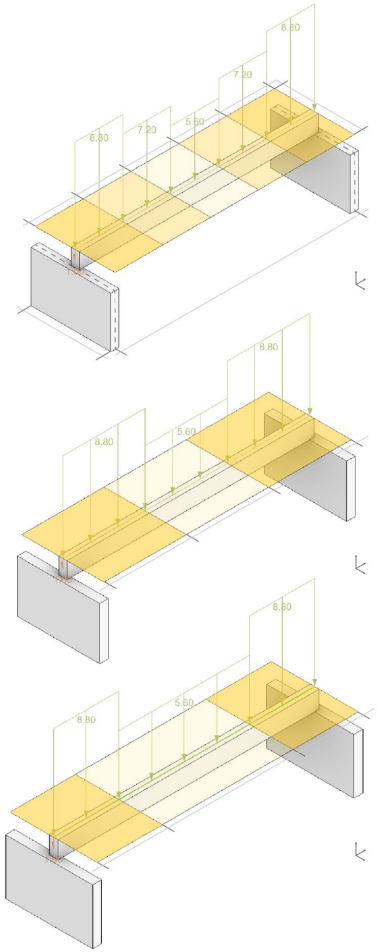
Optimal Load Distribution



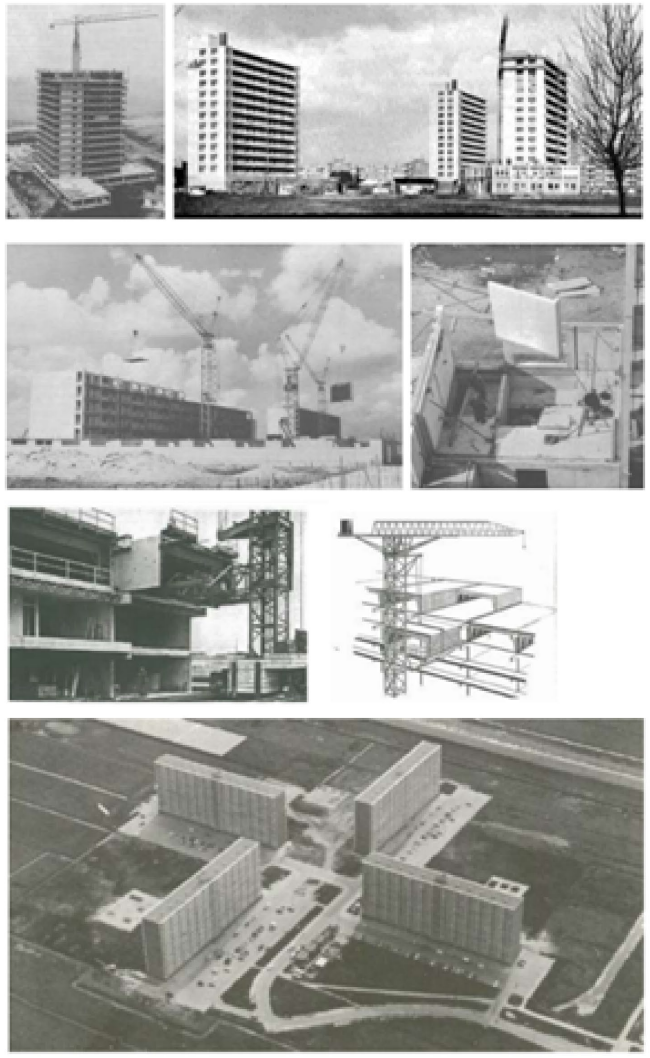
Reduce structural demand

Analyze the effect on the weight

Application of higher loads



Building Scale



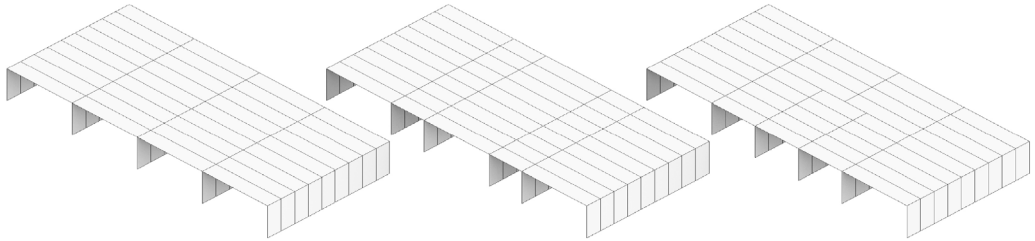
Post-war constructed systems implemented on the city of Rotterdam

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**					
Structural System	Loadbearing wall configurations					

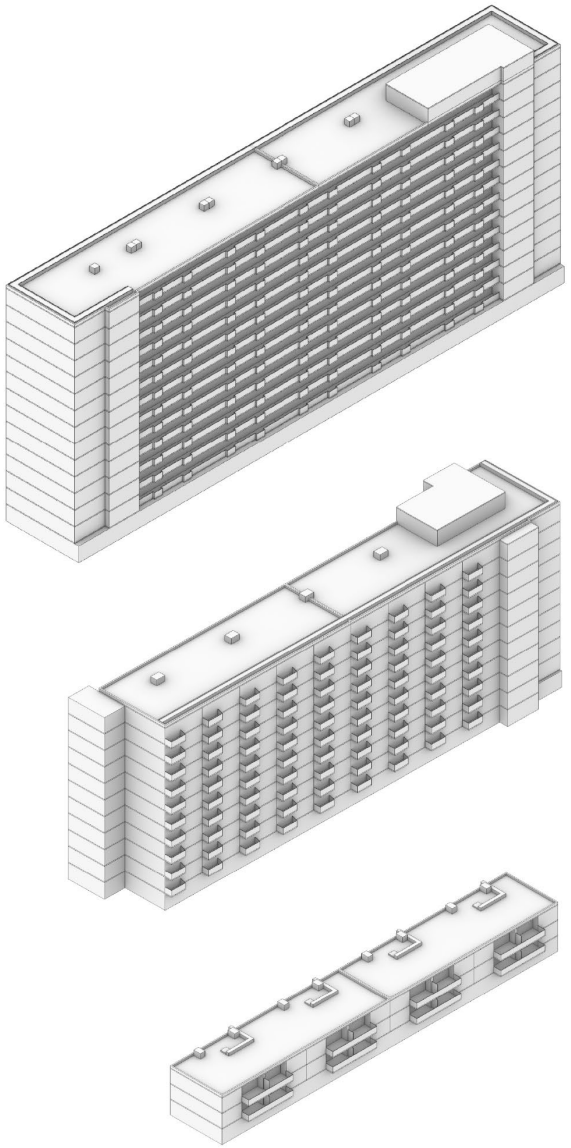
Prefab Concrete

Casted Concrete

Concrete Masonry

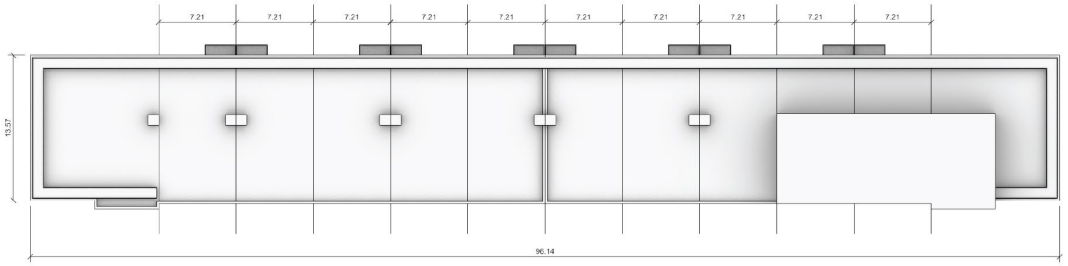


Porch Flats [%]	24.0	45.0 – 55.0	62.0	53.0	-	0.0
Gallery Flats [%]	55.0	55.0 – 45.0	4.0	46.0	-	100.0



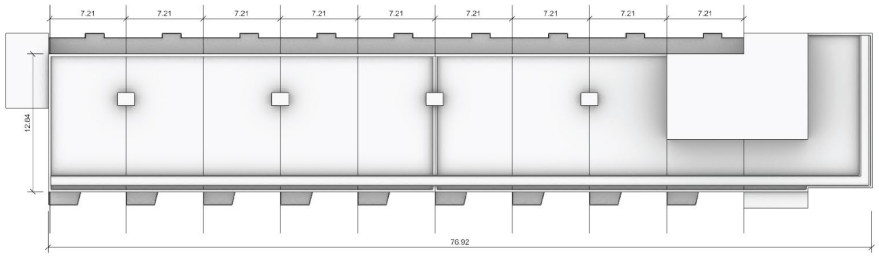
Building Block III

- Gallery Building
- 14 Stories
- 1335.85 m^2



Building Block VII

- Gallery Building
- 10 Stories
- 1018.33 m^2



Building Block IV

- Porch-Flat Building
- 3 Stories
- 786.72 m^2

Concrete Reinforcement Process

Understand const-increasing factors

1) Structural Analysis

- Visual Assessment
- Non-Destructive Testing
- Destructive Testing

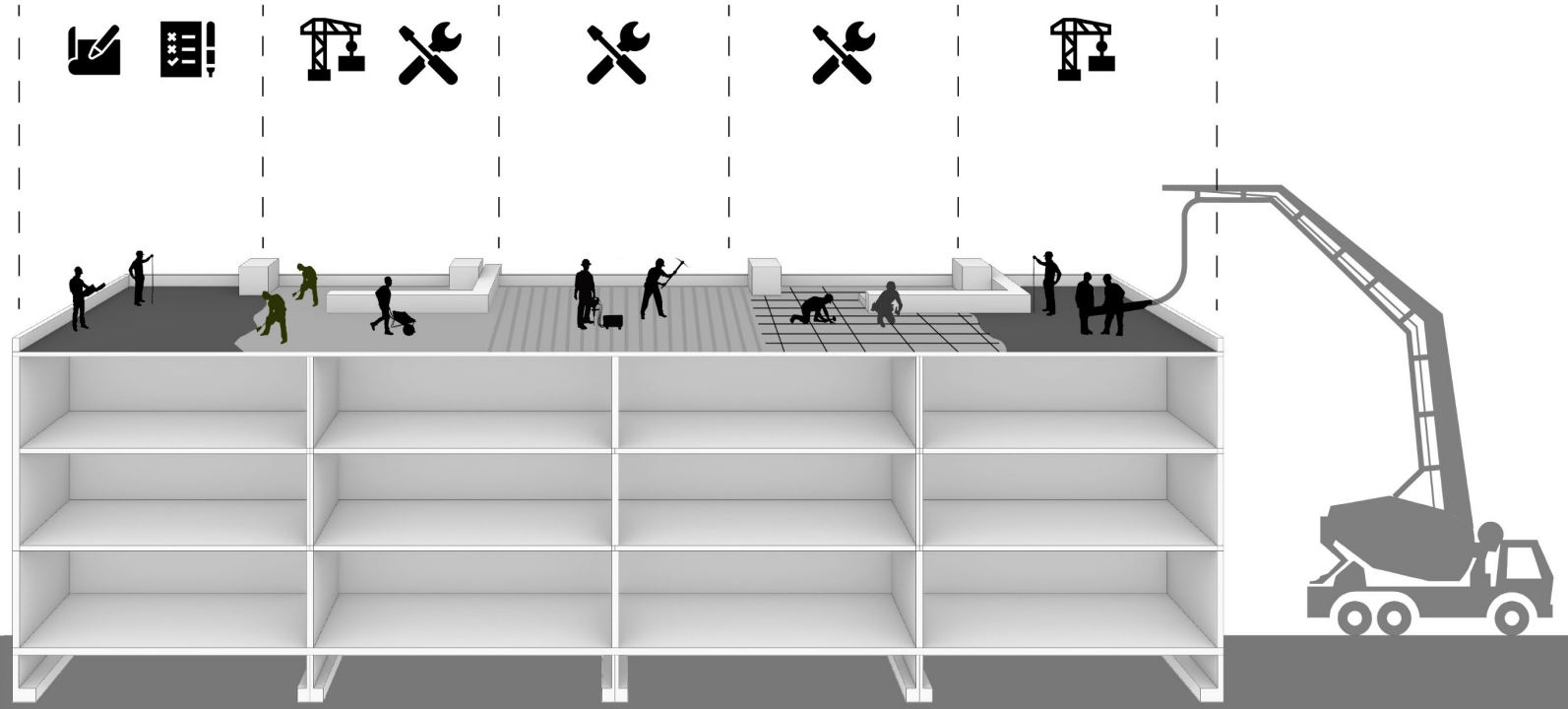
2) Structural Intervention

- Removal of Roof Finishes
- Removal of Waterproof Layer
- Grinding Surface to provide a cohesive join with new layers
- Steel Structural Reinforcement Grid
- Pouring Concrete Reinforcement Layer

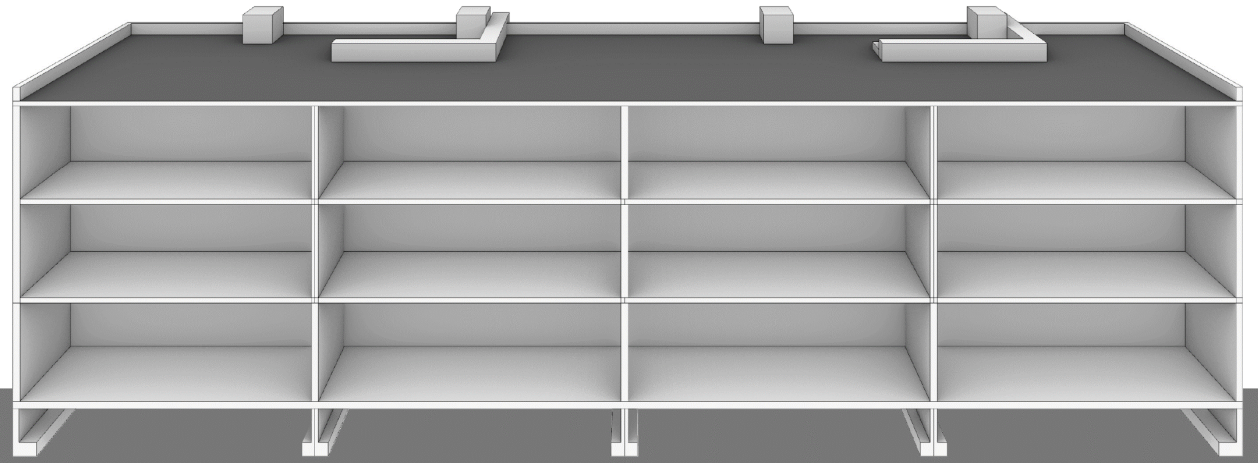
1) Analysis to determine the structure capacity

2) Intensive and Invasive intervention on the structure

- Heavy machinery
- High workload



Building Scale Strategies



Foundation residual Capacity

Maximum load to be added

10% of Building weight

1) Design for the worst-case scenario

Assume the buildings capacity based on the safety parameters

Intensive Structural Analysis

Visual Assessment

Non-Destructive Testing

Destructive Testing

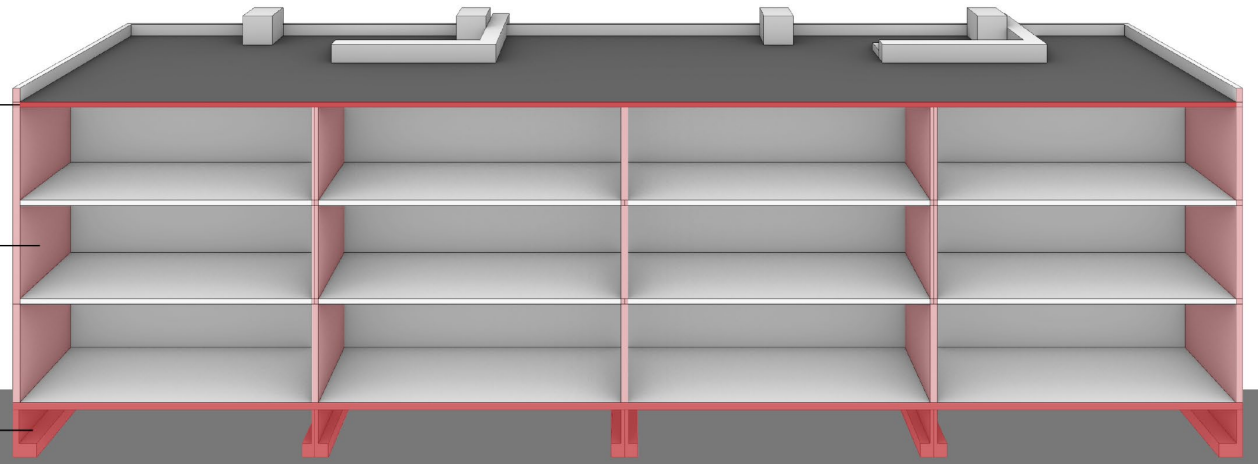
Wall loadbearing capacity

Maximum capacity – Worst case scenario

Masonry Construction systems

Roof Residual Capacity

Minimum capacity designed by the Norm

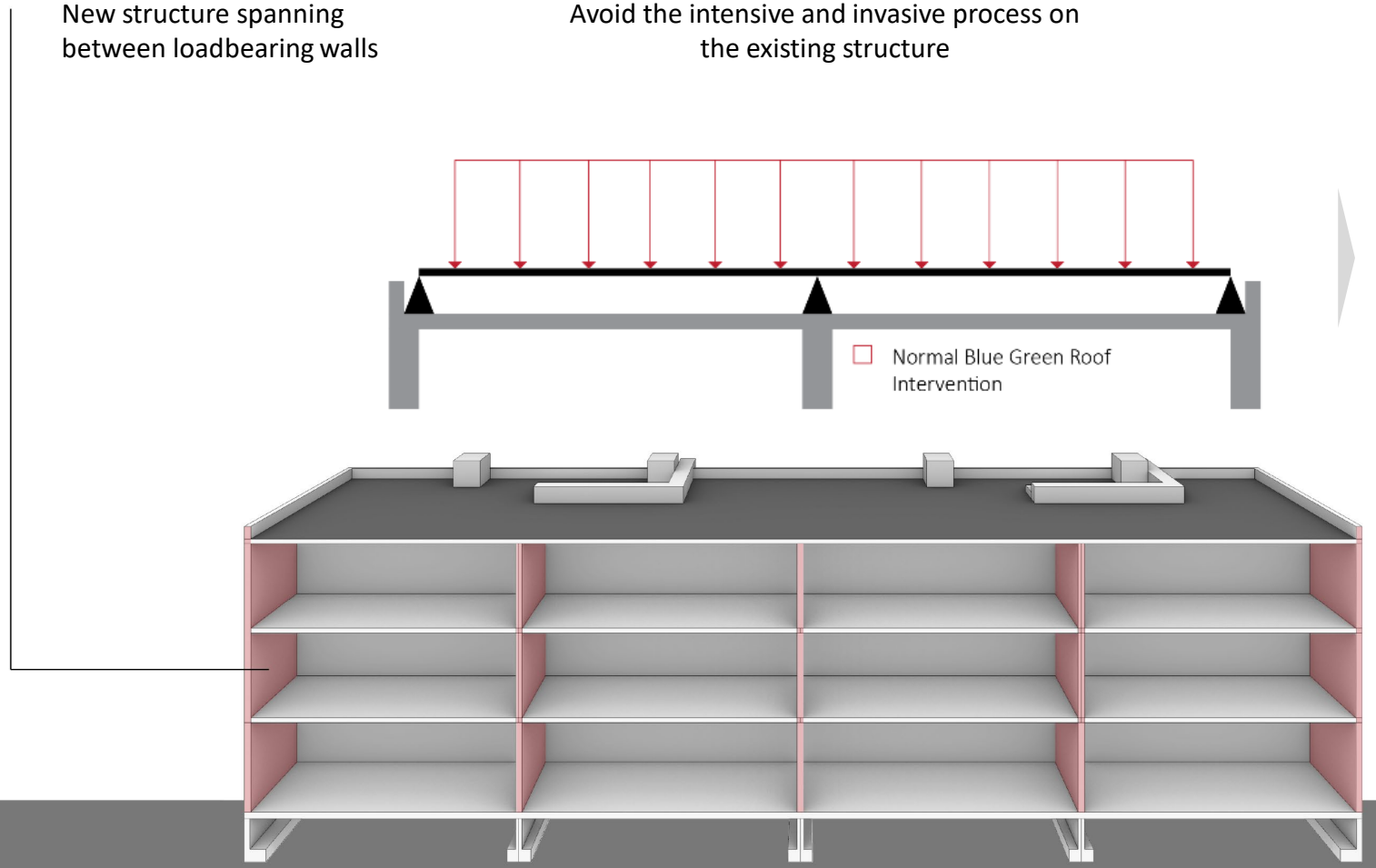


1) Assume the buildings capacity based on the safety parameters

2) External Reinforcement System

New structure spanning between loadbearing walls

Avoid the intensive and invasive process on the existing structure



Structural Analysis

Visual Assessment

Non-Destructive Testing

Destructive Testing

Structural Intervention

Removal of Roof Finishes

Removal of Waterproof Layer

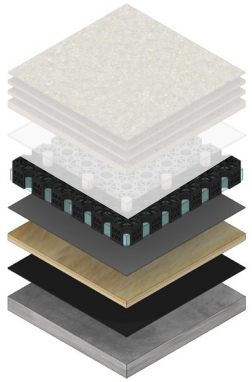
Grinding Surface to provide a cohesive join with new layers

