# TOWARDS A SUSTAINABLE BRIDGE DESIGN

## WITH THE SUPPORT OF OPTIMISATION PROCESSES AND DECISION MAKING SYSTEMS

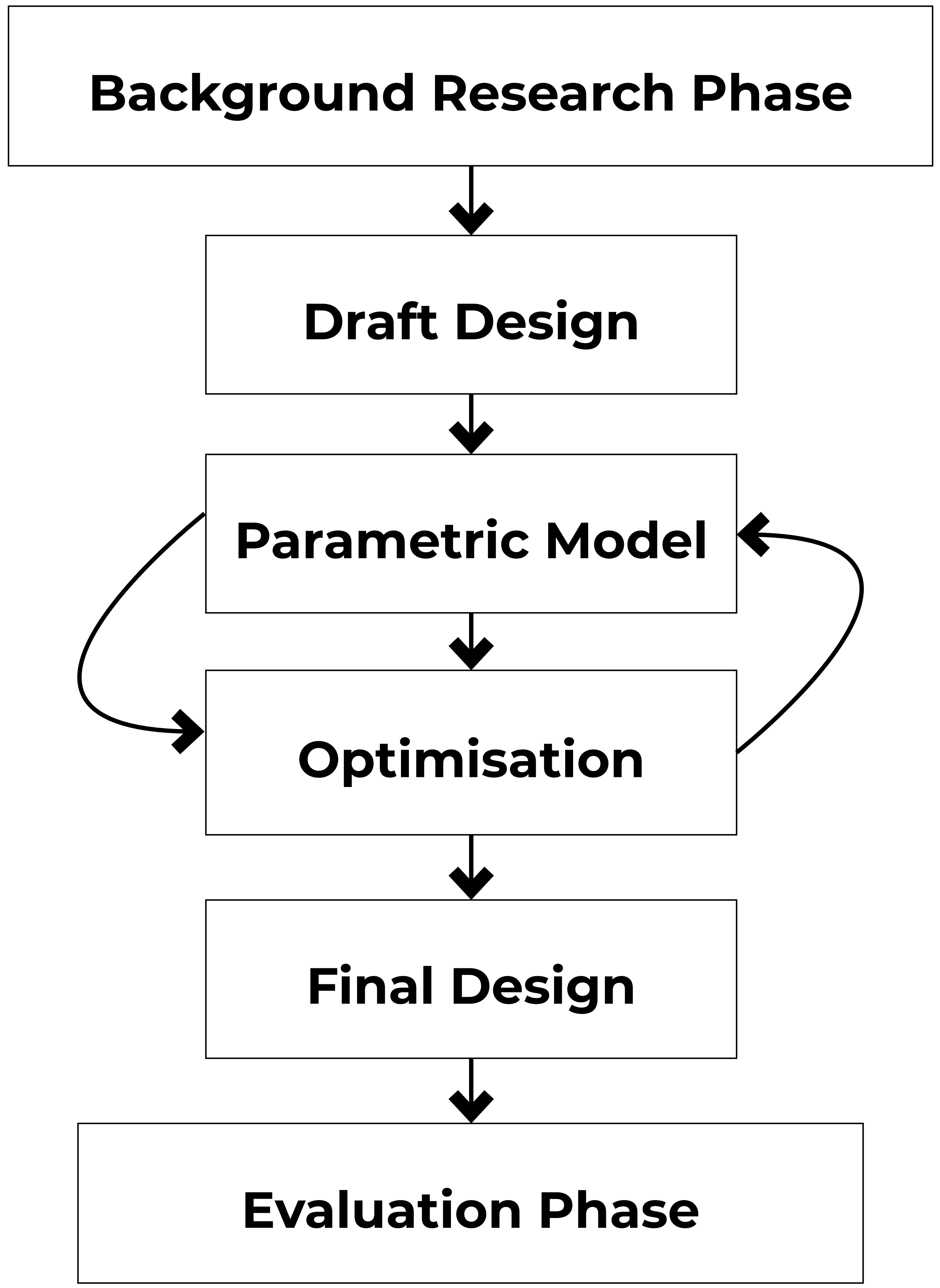
**Alessio Vigorito** 4946219

MSc. Architecture, Urbanism, and Building Science
Building Technology Track

**Joris Smits** (first mentor) | **Michela Turrin** (second mentor)
**Stijn Joosten** (external mentor) | **Huib Plomb** (delegate of the board of examiners)

# Content

# Content


Background Research Phase
Draft Design
Parametric Model
Optimisation
Final Design
Evaluation Phase

# Methodology

# Problem statement

In 2000, **Rome’s municipality** solicited a design competition for a new bridge located in the South-West quadrant of the city, expressing the desire to build it for 2025.

The bridge’s design must be able to satisfy the functional requirements while being aesthetically pleasing, keeping in mind the strong relationship it will have with the nearby E.U.R. district, dominated by a **monumental and rationalist architecture**.

# Research objectives

The primary purpose of this research is to design a bridge that not only meets structural performance criteria and architectural beauty but that also aims for an effective use of the materials in order to fulfill one of the numerous criteria involved in the definition of a sustainable design.