Steel Structural Reinforcement Grid

Pouring Concrete Reinforcement Layer

1) Assume the buildings capacity based on the safety parameters

2) External Reinforcement System



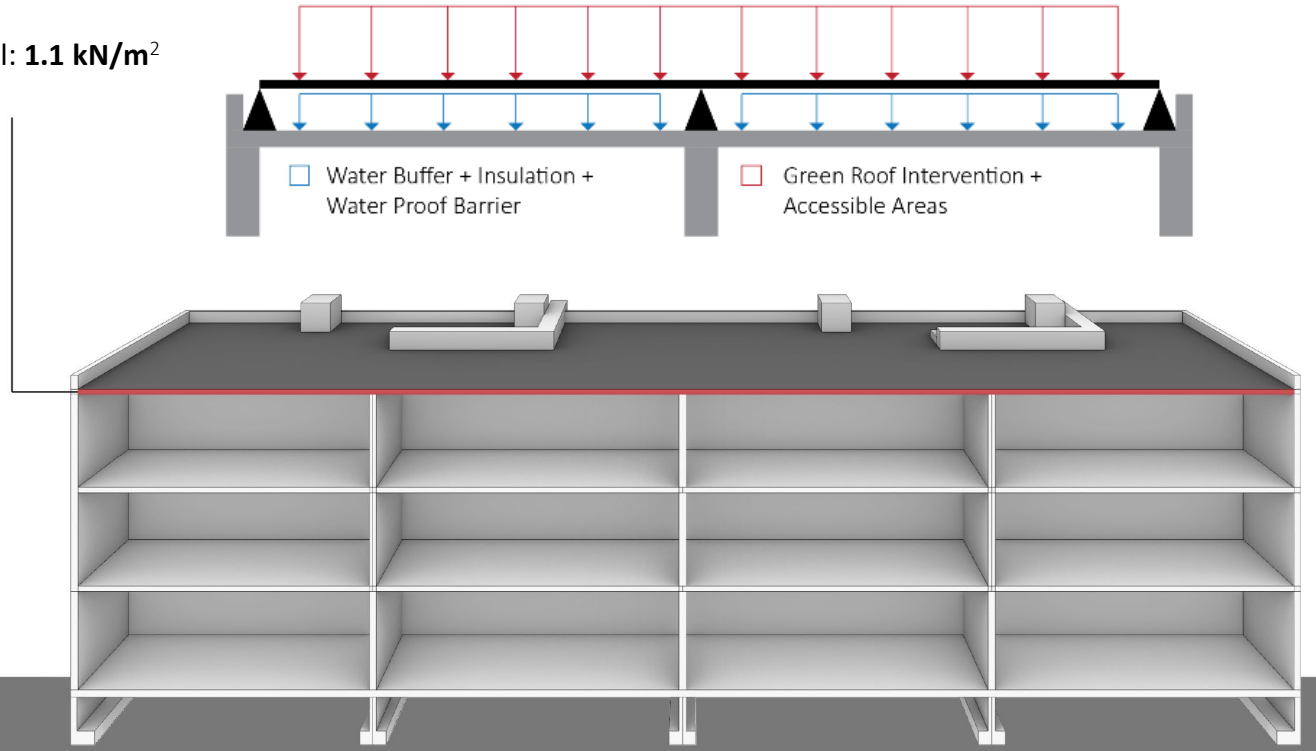
Roof Residual Capacity

- Insulation
- Waterproof barrier
- Rainwater buffer

Total: **1.1 kN/m^2**

3) Reuse of existing structure

Reduce the structural demand on the structure



Structural Analysis

Visual Assessment

Non-Destructive Testing

Destructive Testing

Structural Intervention

Removal of Roof Finishes

Removal of Waterproof Layer

Grinding Surface to provide a cohesive join with new layers

Steel Structural Reinforcement Grid

Pouring Concrete Reinforcement Layer

Design Stage

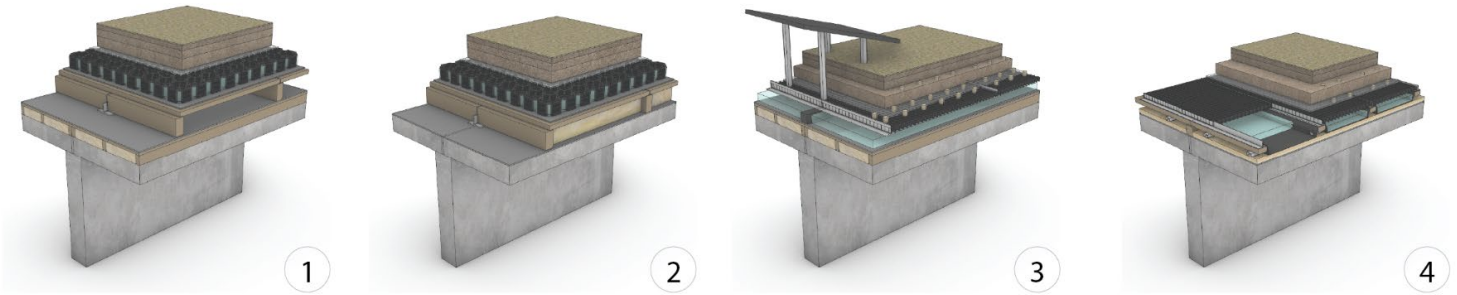
Design Premises

Multifunctional Roof

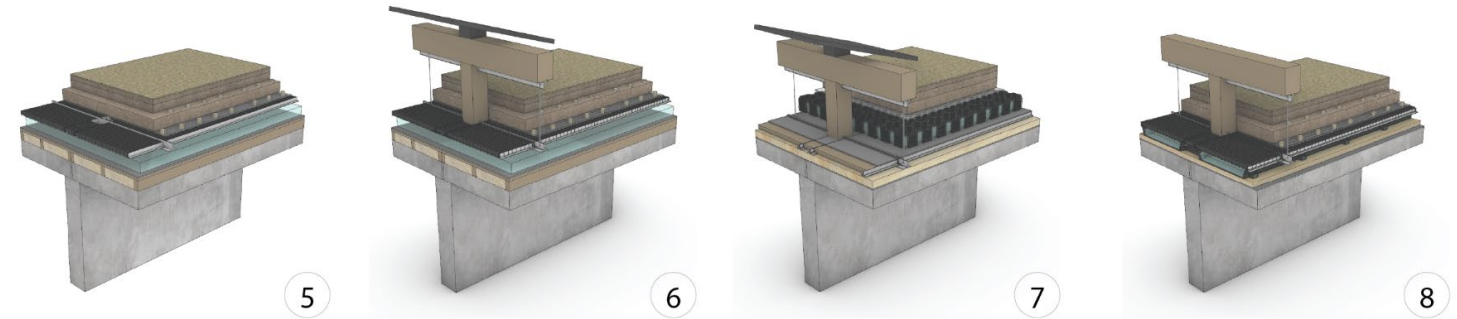
- Design Freedom
- Compactness
- Accessible Waterproof Layers
- Compatibility with Polder Roof System
- Compatibility with Existing Products
- Material Durability

Cost-reliving Factors

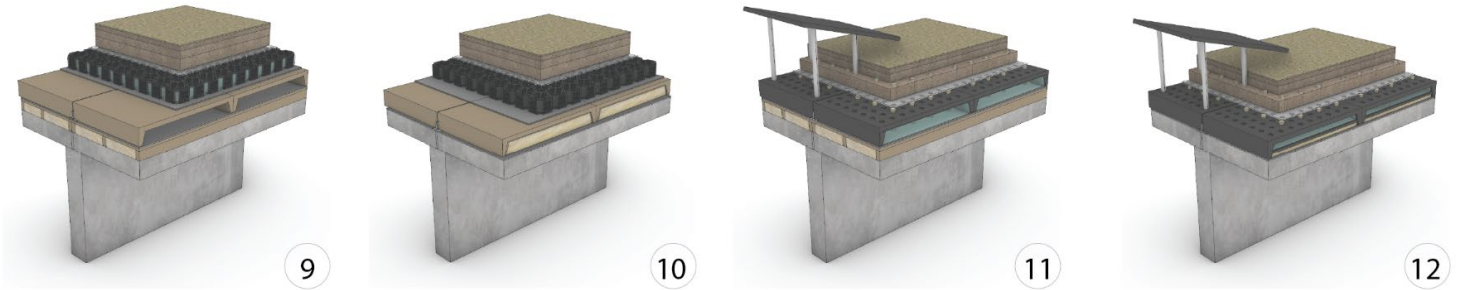
- Assume Building Capacity by Norm and Design Specifications
- Reduce Intervention on Existing Construction
- Weight of Structure
- Number of Elements
- Adaptability



Linear Arrangement



Grid Arrangement

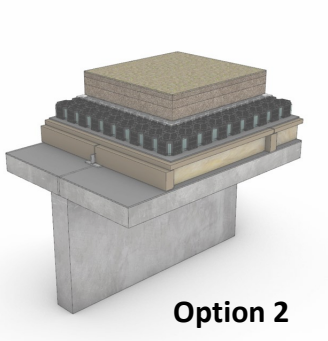


Box Arrangement

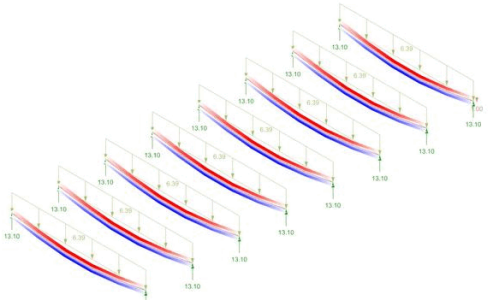
Structural Evaluation System

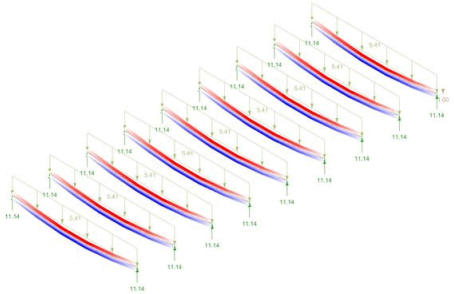
Different Span Lengths

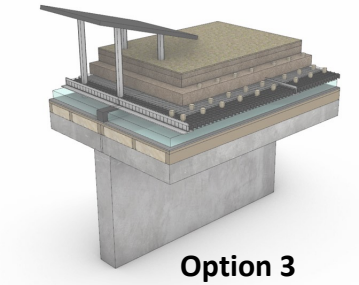
Different Load Combinations



Option 2







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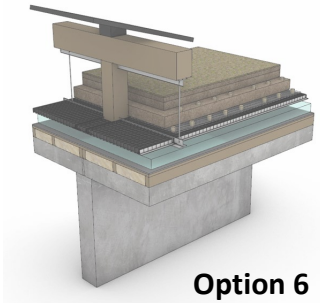

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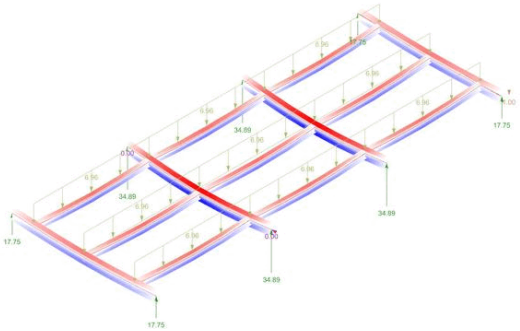
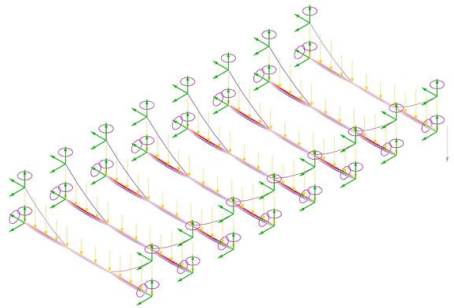
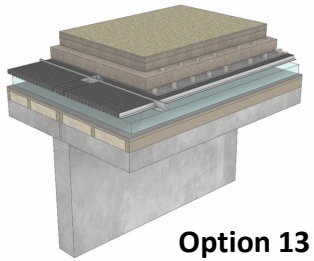
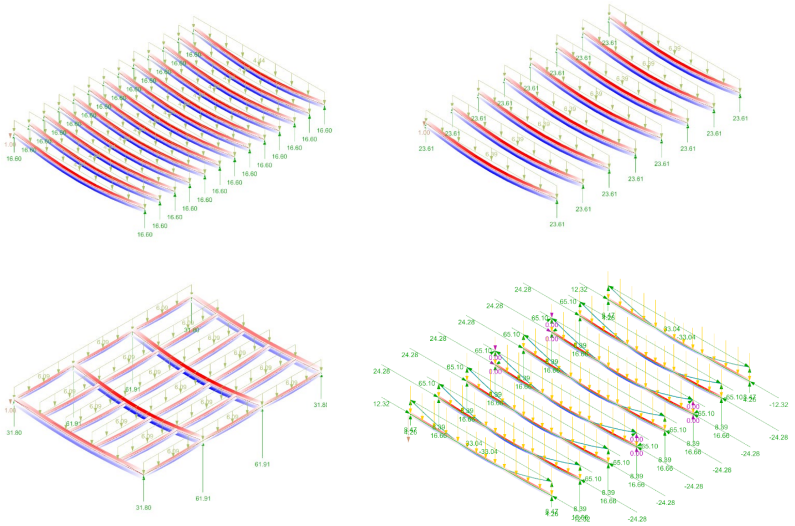




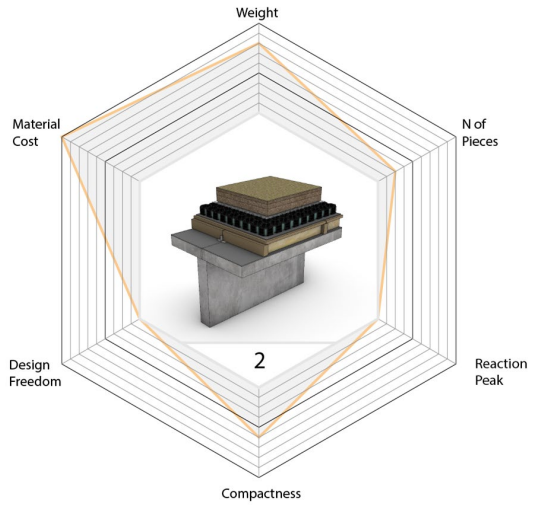


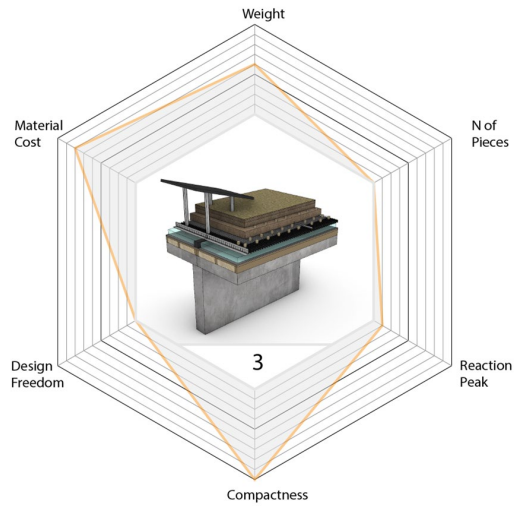
Option 13

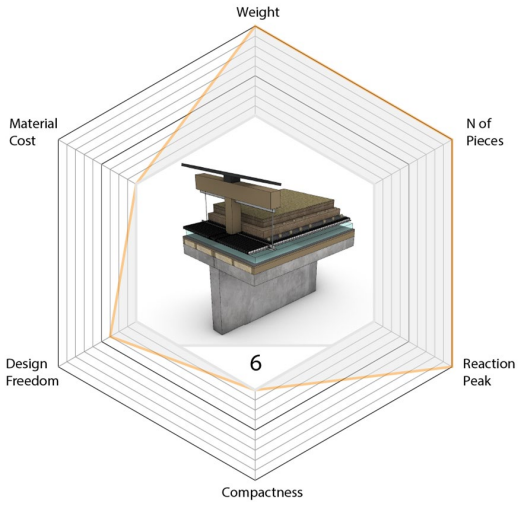


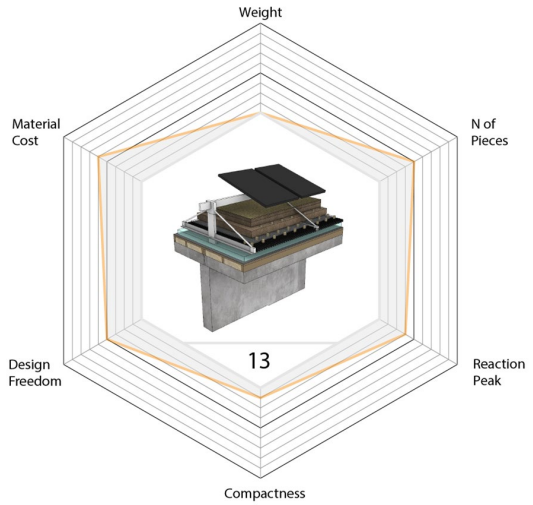
Structural Requirements	
Utilization Max – ULS [100%]	Deflection Max - SLS [L/340]

Parameters for comparison	
Quantitative	Qualitative
▪ Structure Weight ▪ Material Cost ▪ Number of Elements ▪ Peak Reaction Force ▪ Compactness of solution	▪ Accessibility to layers for maintenance and repair ▪ Design Freedom provided by the system







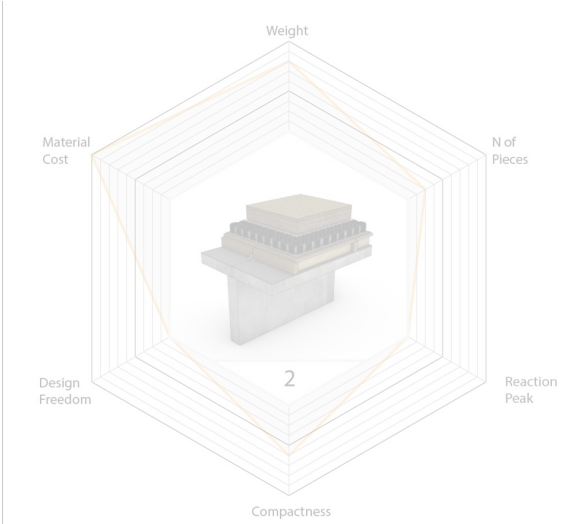


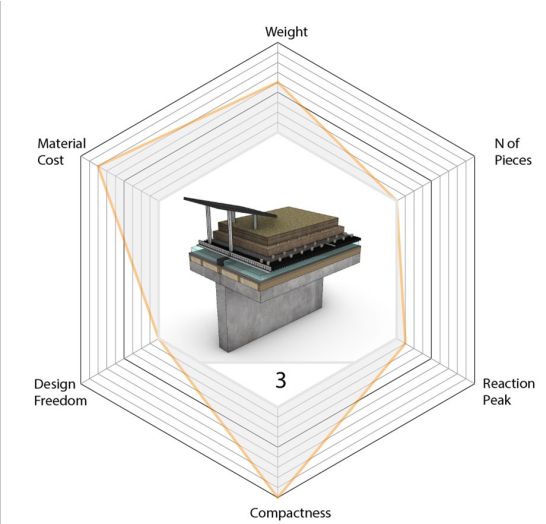
Evaluation and selection process

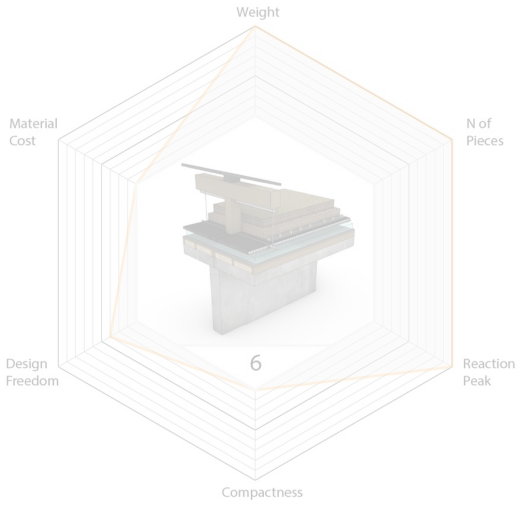
Systemic solution → Replicable in the largest possible group

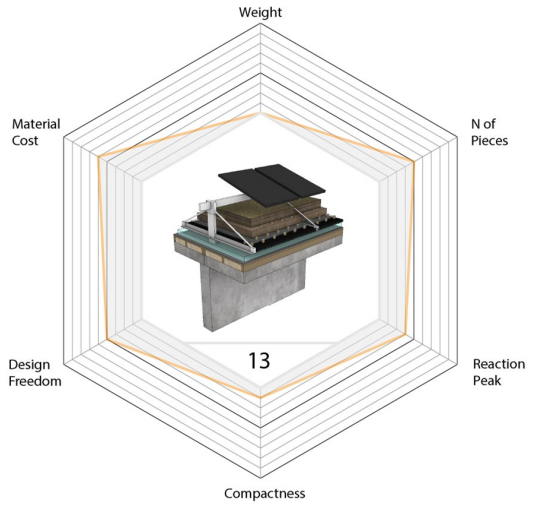
Designed for the best and worst-case scenarios

- **Structural characteristics**
- **Constructive characteristics**
- **Assembly Strategy**



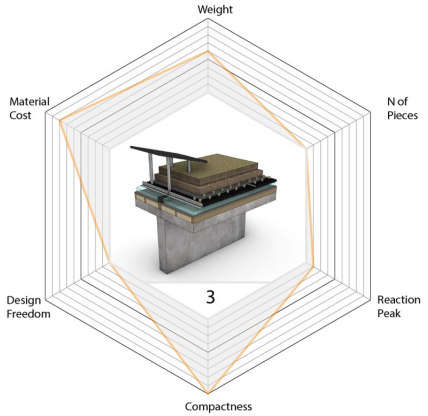




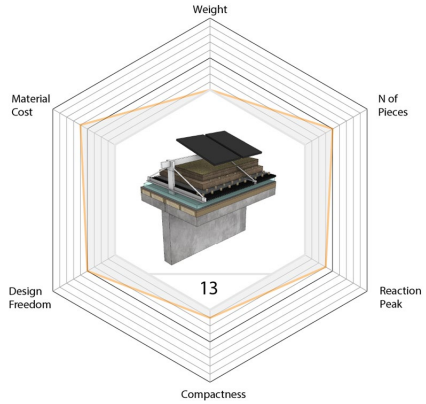


Selected Strategy

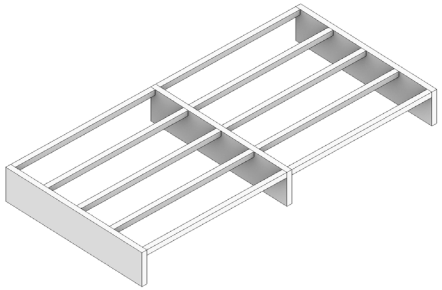
Selected options



Option 3

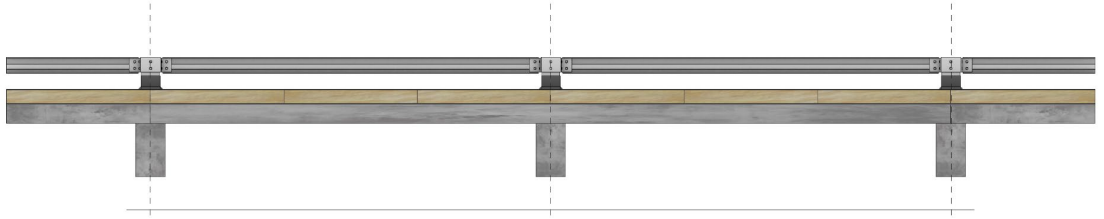


Option 13

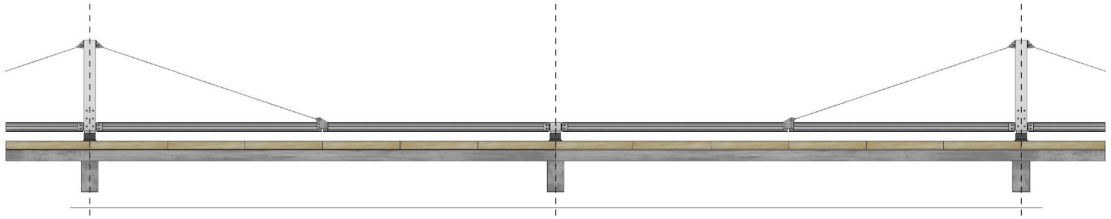


Uni-Directional System

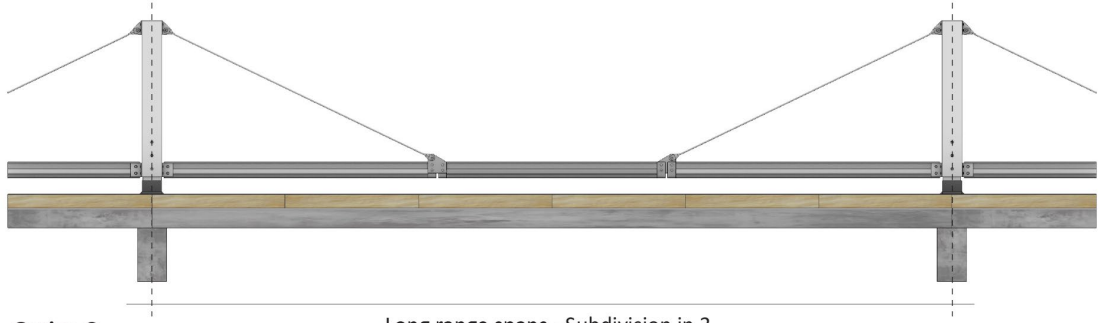
Permeable Structure



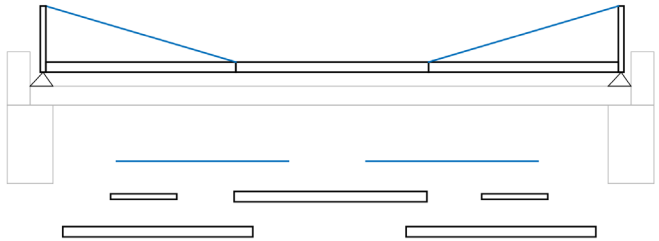
Option A — Short spans - No subdivision



Option B — Mid range spans - Subdivision in 2



Option C — Long range spans - Subdivision in 3

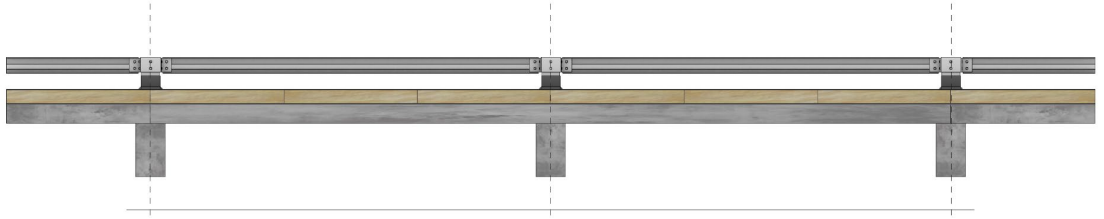


Segmented Structural Elements

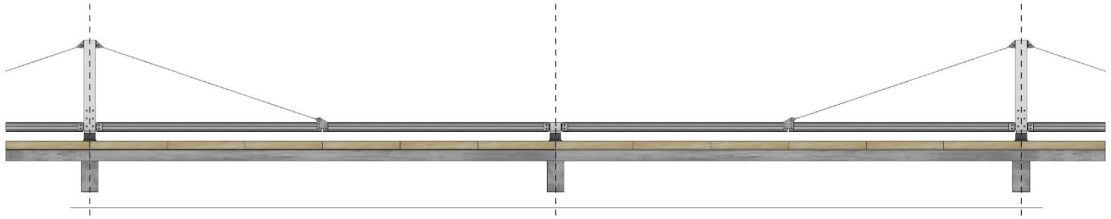
Reduce the weight and ease transportation and assembly process

Avoid Heavy Machinery requirements for assembly process

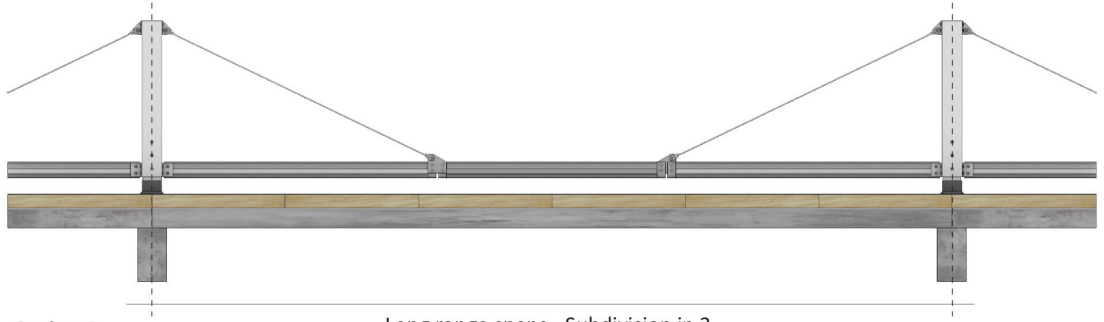
Ease installation on any building/urban context



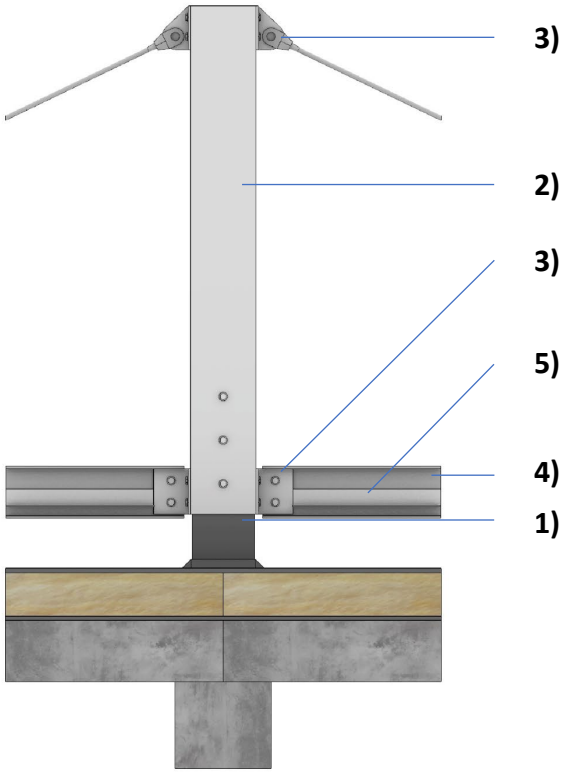
Option A Short spans - No subdivision



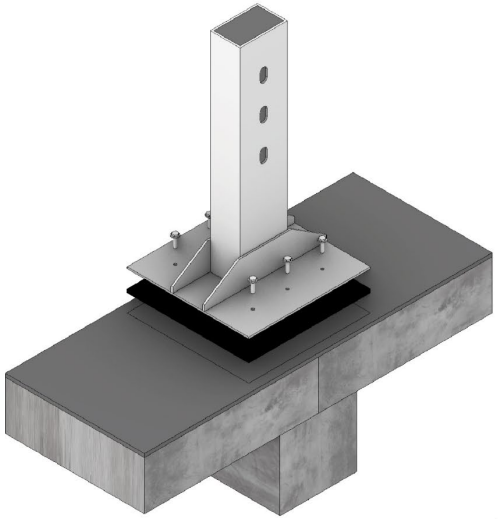
Option B Mid range spans - Subdivision in 2



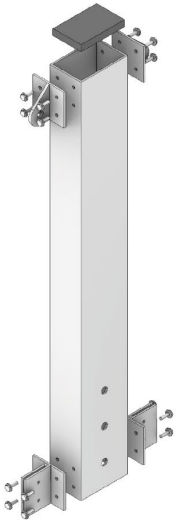
Option C Long range spans - Subdivision in 3