With the support of multi-objective optimisation processes and multi-criteria decision-making methods, the goal will be to optimize the project to obtain a satisfactory design for **architectural quality, safety, and reduction of material usage**.

# Research question

***In what ways does the optimisation method impact the design process workflow and to what degree do these add value in respect to the project's sustainability?***

Sub questions:

- What are the main parameters to consider in order to make a **parametric model** suitable for this research?
- How can a system to support **decision-making** from the output of the optimization process be implemented?
- To what extent can a **designer influence** the final result of the optimisation process in order to remain in control of the outcome of the original design?
- Can the optimisation method used provide the designer **directly** with an optimal solution?

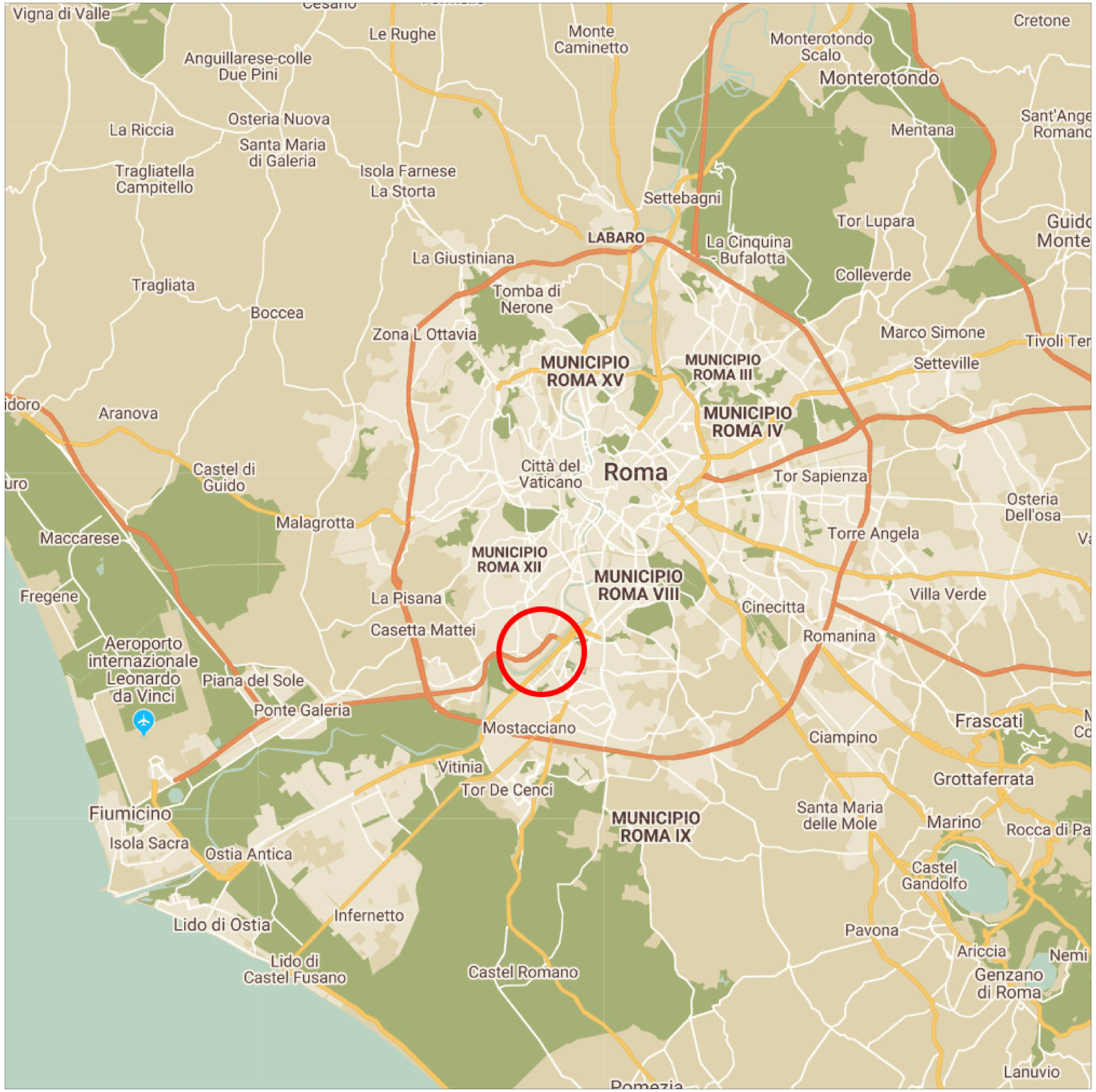
# Draft Design

# Location

The chosen location is in the South-West quadrant of the city of **Rome, Italy**.

The new bridge will connect the two districts **Magliana** and **EUR**, separated by the river Tiber.

A connection is already present, the **Magliana bridge**. Still, it is not sufficient to satisfy the needs of the current traffic flows and future ones due to the **new football stadium**'s construction in the South.



# Bridge location

# E.U.R.

The name derives from the acronym Universal Exposition of Rome as it was designed for the **1942 World Expo.** The urban plan was commissioned by Benito Mussolini to celebrate the twenty years since Fascism took power and with the circumstance of the upcoming exhibition.