1) Base Support

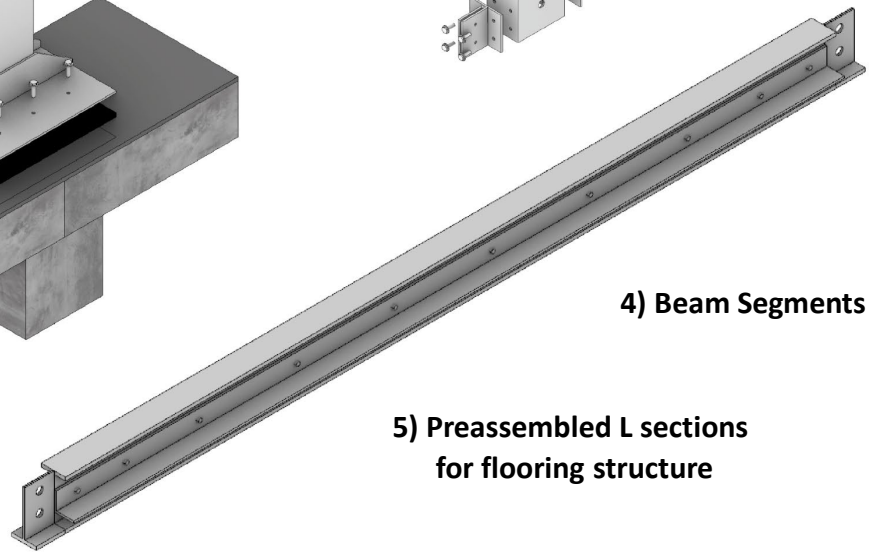


2) Column Segment

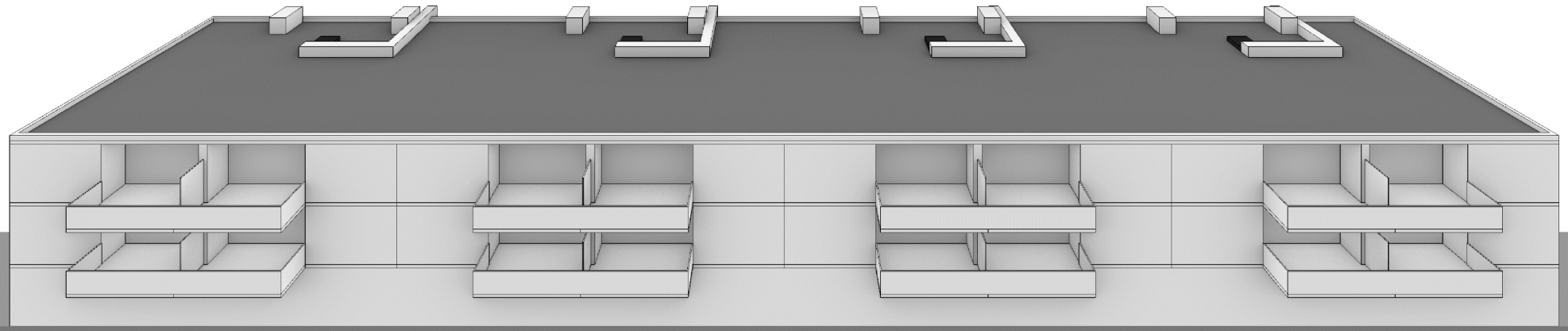


3) Preassembled Mounting Brackets

4) Beam Segments

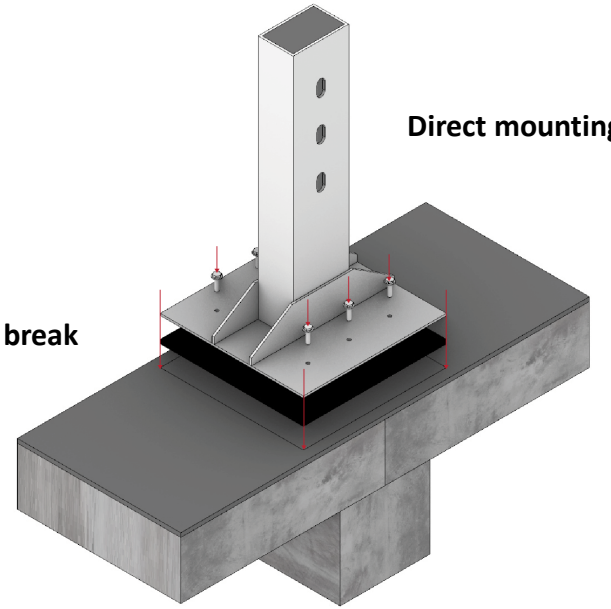


5) Preassembled L sections for flooring structure

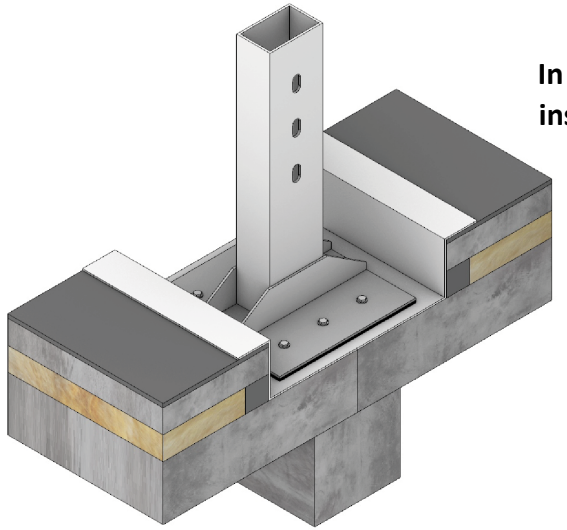


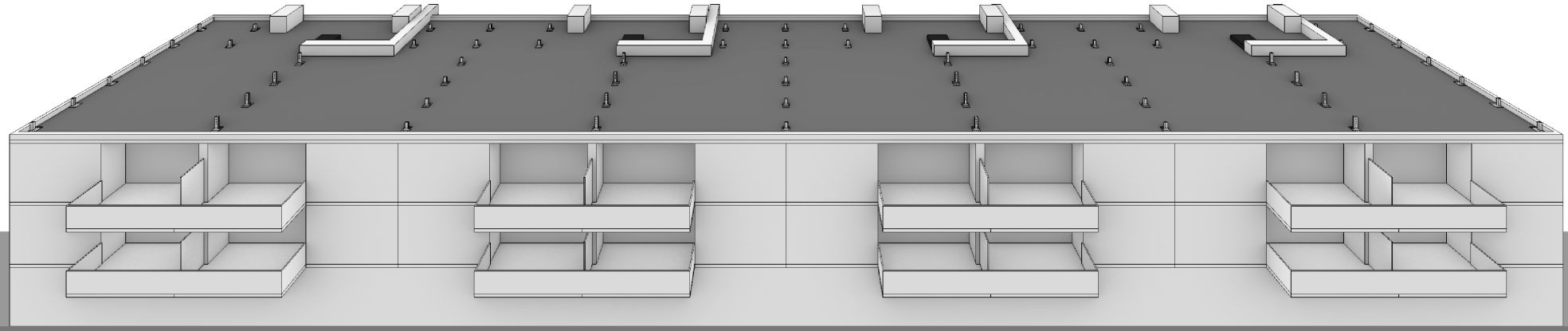
Direct mounting

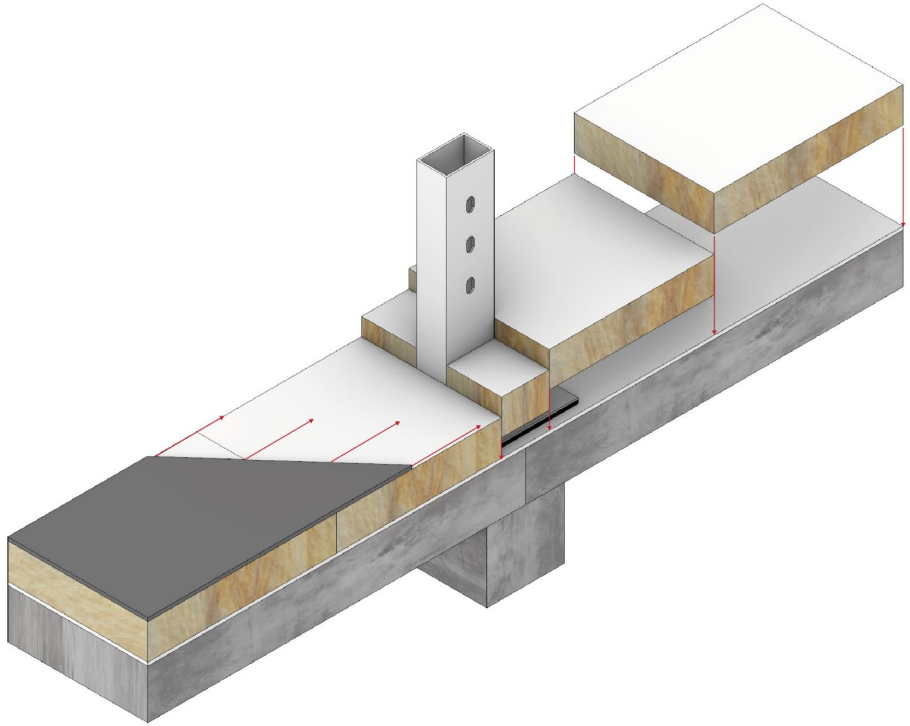
Thermal break

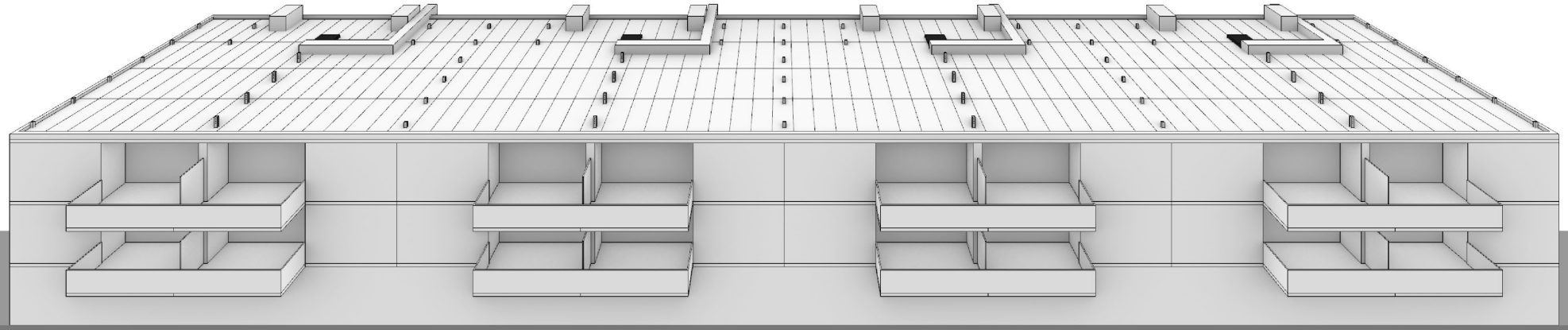


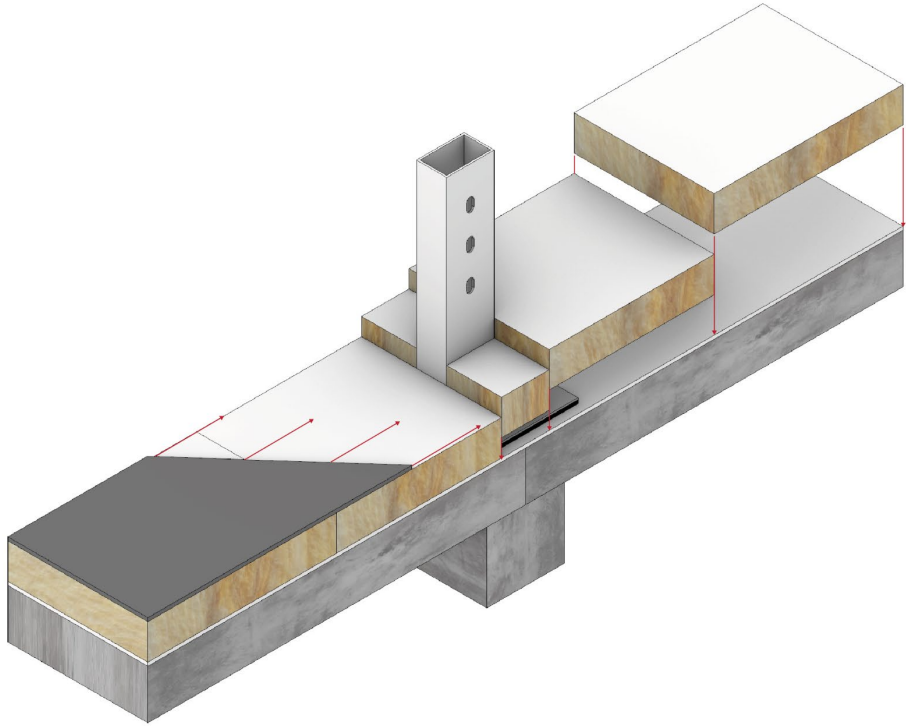
In case of existing insulation system



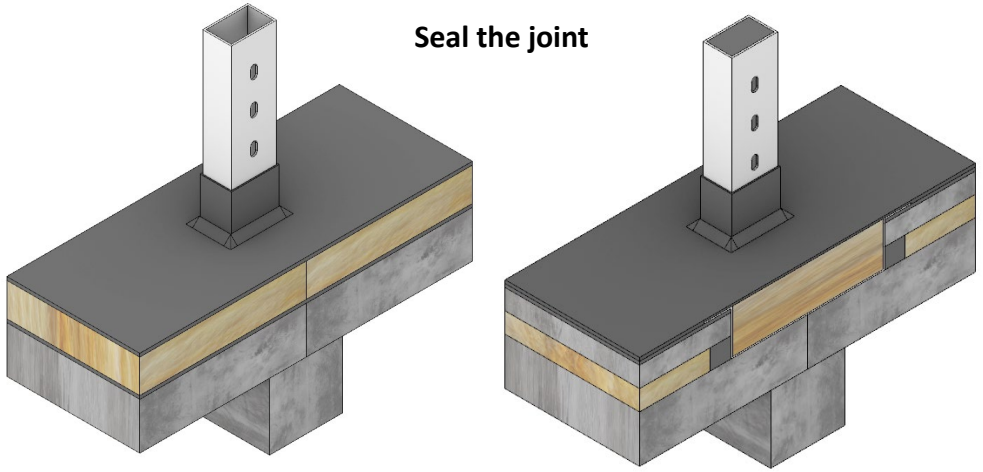


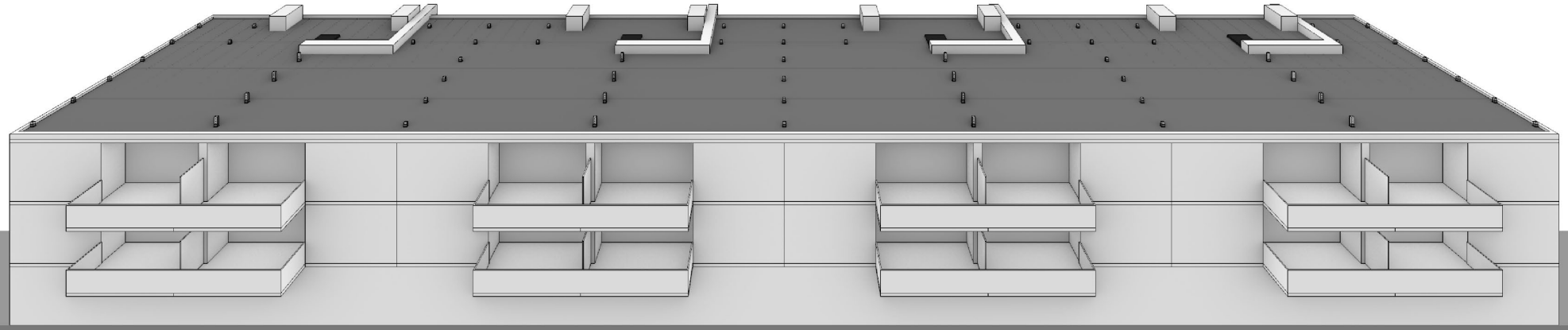


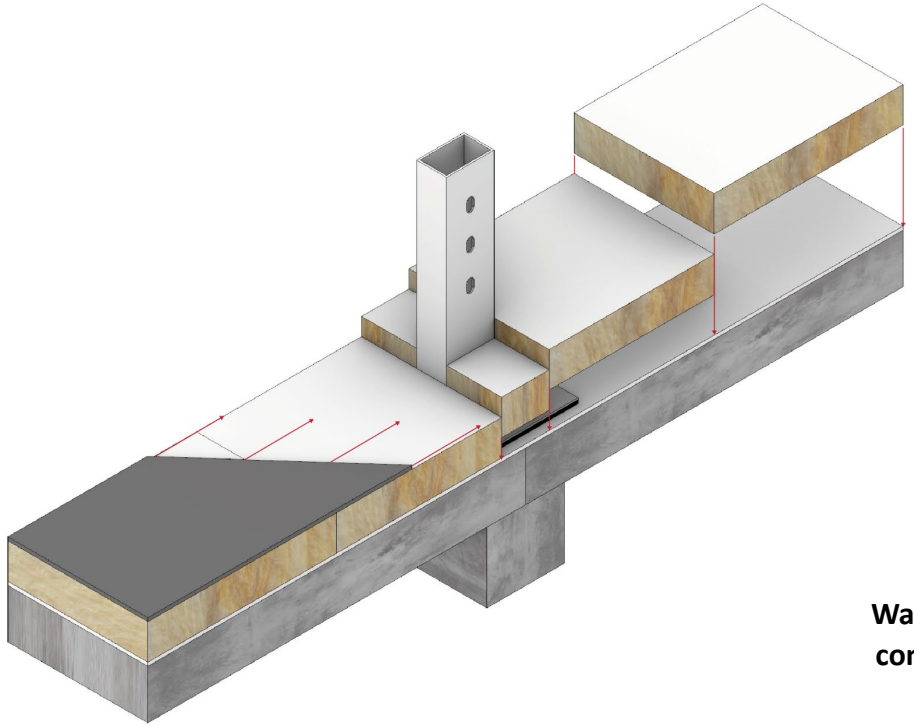




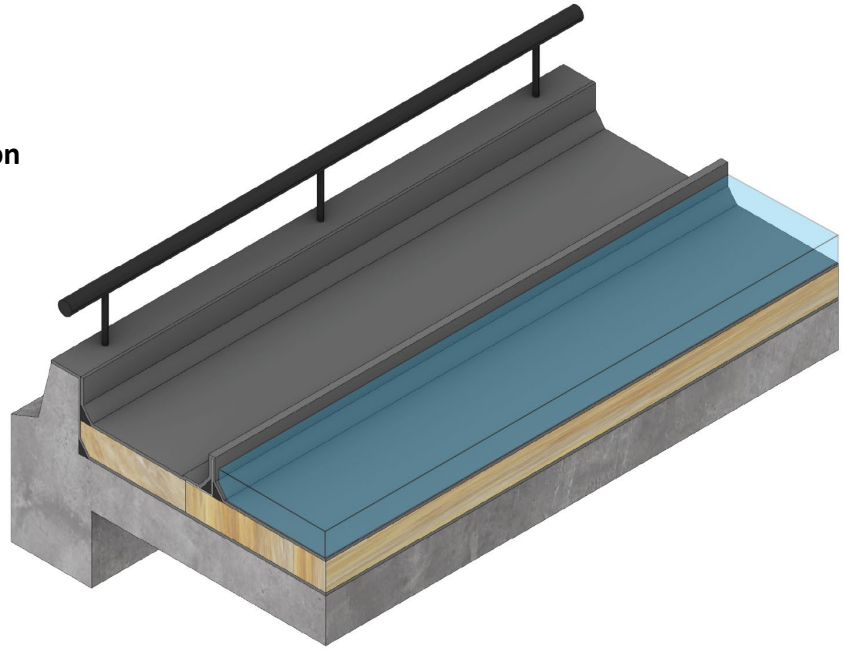
Seal the joint



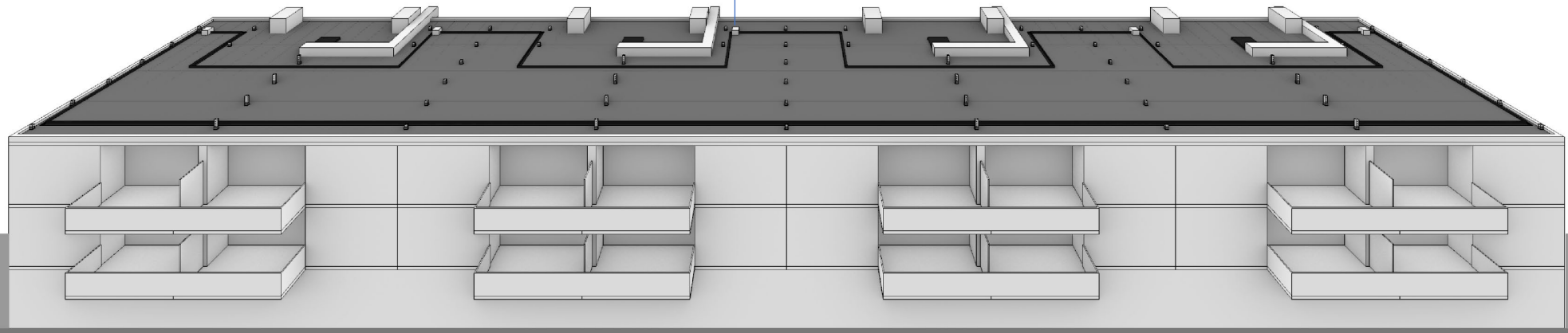


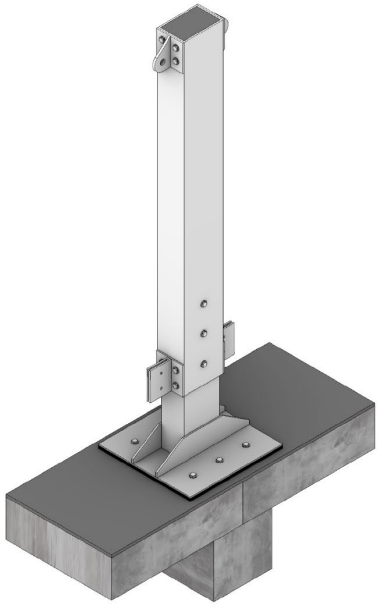


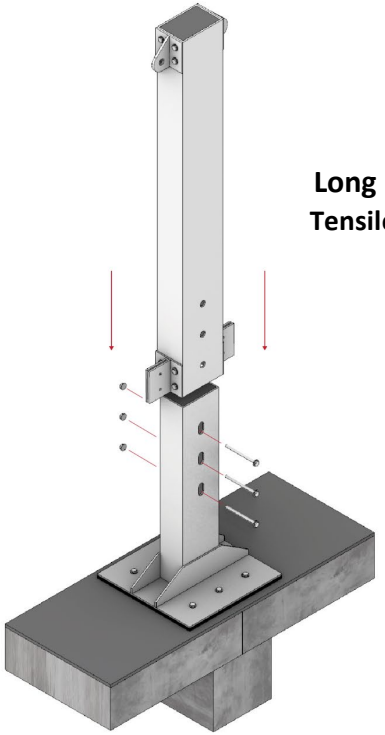
Water contention structure



Water drainage control system

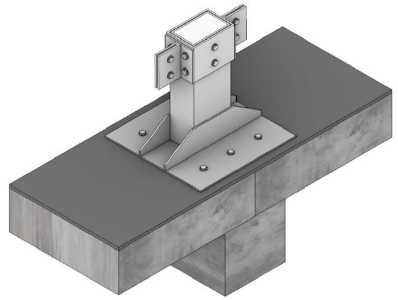


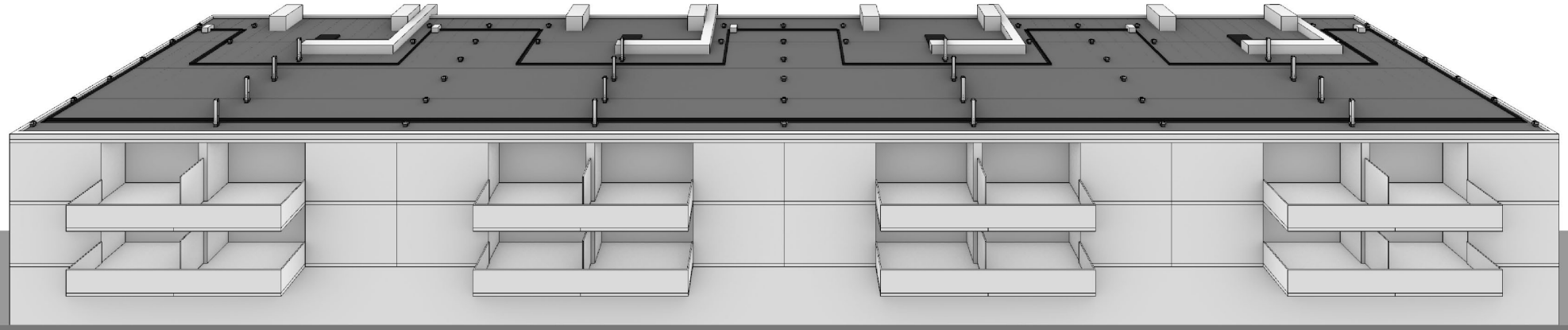


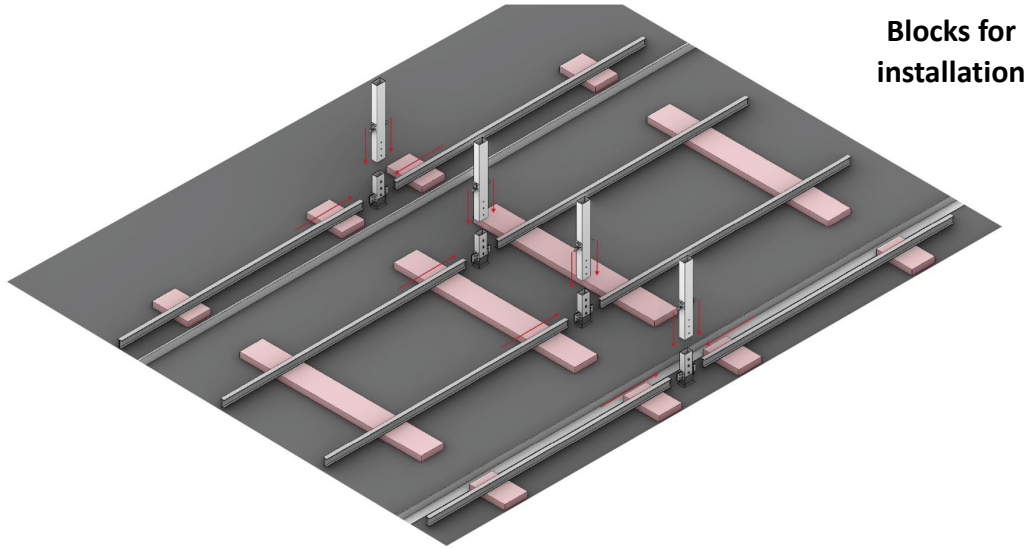


Long segments
Tensile structure

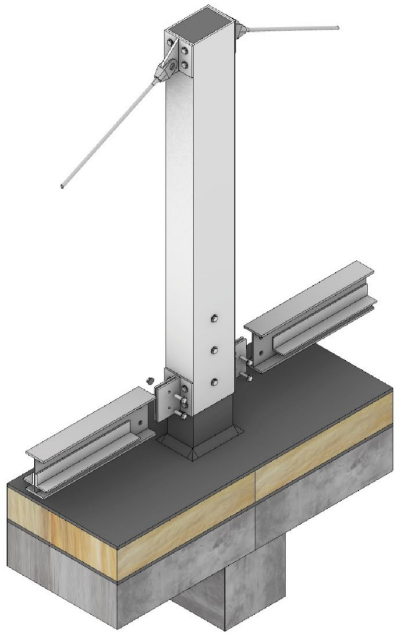
Short segments
Simple supported beams

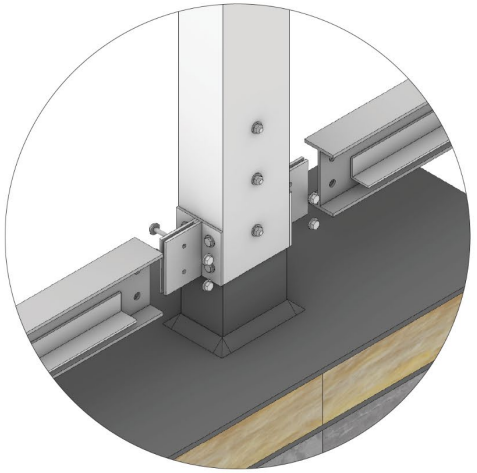


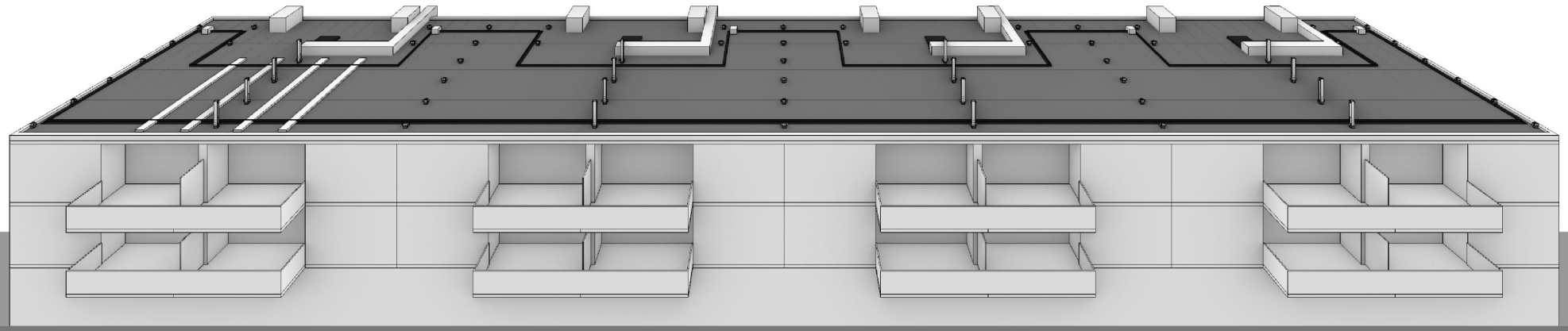


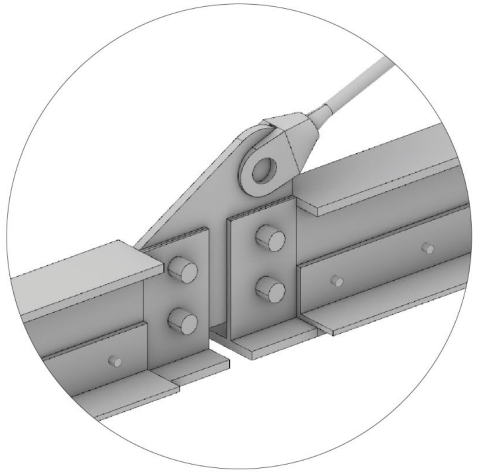


Blocks for installation

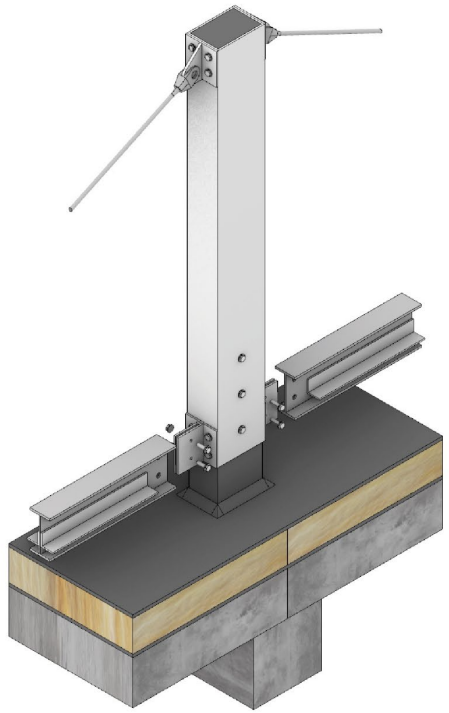


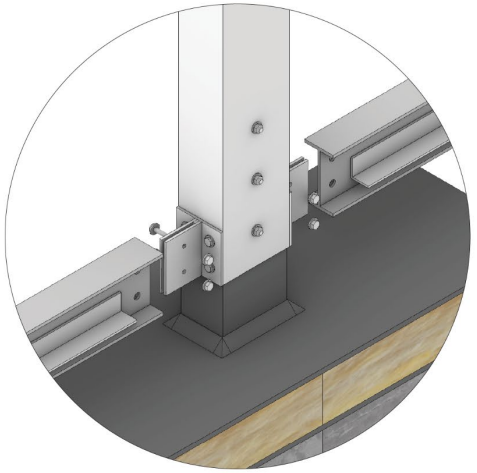


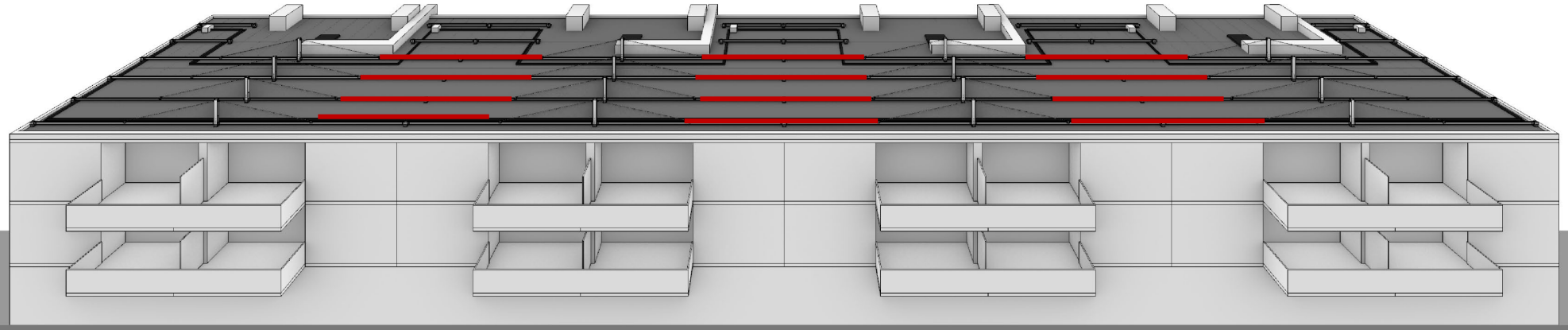


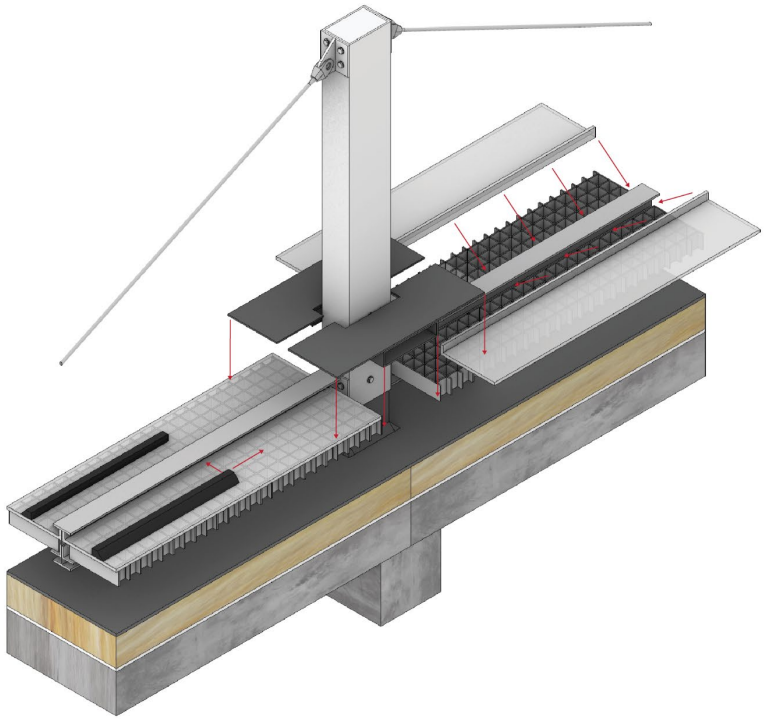


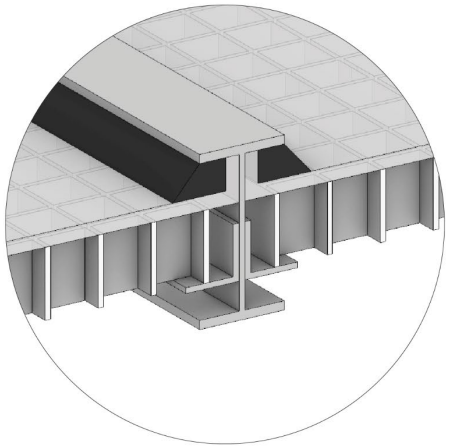
Plates and Tensile Rods







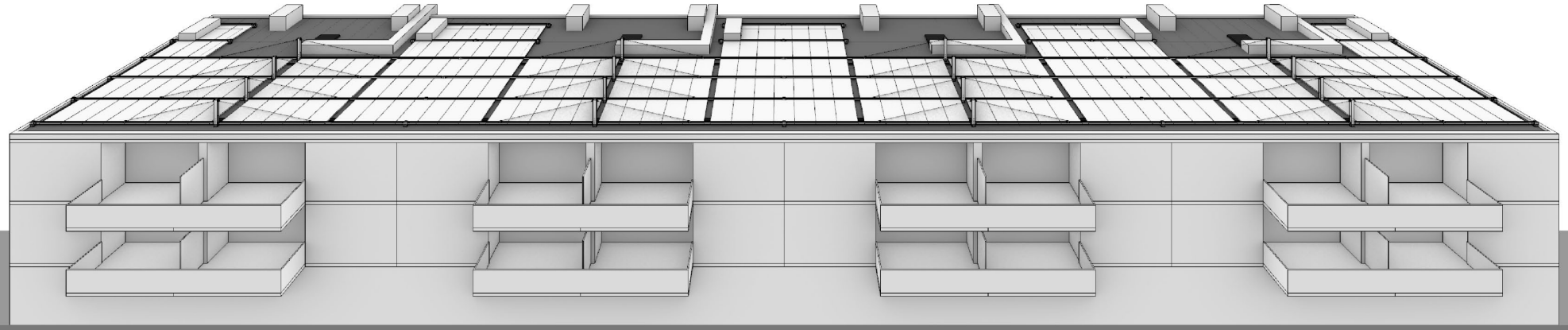




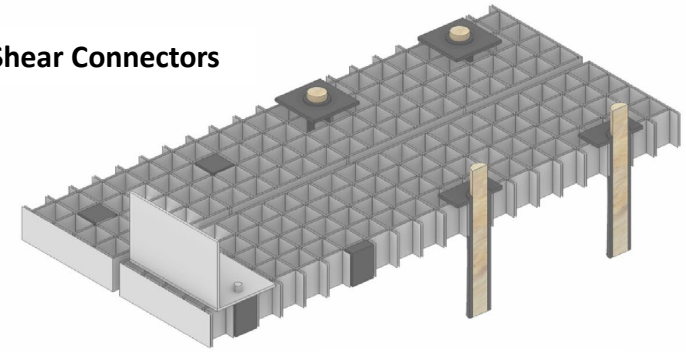
EPDM Gaskets

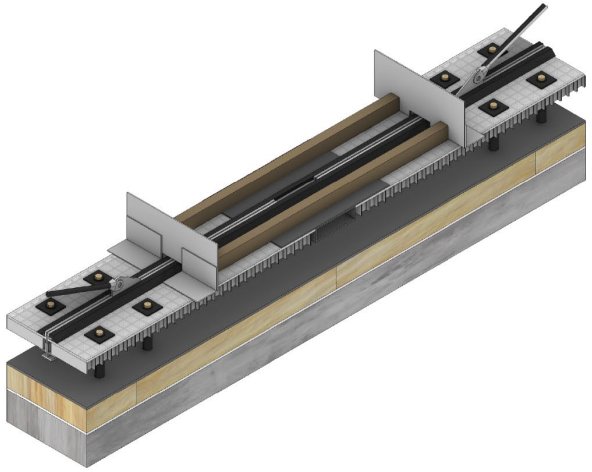
Filtration Mat

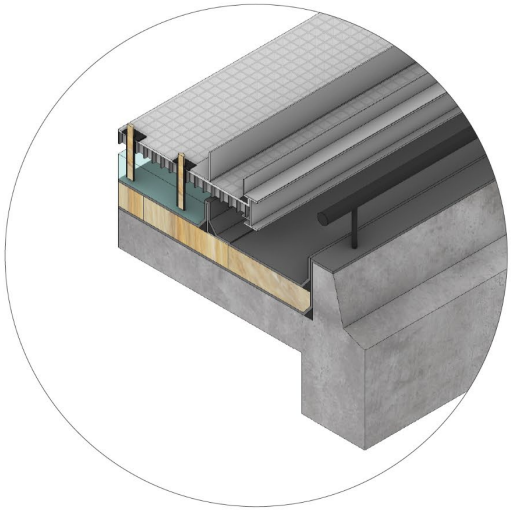
Grating System



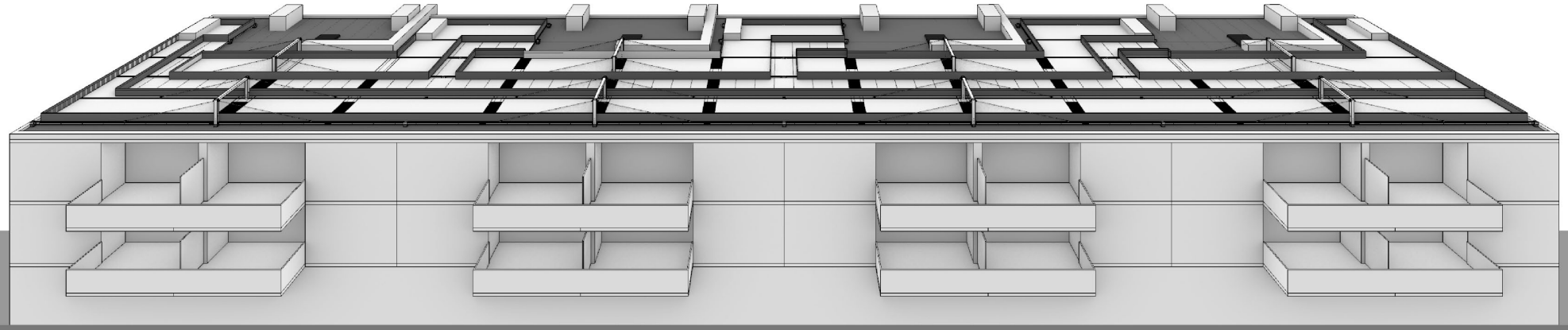
Shear Connectors





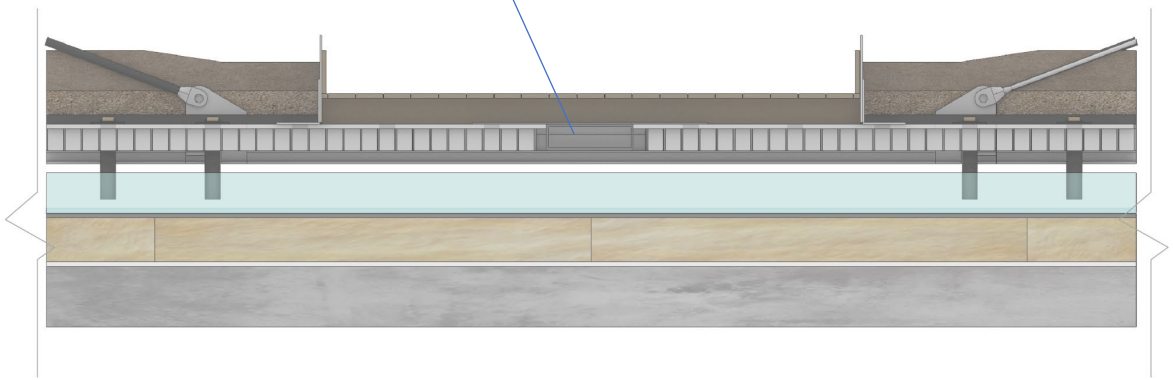


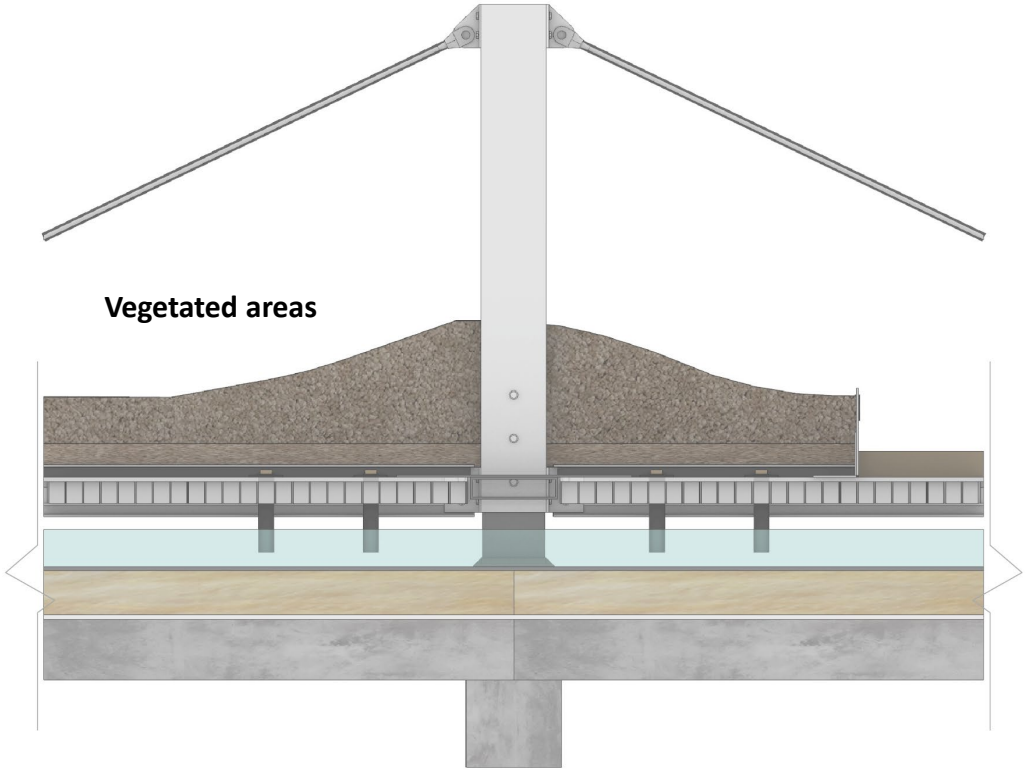