The project is a direct expression of the fascist ideology, inspired by classical roman urban planning and elements of **neoclassicism** and **Italian rationalism**, the "statal architecture". The urban layout includes orthogonal axes and monumental architectural buildings, massive and square, covered with **marble and travertine**.


(Source: hoteldeicongressiroma.com)


(Source: romasparita.eu)

# E.U.R. district

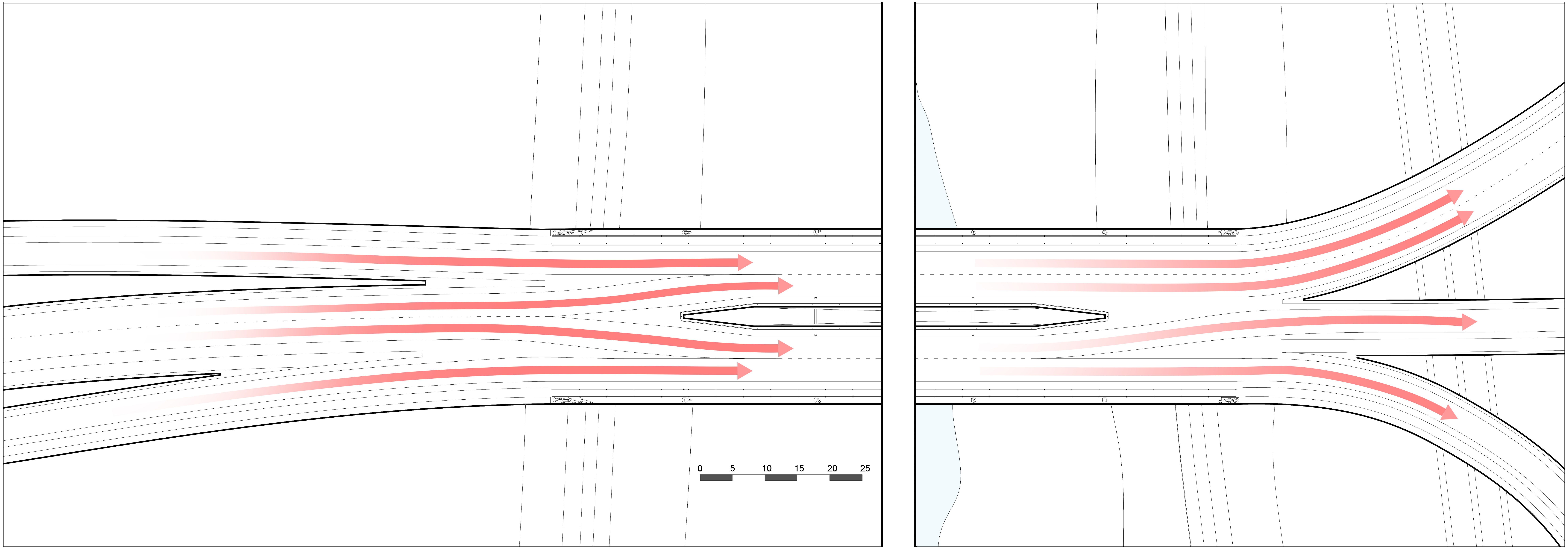

(Source: albertocogo.wordpress.com)

# Bridge requirements

- **Span of minimum 170m**
- **4 one-way lanes for car traffic**
- **Connection for pedestrians**
- **A new landmark and gateway to the city**

# Road system

# Traffic flows management



# Architectural language

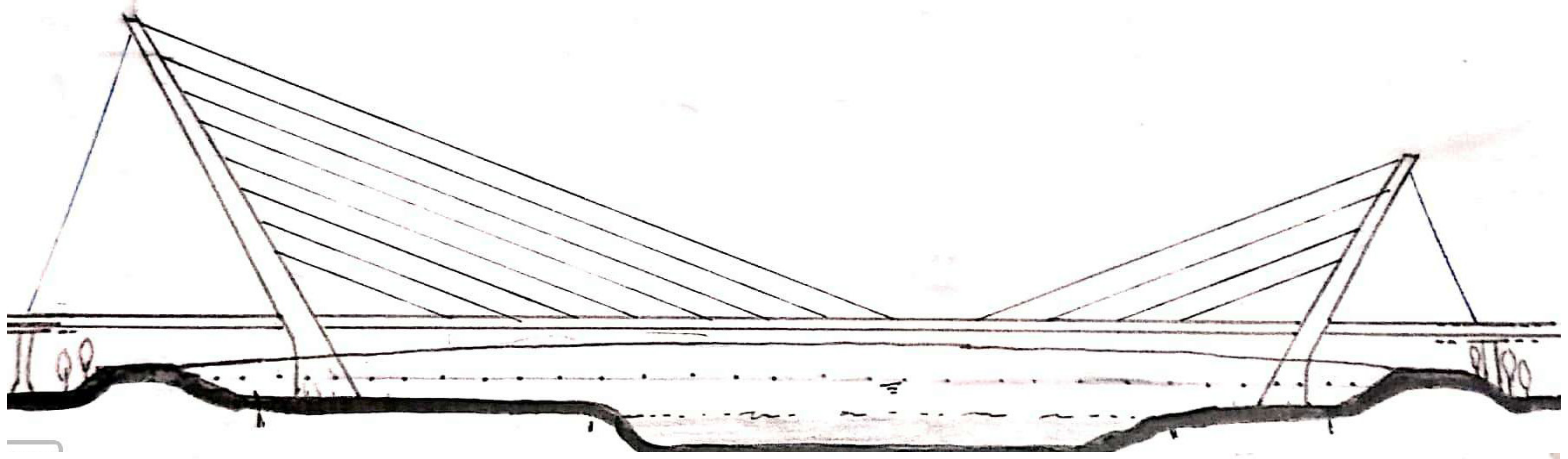
(Source: cesar-eur.it)

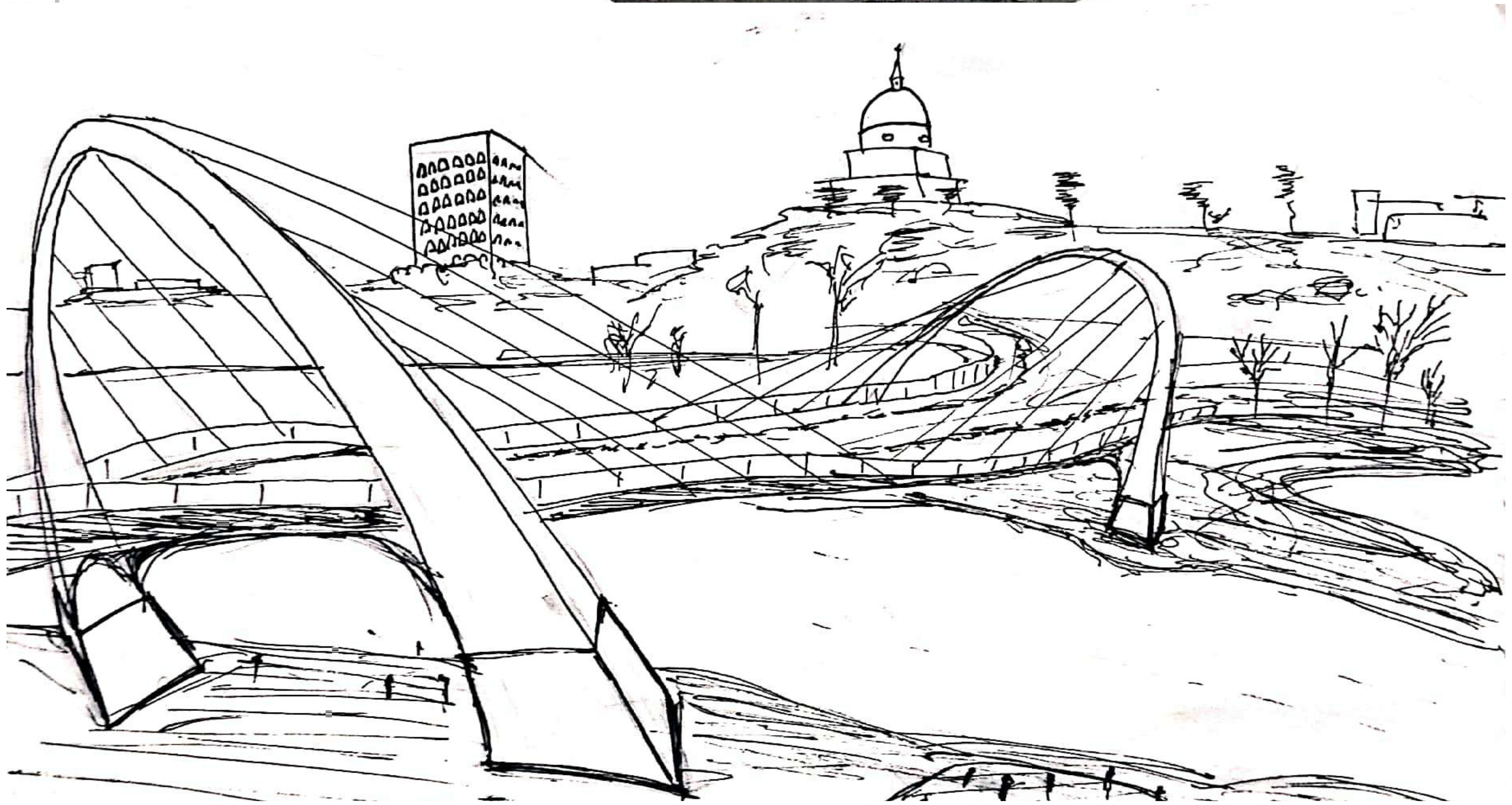
• **Palace of the italian civilization**