Capillary cones

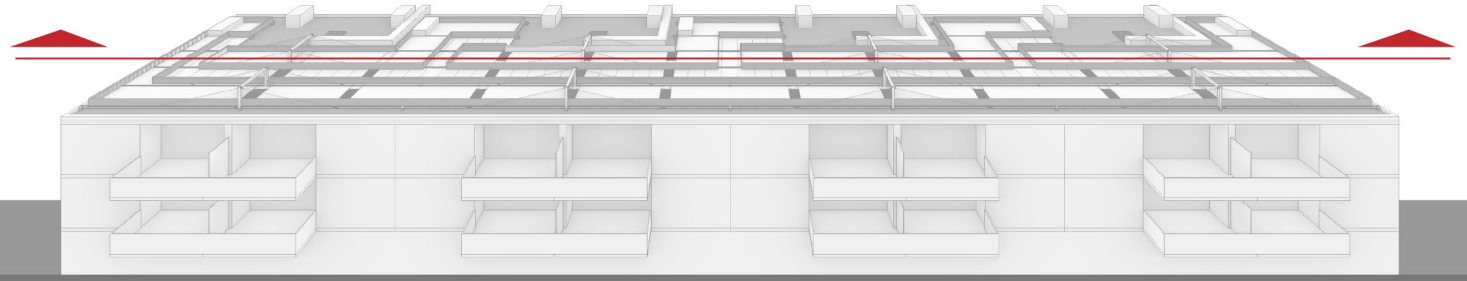


Installation of spacers

Avoid variations on grating sizes



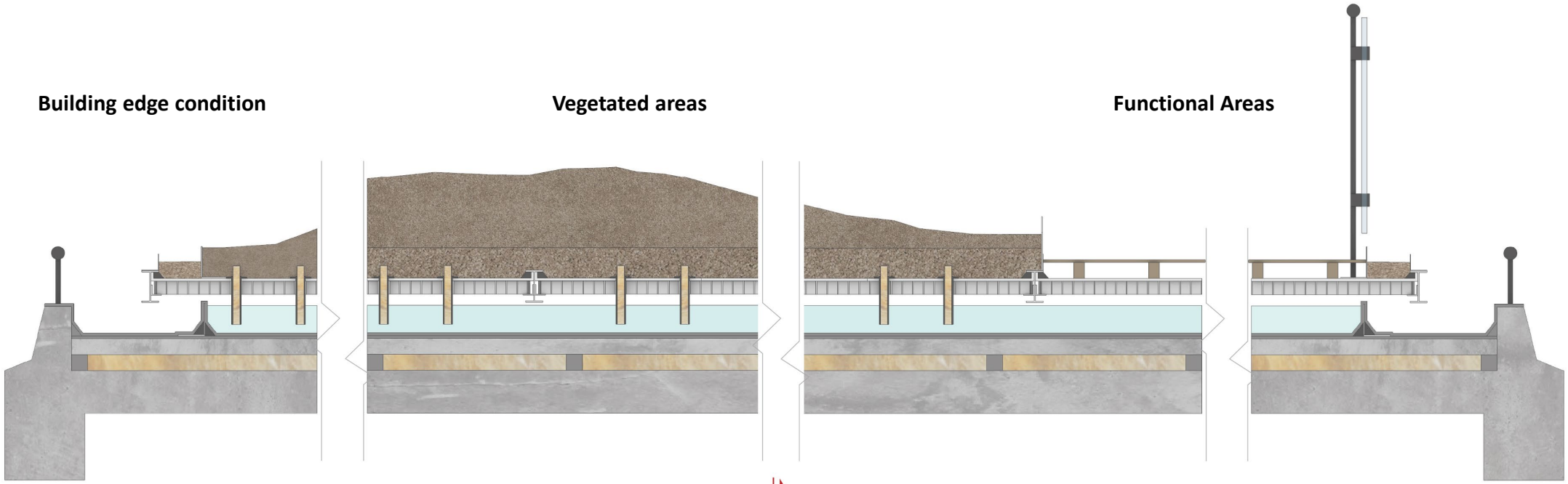




Building edge condition

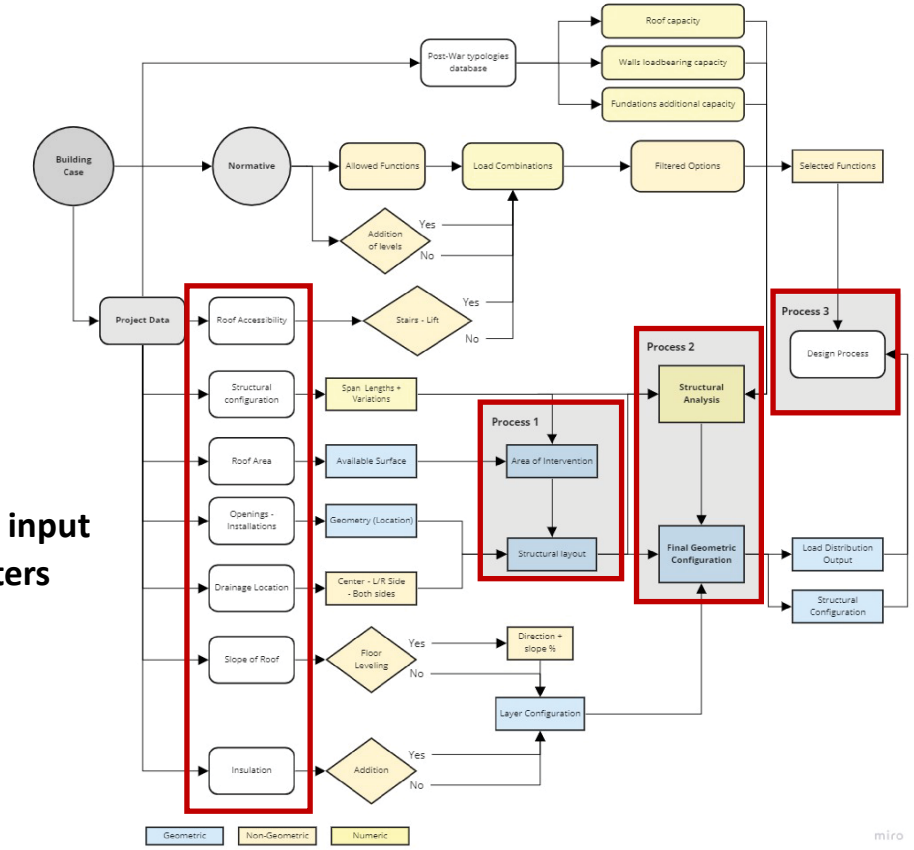
Vegetated areas

Functional Areas



Design Tool

Building input parameters



Process 1

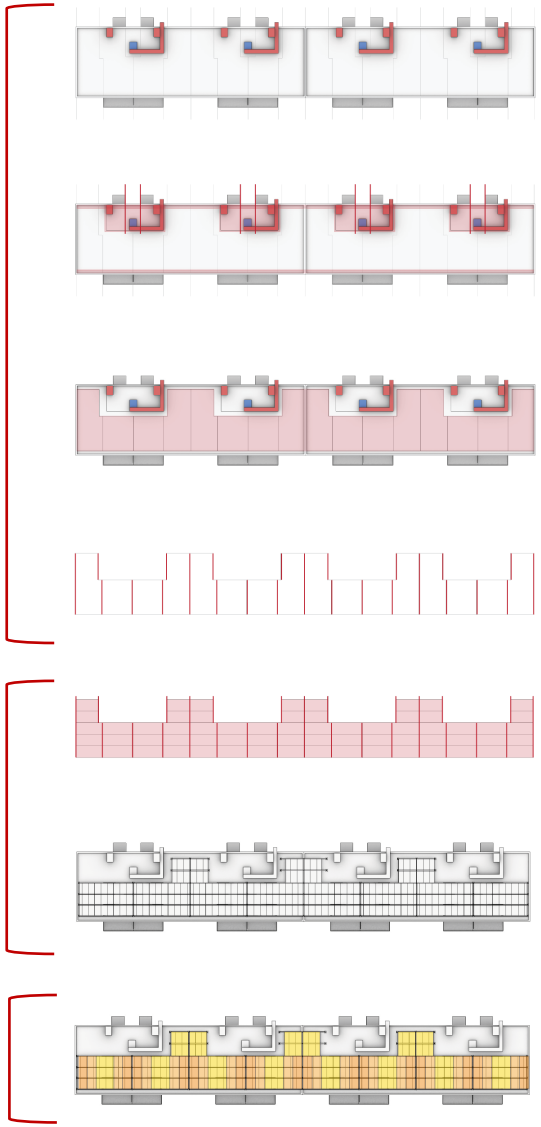
Geometric configuration of structure

Process 2

Structural Analysis

Process 3

Design Tool output

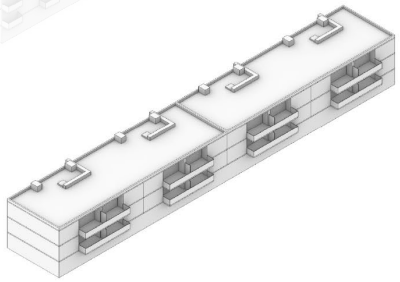


Building Block III

- Gallery Building
- 14 Stories
- 1335.85 m^2

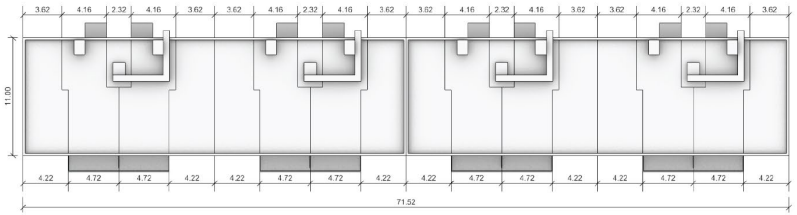
Building Block VII

- Gallery Building
- 10 Stories
- 1018.33 m^2

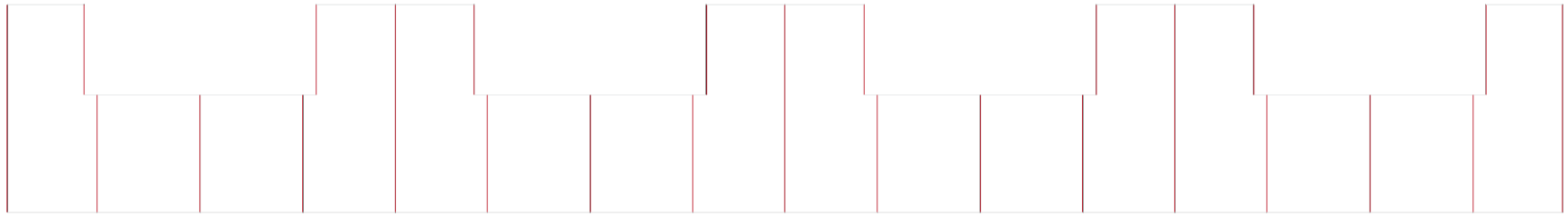


Building Block IV

- Porch-Flat Building
- 3 Stories
- 786.72 m^2

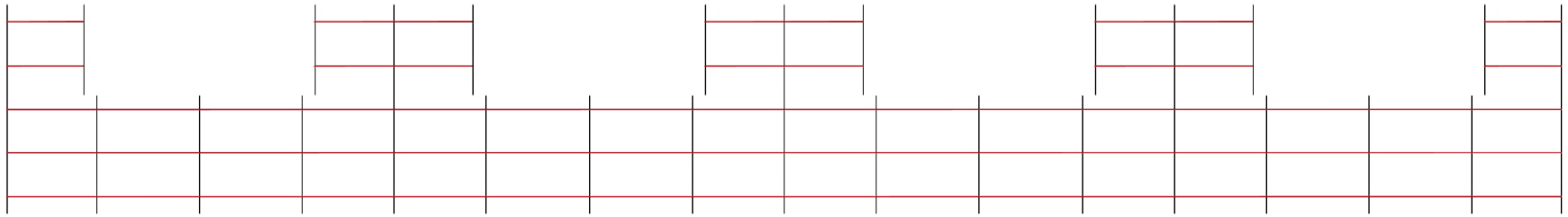


Process 1



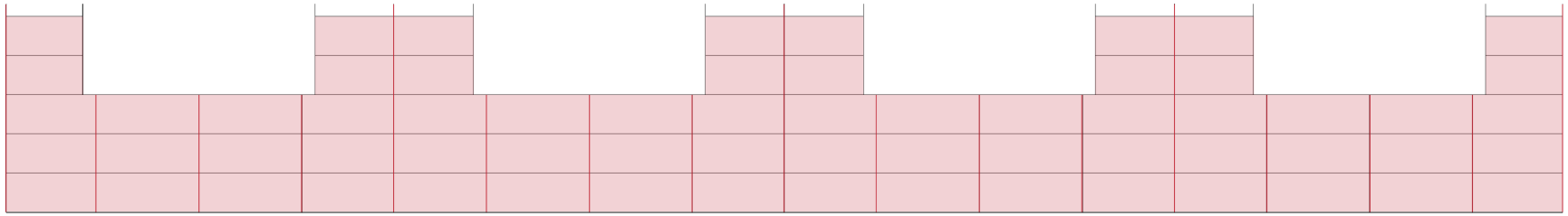
Final output for structural analysis — Available wall segments