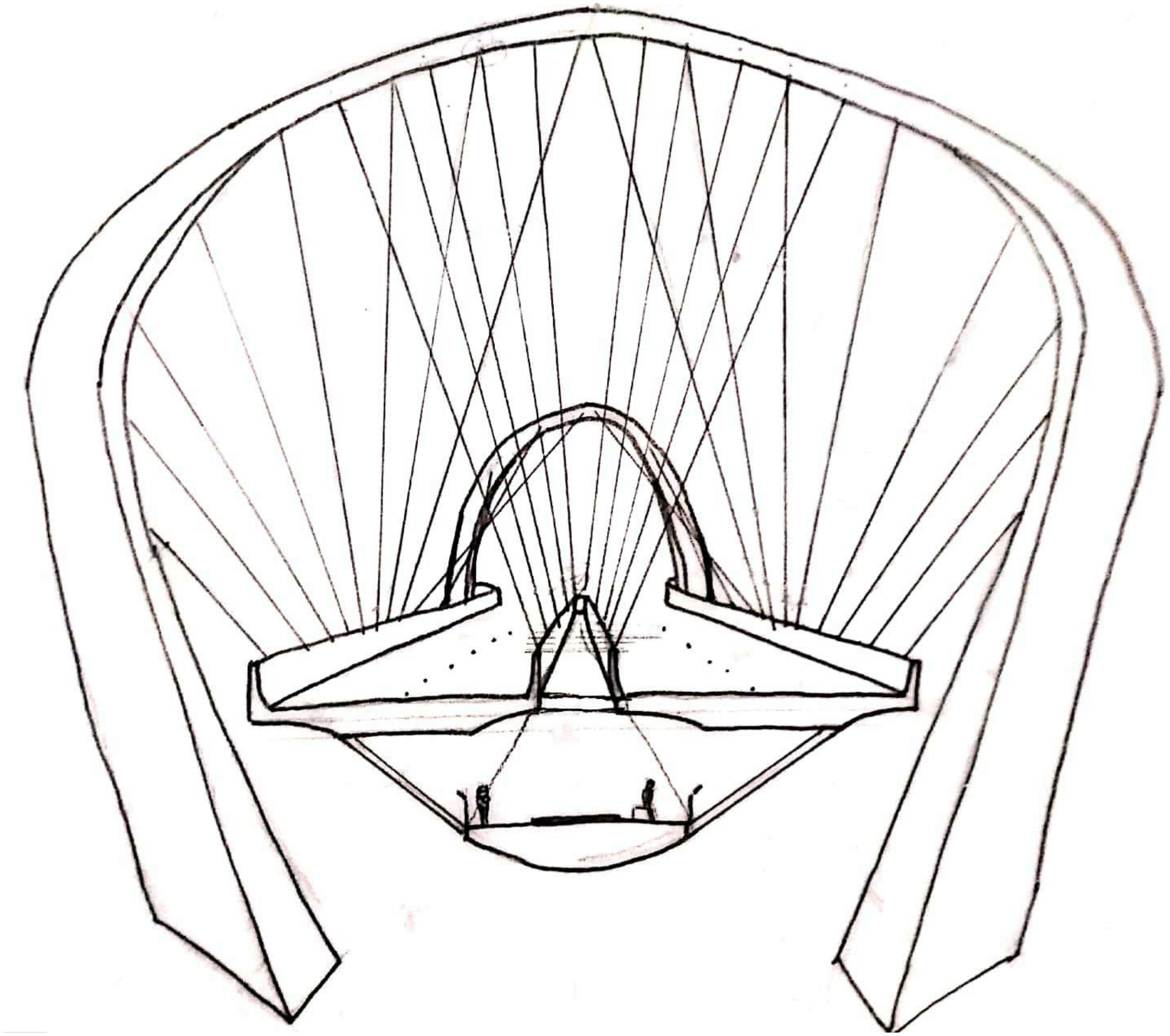
(Source: cesar-eur.it)

• **Libera's monumental arch**

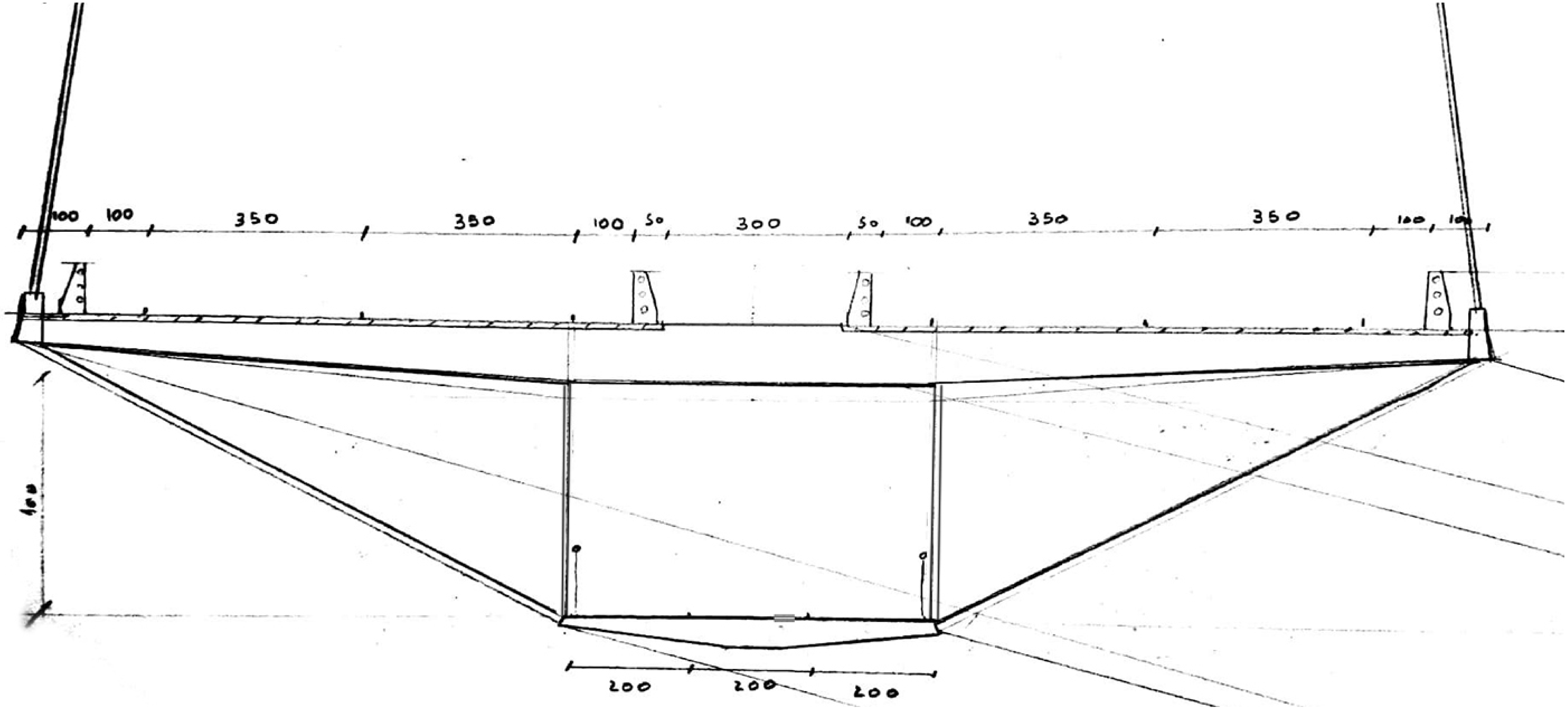
# Architectural language







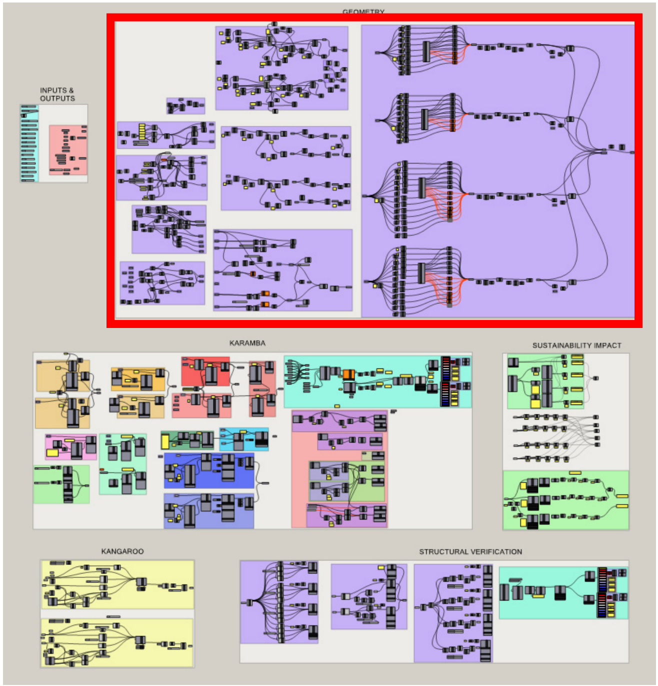
# Deck draft design



# Parametric Model

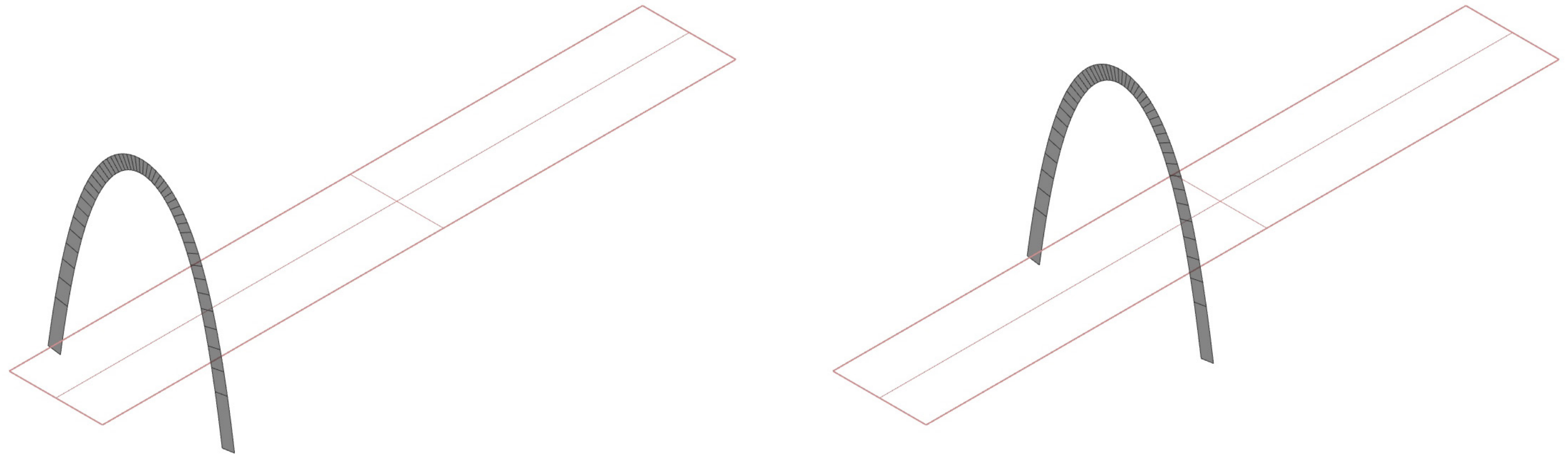
# Constraints

- **Cable-stayed typology**
- **Decks width**
- **Shape of the pylons (arches)**
- **Equidistance of main cables and footbridge supports**
- **Position of the landings**