Process 1

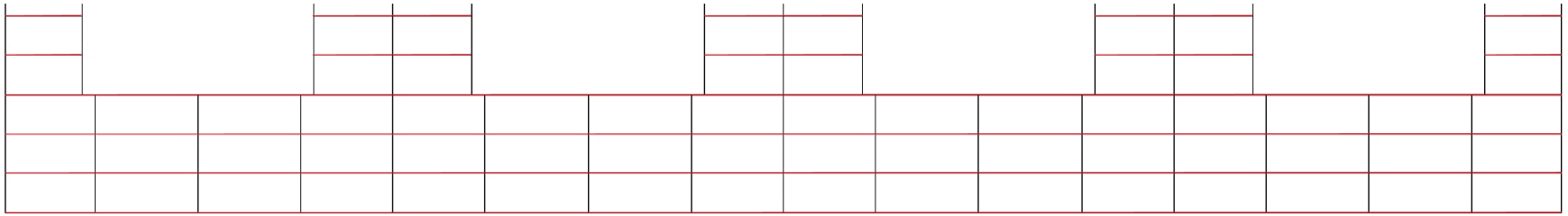


Subdivision: 2.00 m N. Seg. = 64 Area = 90%

Process 1



Final geometric Input for structural calculations



Subdivision: 1.80 m N. Seg. = 80 Area = 94%

Process 2

Short-Range Span

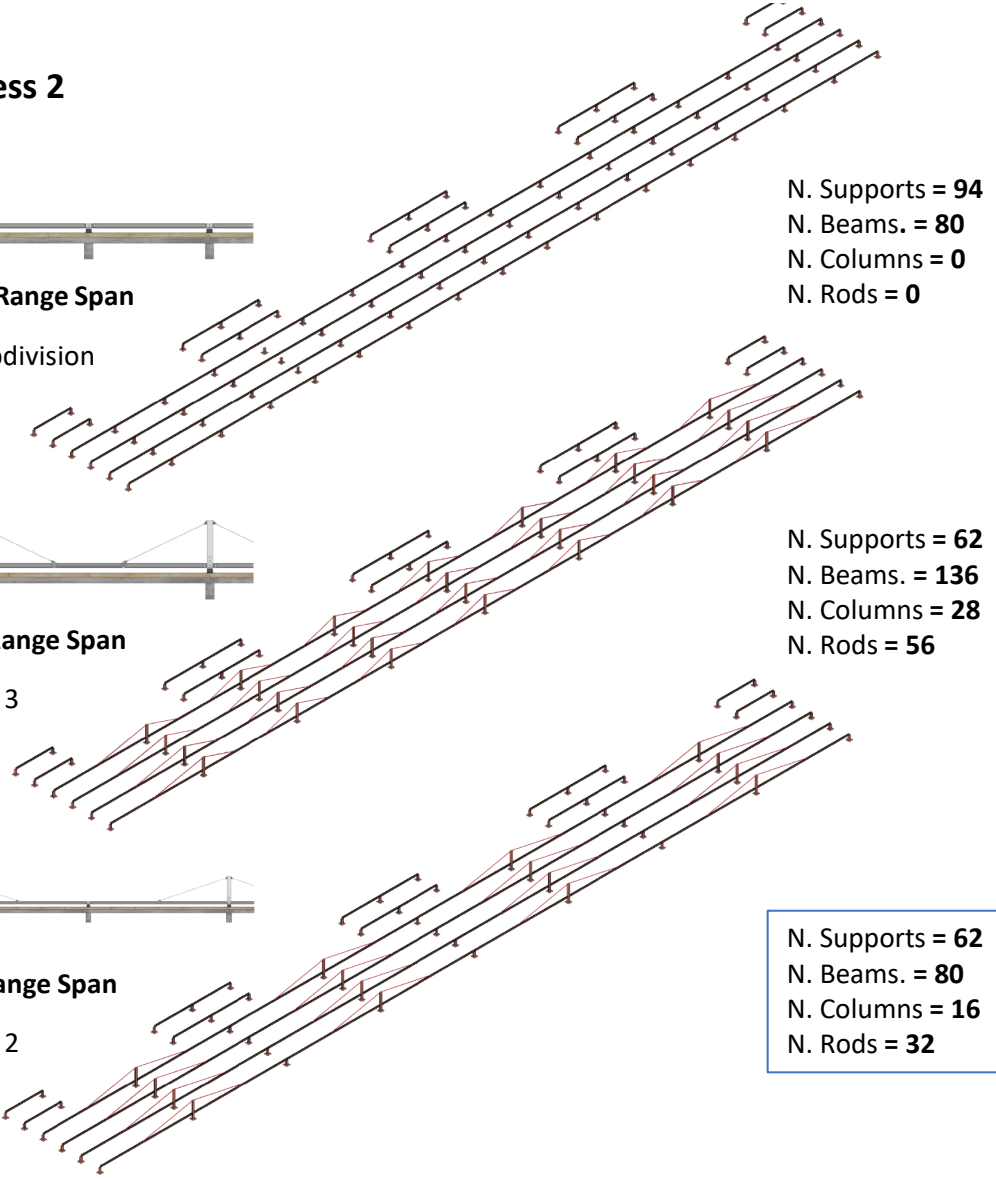
No Subdivision

Long-Range Span

Sub. in 3

Mid-Range Span

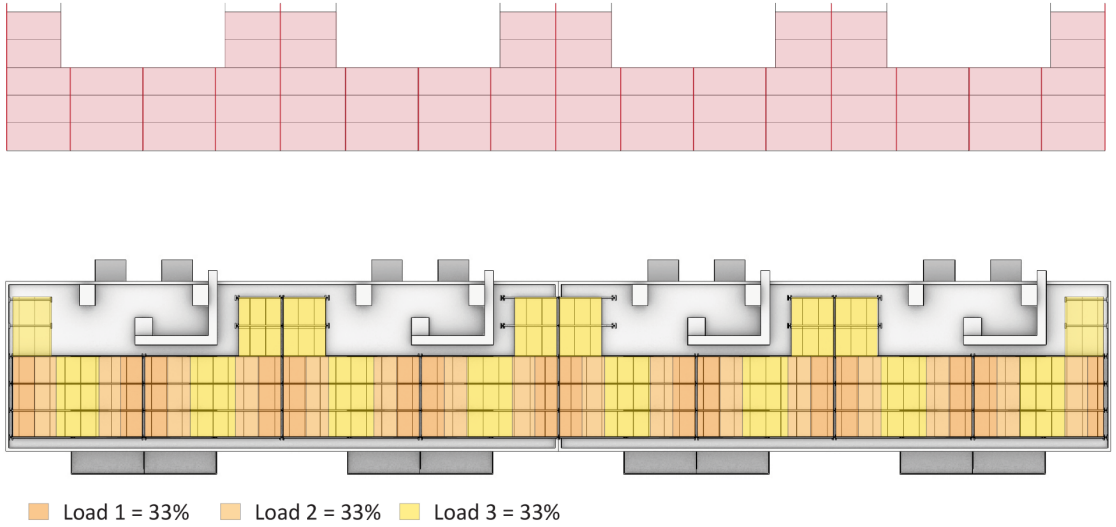
Sub. in 2



N. Supports = **94**
N. Beams**.** = **80**
N. Columns = **0**
N. Rods = **0**

N. Supports = **62**
N. Beams. = **136**
N. Columns = **28**
N. Rods = **56**

N. Supports = **62**
N. Beams. = **80**
N. Columns = **16**
N. Rods = **32**



Compactness

Reduced Element Number

Reduced Tensile connections

Process 3

Building IV

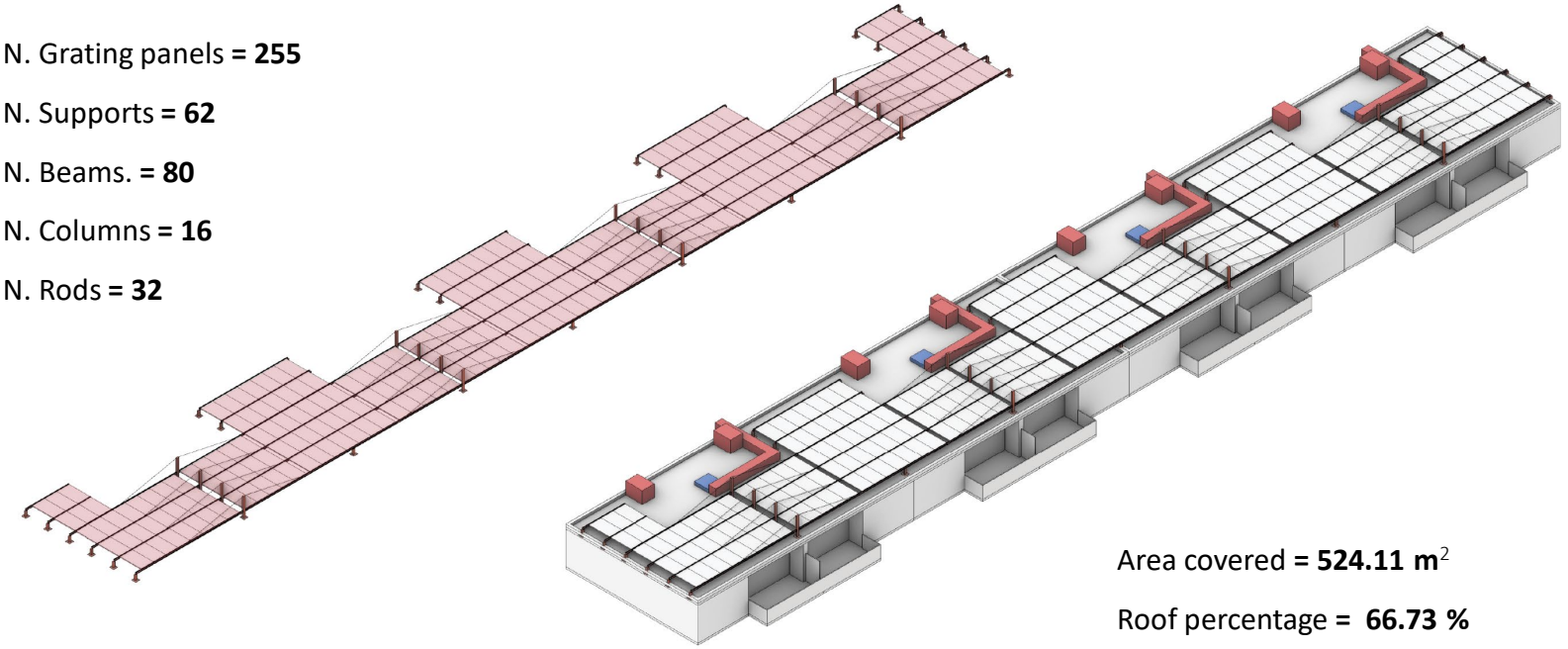
N. Grating panels = **255**

N. Supports = **62**

N. Beams. = **80**

N. Columns = **16**

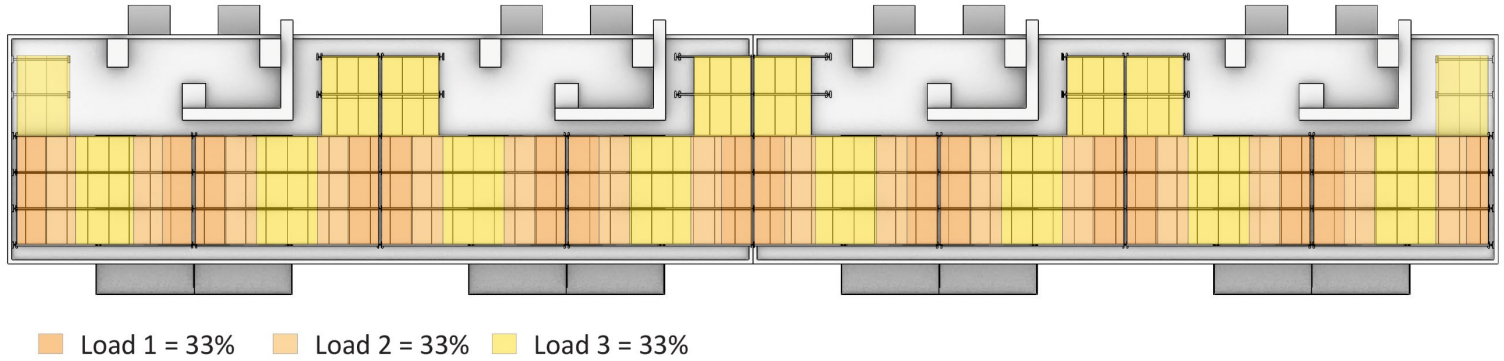
N. Rods = **32**



Area covered = **524.11 m^2**

Roof percentage = **66.73 %**

Water buffer capacity = **35 000 L**



Process 3

Building VII

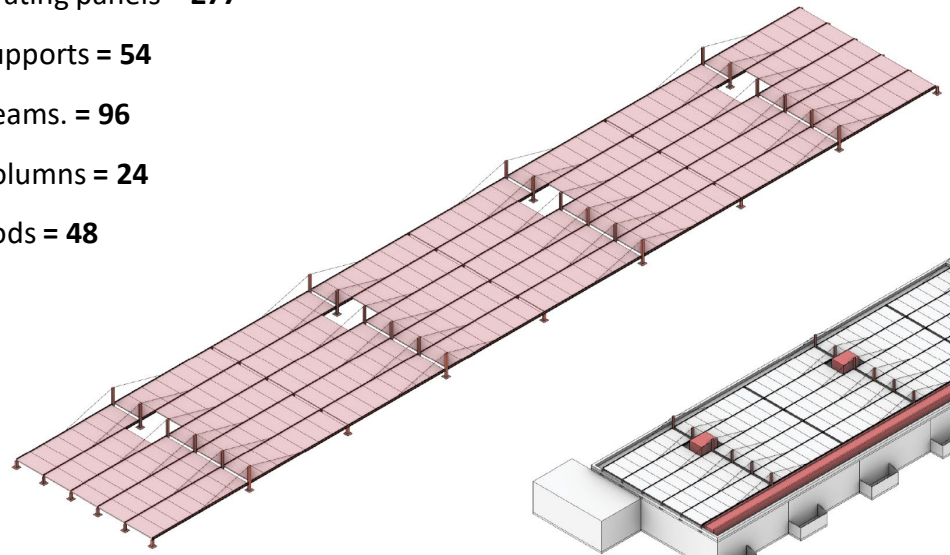
N. Grating panels = **277**

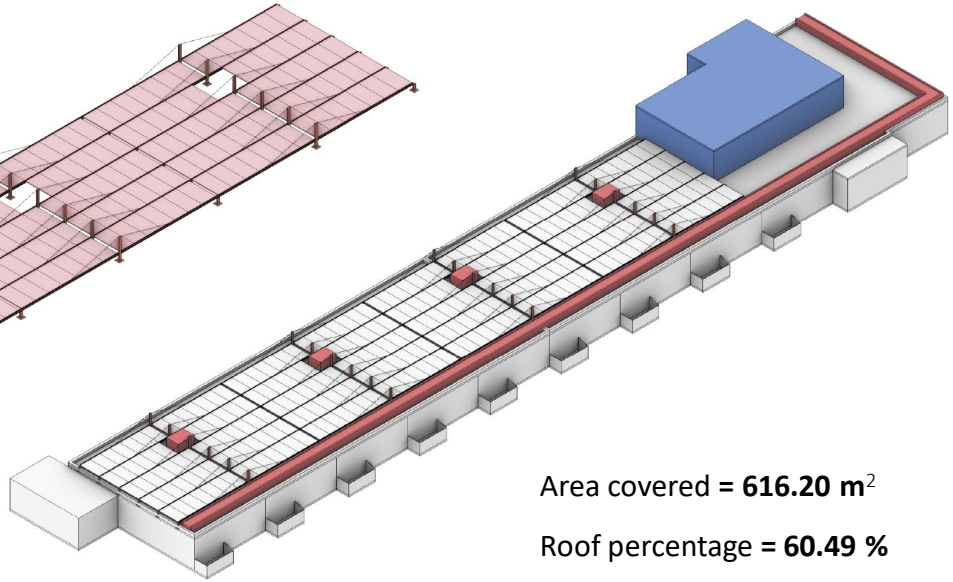
N. Supports = **54**

N. Beams. = **96**

N. Columns = **24**

N. Rods = **48**

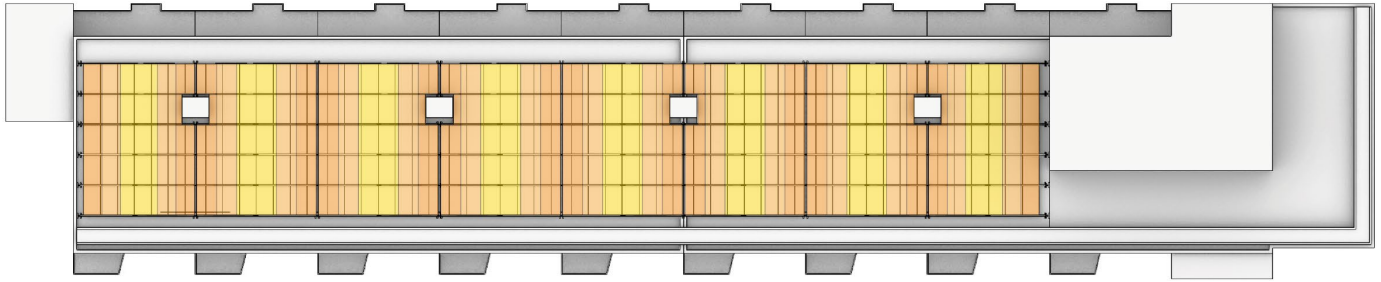




Area covered = **616.20 m^2**

Roof percentage = **60.49 %**

Water buffer capacity = **43 600 L**



Process 3

Building III

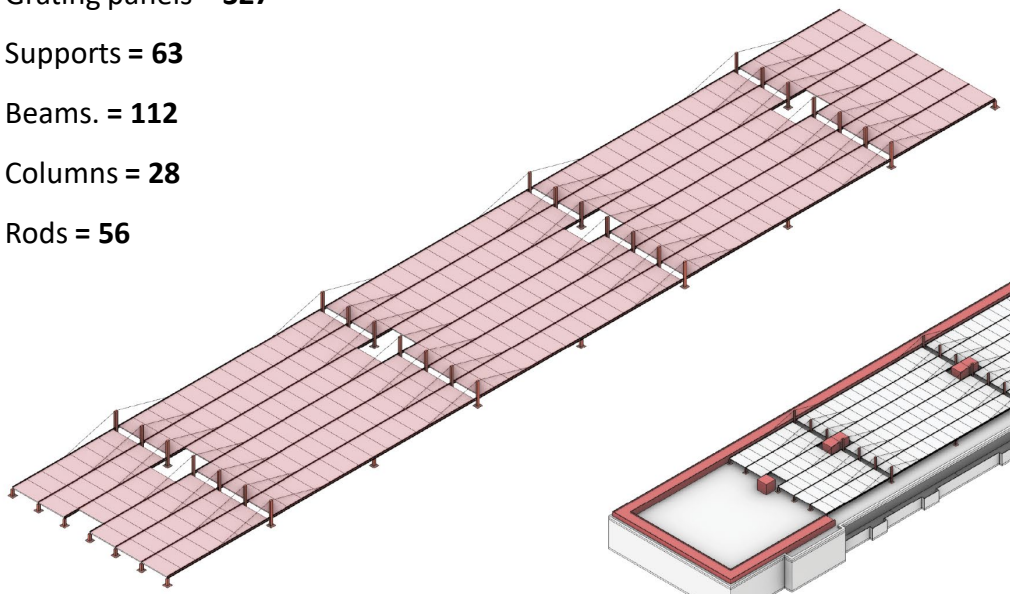
N. Grating panels = **327**

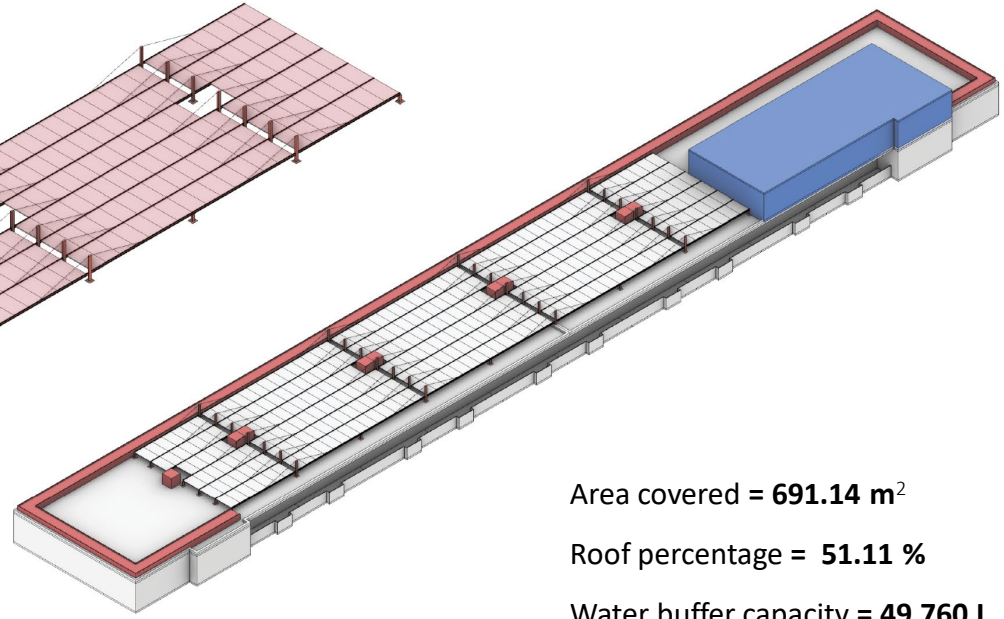
N. Supports = **63**

N. Beams. = **112**

N. Columns = **28**

N. Rods = **56**

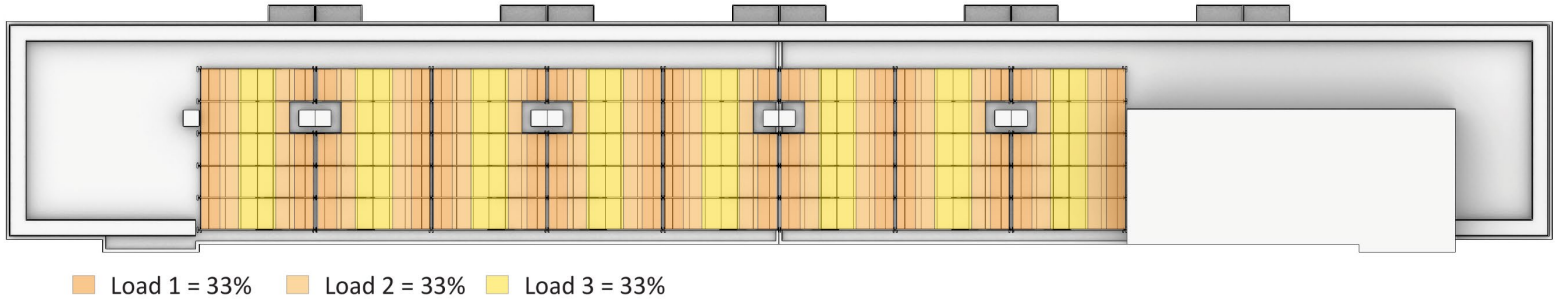




Area covered = **691.14 m**^{2}

Roof percentage = **51.11 %**

Water buffer capacity = **49 760 L**



Design Scenario 1

Building Block IV - Maximum capacity: **5.06 kN/m^2**

Equally distributed Load (EDL):

- Restricted to Load Combinations **A, B, D, E, G, H**
- Designed for: 5.14 kN/m^2

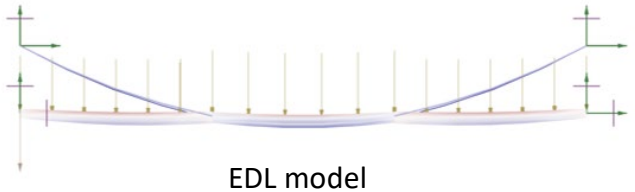
No Intensive Green roofs

Unequally distributed Load (UDL 3+):

- Load 1: **7.14 kN/m^2**
- Load 2: **5.68 kN/m^2**
- Load 3: **4.22 kN/m^2**

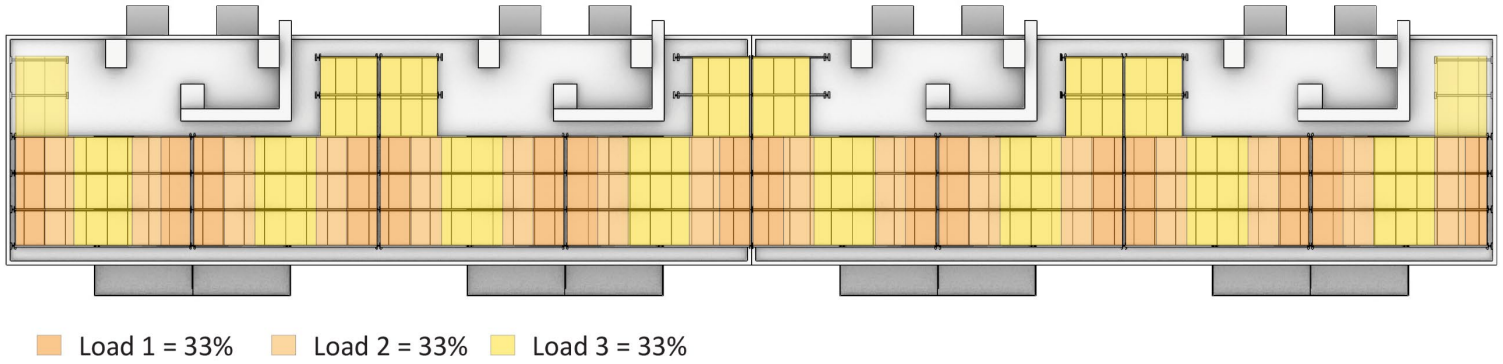
66% of Roof Area available for Intensive Green roofs

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



EDL model

UDL 3 model



(Theoretical case of a 2 stories heigh building)

Design Scenario 2

Building Block IV - Maximum capacity: **4.01 kN/m²**

Equally distributed Load (EDL):

- Restricted to Load Combinations **A**
- Designed for: 5.14 kN/m²

Extensive Green roofs

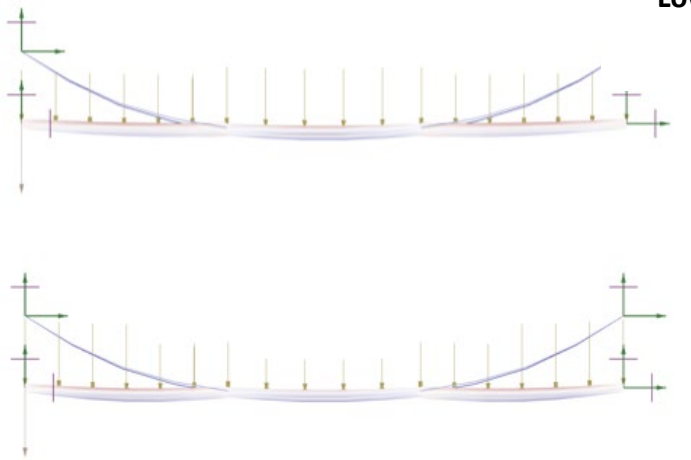
Maintenance only

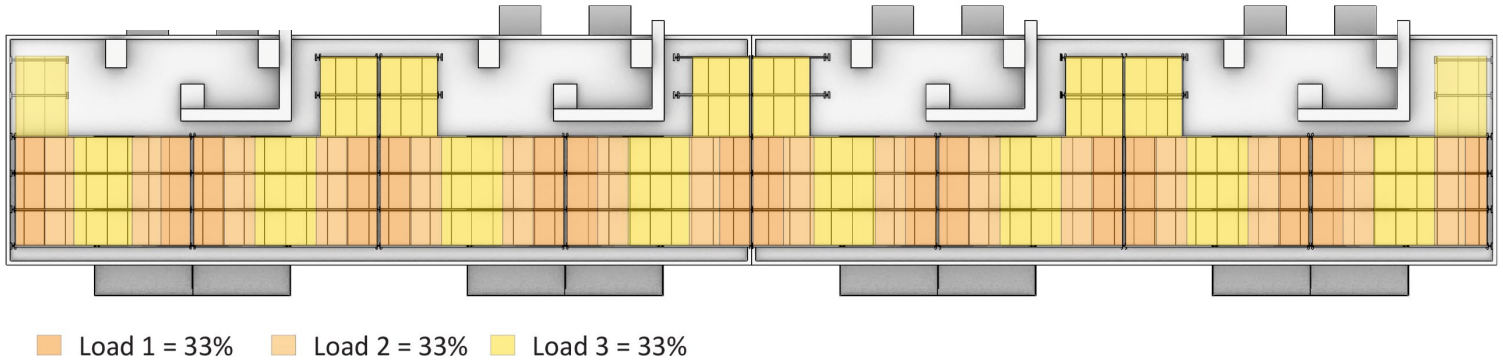
Unequally distributed Load (UDL 3+):

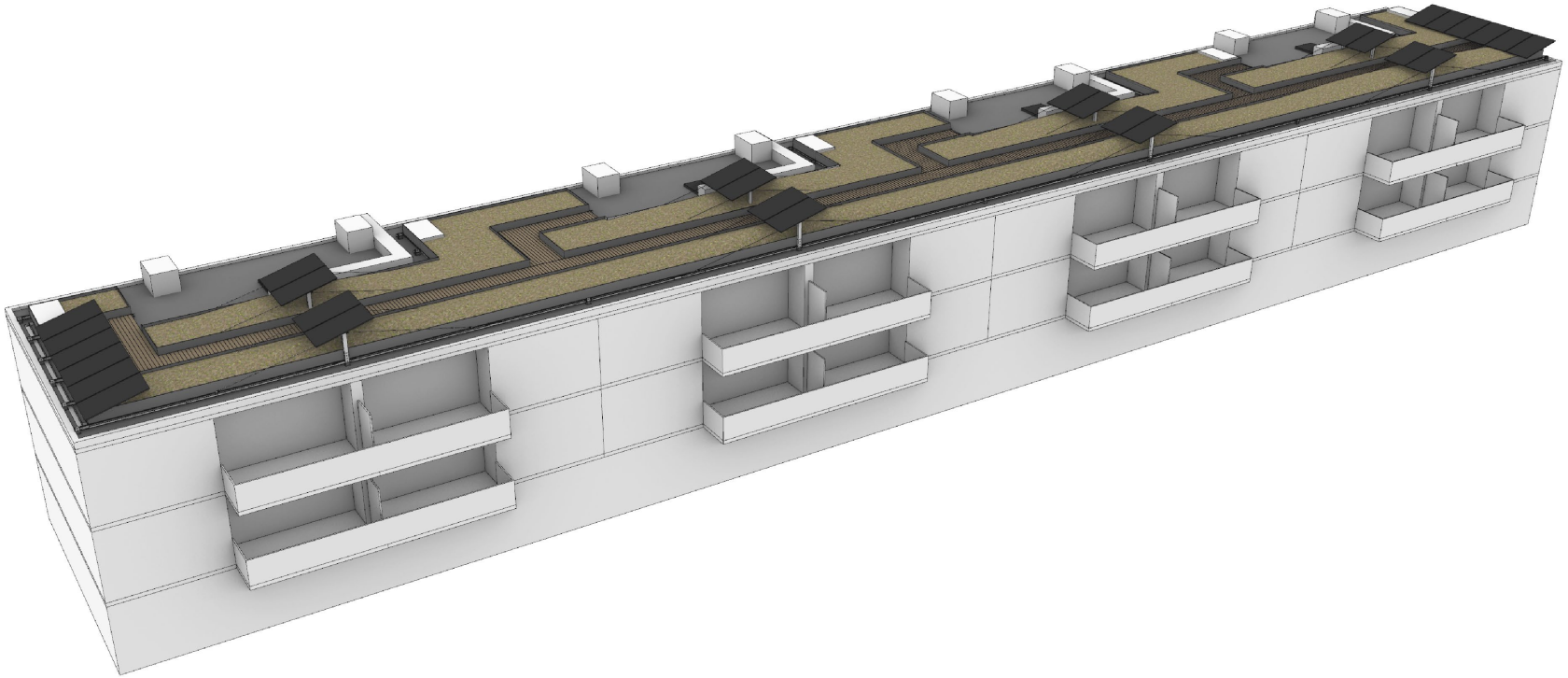
- Load 1: **5.14 kN/m²**
- Load 2: **3.68 kN/m²**
- Load 3: **2.22 kN/m²**

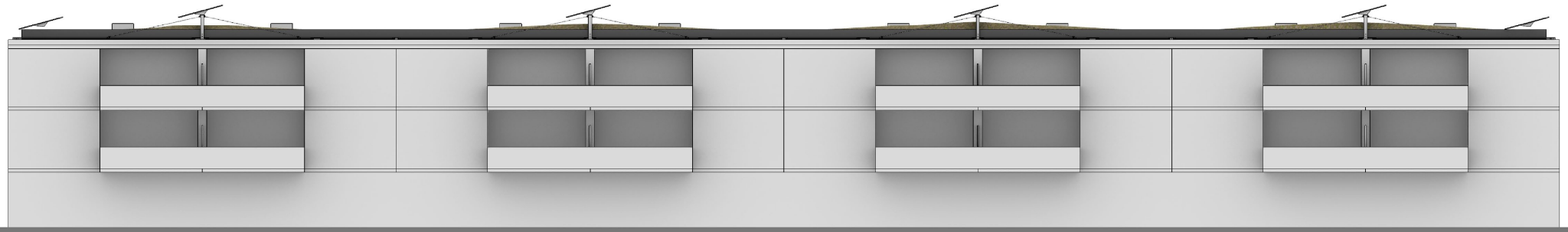
- 33% of Roof Area available for **extensive and semi–Intensive GR**
- 33% of Roof Area available for **Private and Public functions**
- 33% requires to be **interrupted for Low Extensive functions only**