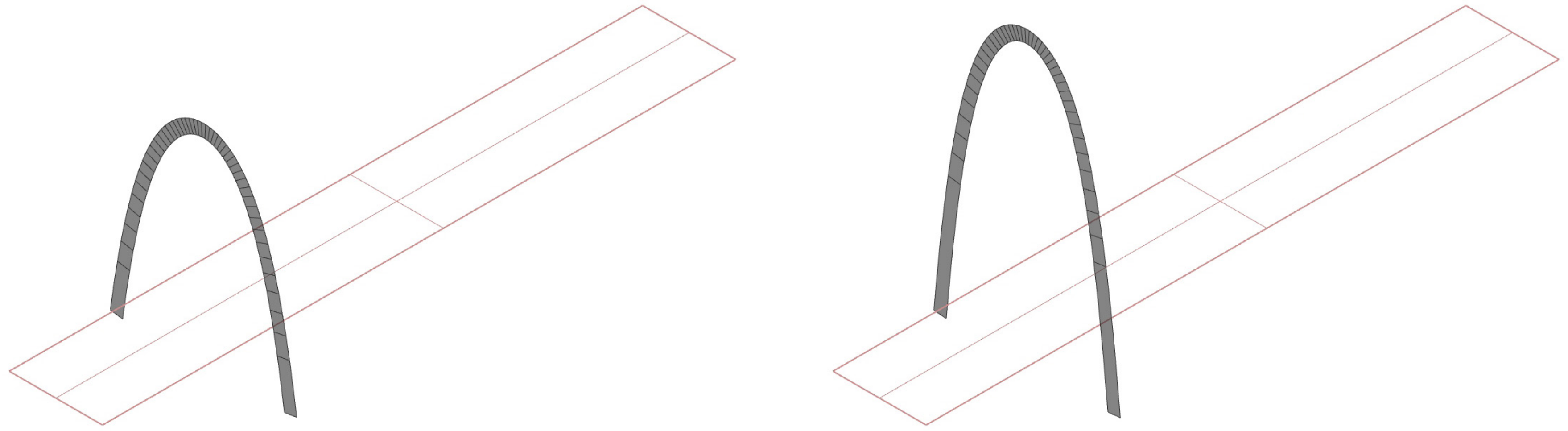


# Variables

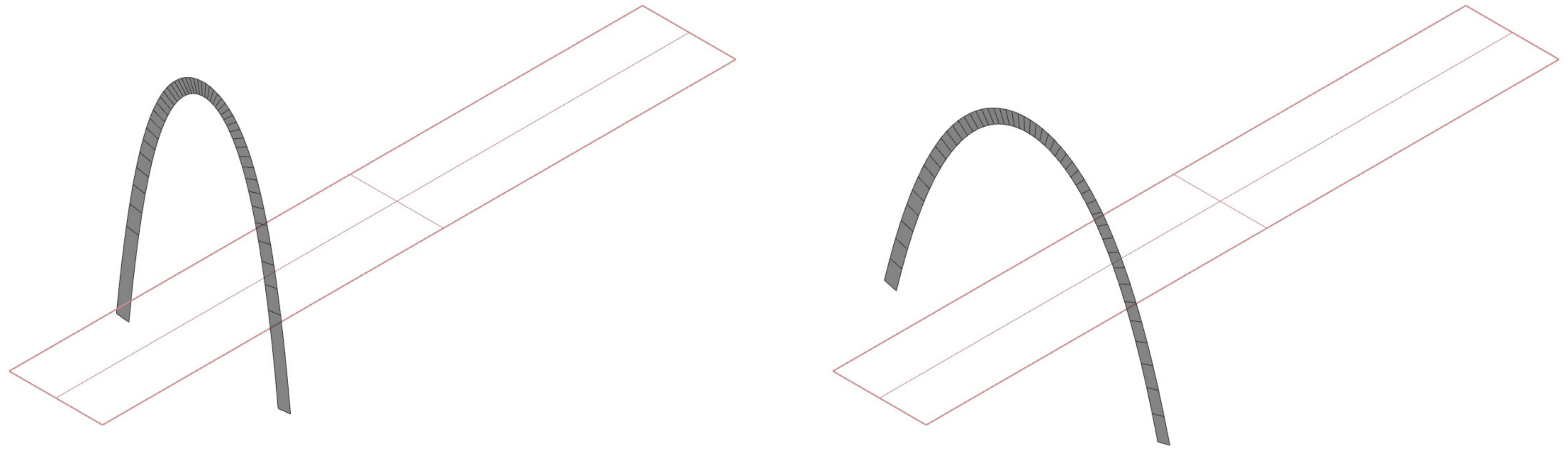
- **Pylon's position**