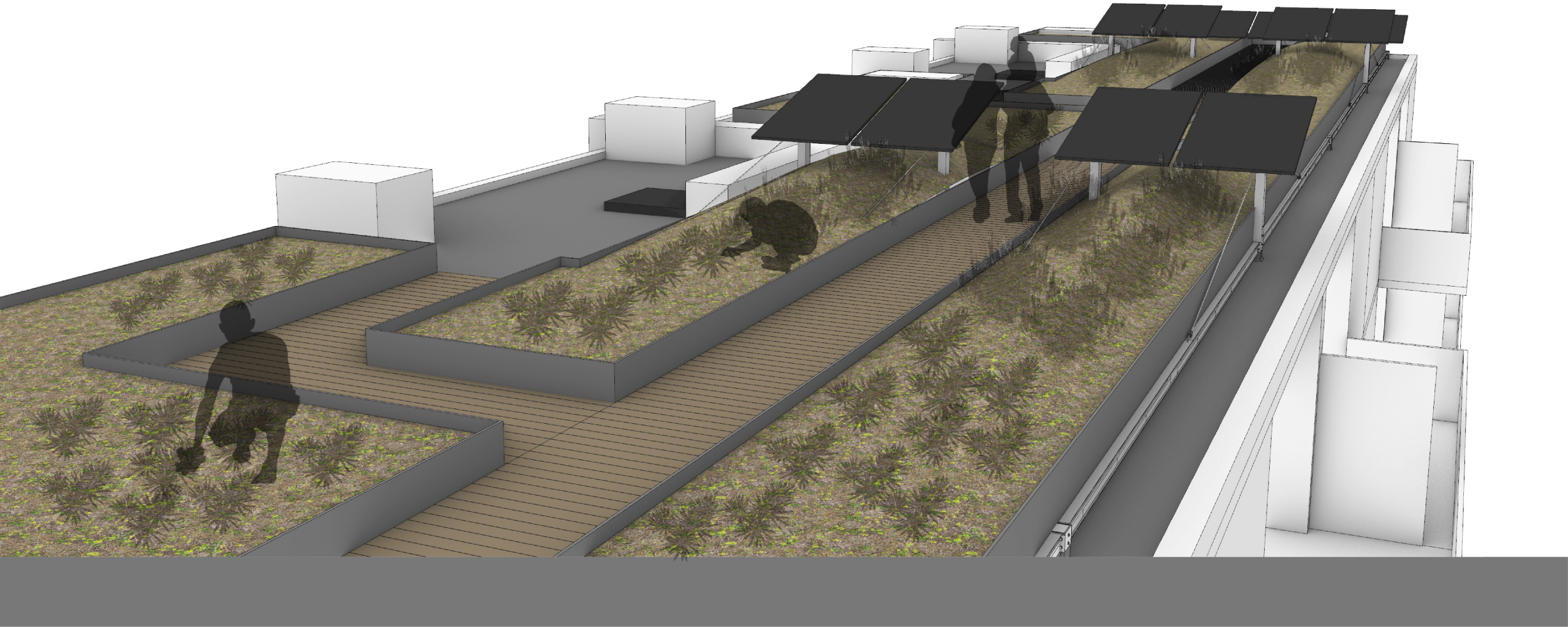
Area [50.4m2]	EDL	UDL 2	UDL 3
Loaded Areas [kN/m2] [%]	40.1 [100]	5.14 – [66.66] 2.22 – [33.33]	5.14 – [33.33] 3.68 – [33.33] 2.22 – [33.33]
Cross Section Height [mm]	140 – 120	140 -100	120 – 100
Wight of Structure [kg/m2]	0.44	0.43	0.42
Peak Reaction Force [kN]	27.56	28.71	25.41
Total Reaction Force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

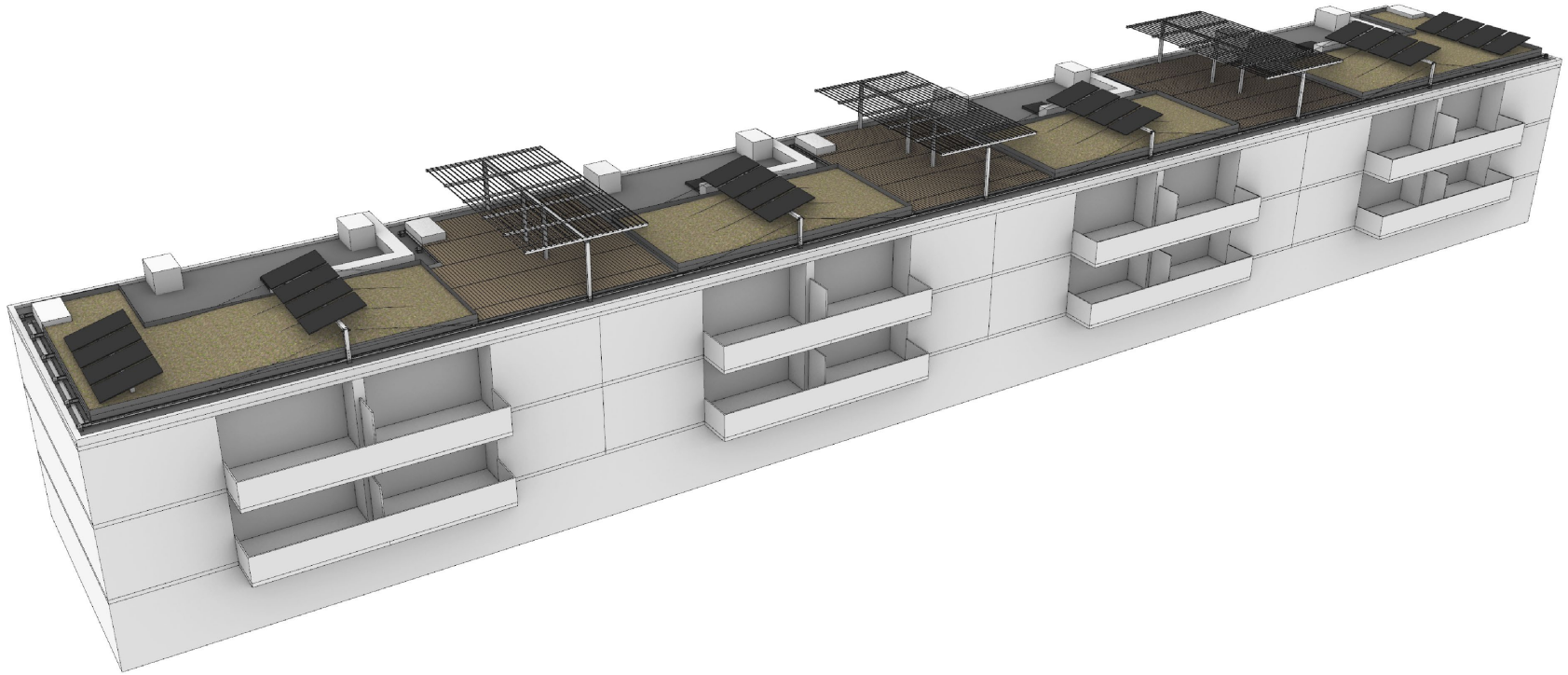


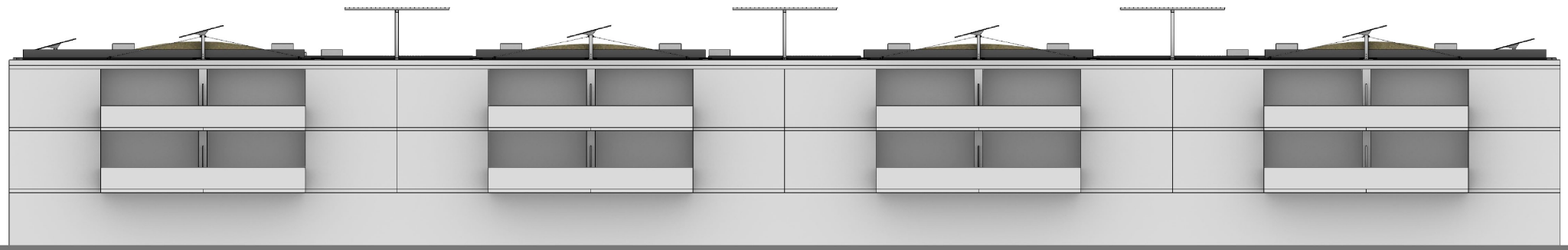


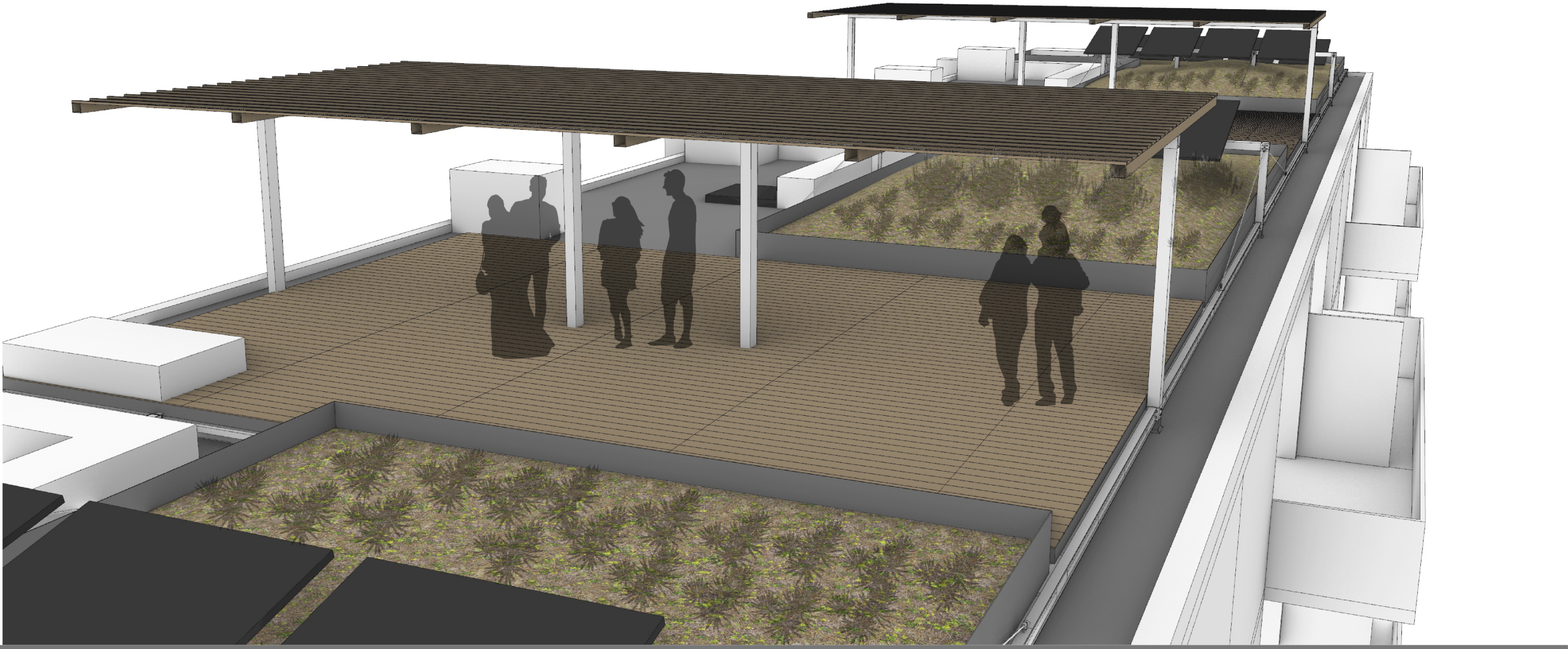












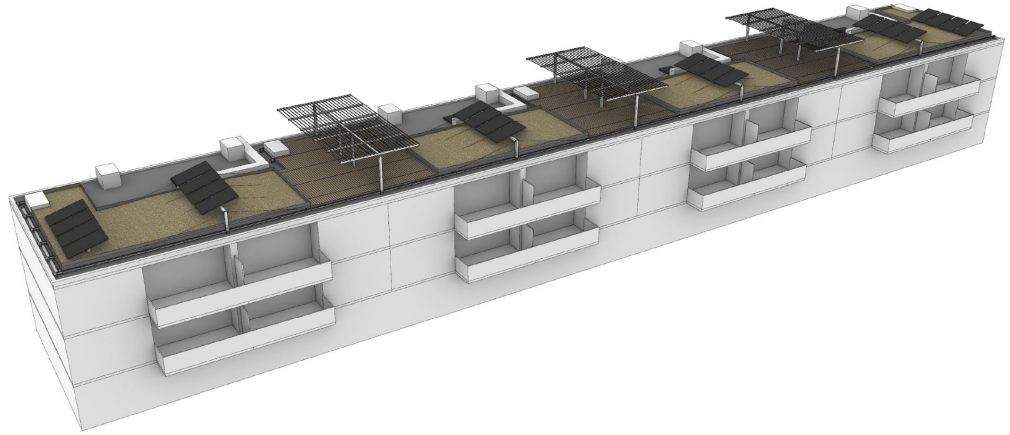
Conclusions, considerations and further steps

Advantages

Adaptability

- Different span lengths and their variation will determine the ideal solution for every case.
- Independency from the existing structure and the insulation and water buffer layers

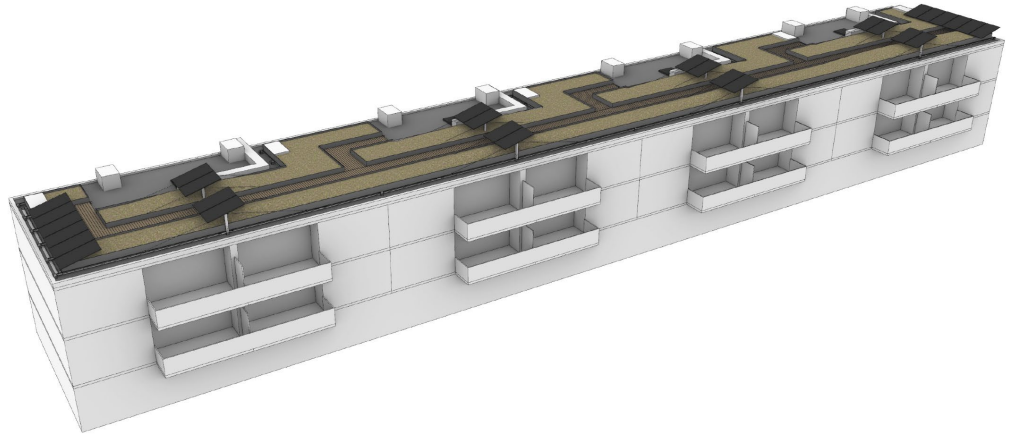
➢ Allows the system to cover the maximum amount of roof area as possible, while preventing drastic interventions on the roof and ease its implementation



Integrated Structure

- Integrating additional functions to the structure without further modifications

➢ Sun shading systems, roofs, solar panels and more



Sustainability

- More sustainable approach than concrete
- The system can be adapted or completely disassembled and reused

➢ Modifications of the system

➢ Further renovation processes for other functions,

Advantages

Design Aid Tool

- Load-Distribution strategy

➢ Great potential for small buildings of reduced capacity

➢ Allow the implementation of higher loads for more impactful interventions

- Allows to run fast simulations of the solutions
- Produce data that can be used for other applications

➢ Quickly Estimate the potential of buildings according to their loading capacities, coverage areas and water buffer capacity

➢ Data for simulations of environmental performance, automatization of production sequences of the strategy and more.

Disadvantages

Limited Design Freedom

- Less restrictive as initially thought

➢ it was possible to see that the solutions will be guided by the two main factors

Structural balance

- Situations that might bring unbalance on the structure:

➢ Construction process

➢ Maintenance: Removal of soil and plants

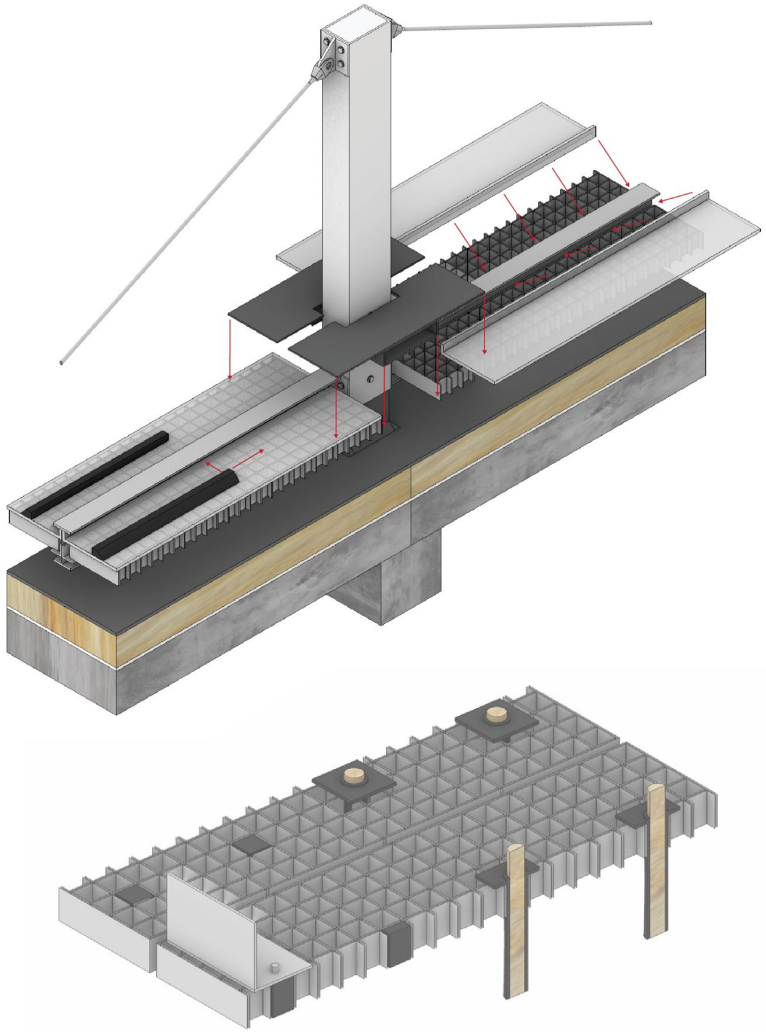
➢ Unpredictable growth of plants

➢ Use of functional areas

Custom components

Design premises: Avoid custom components

- Shear connectors for the grating system
- PET tubes for capillary cones
- FRP box spacers
- EPDM gaskets for the filtration mat.



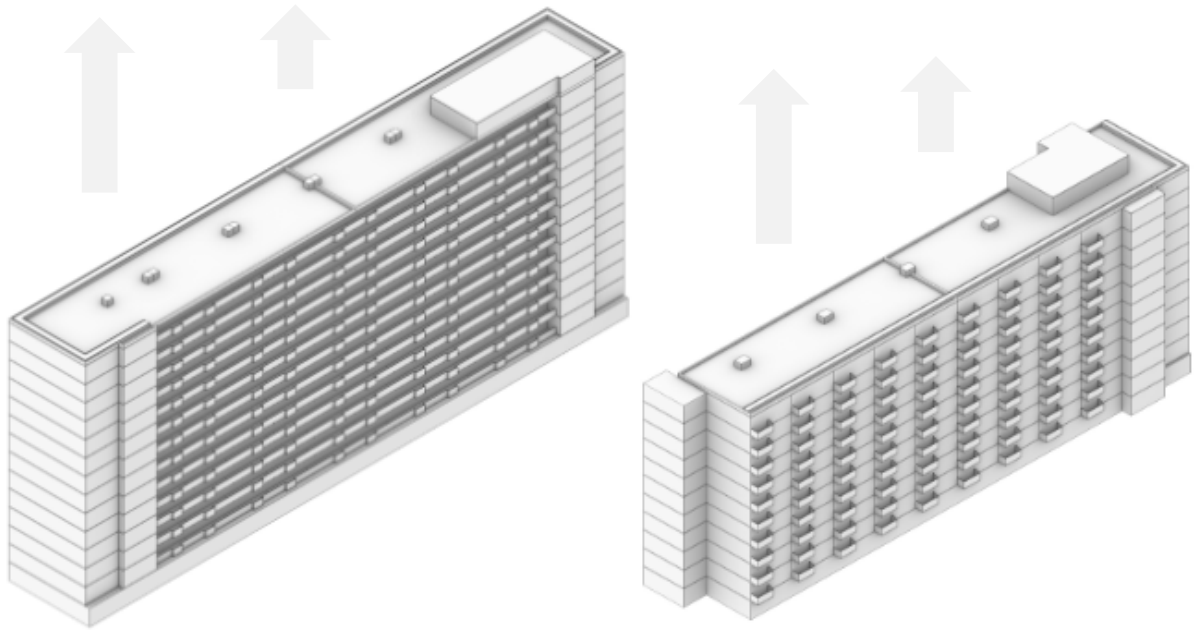
Other considerations

Universal solution

- ➢ Lower safety margins could lead to other possible solutions
- Assembly strategy
- ➢ Buildings above a certain high will require Heavy machinery for installation in any case
- ➢ Could lead to other potential solutions like preassembled units.
- Determining more concise groups of similar characteristics

Residual Capacity of High-Rise Buildings

- Loads that could allow additional floors
- By the same premise of non-regret solutions, simple green roof installations could be considered to not take full advantage of these areas.
- ➢ Additional floors for other functions
- ➢ Roof structures designed for multifunctional roof strategies from start.



Further Steps

Cost estimation of the intervention

- Conduct proper analysis to determine cost
- Determine if solution provides a more accessible solution for investors

Post-War construction typologies database

- Obtaining more data from the different systems

➢ Potential to designate more concise groups

➢ Determine the ideal group of intervention

➢ Other Retrofitting strategies to increase the value of post-war typologies

Design Tool

- Finish Design tool

➢ Segmented functions still required to be linked

Process 1

Geometric configuration of structure

Process 2

Structural Analysis

Process 3

Design Tool output