- **Pylon's height**

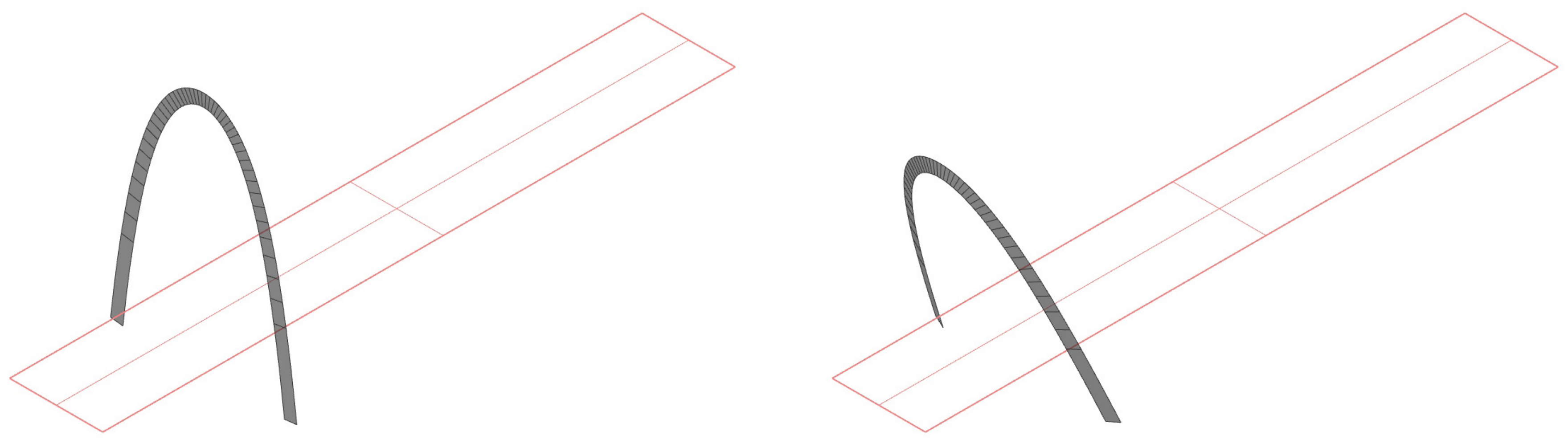


- **Pylon's width**

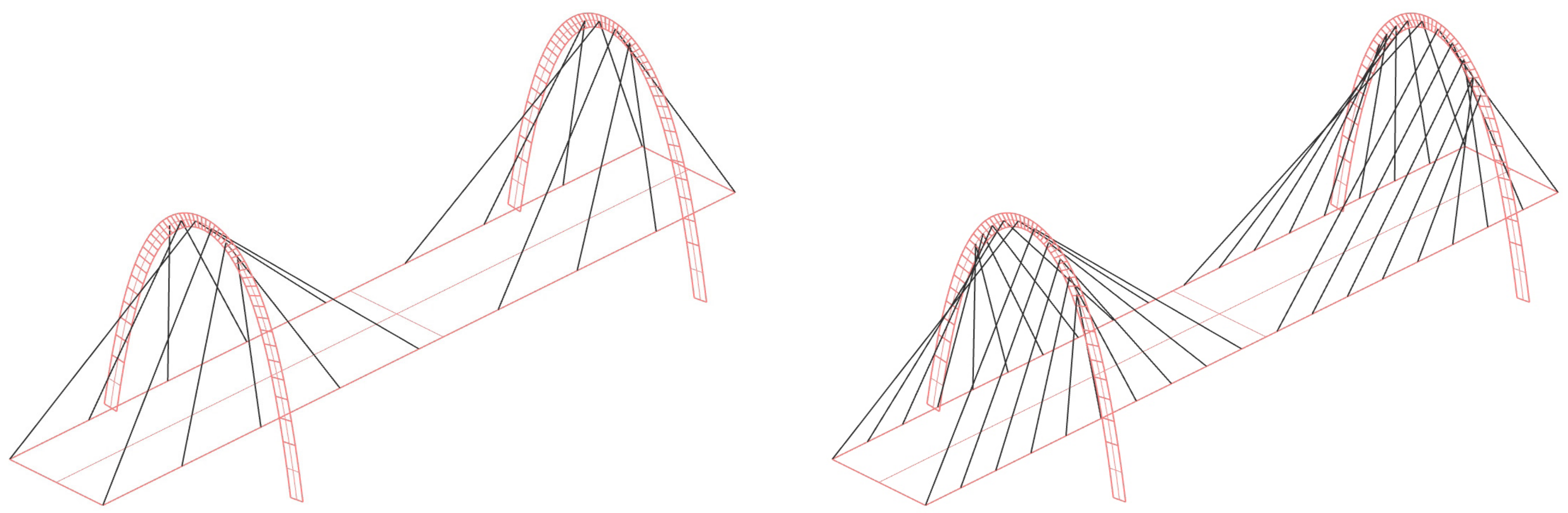


# Variables

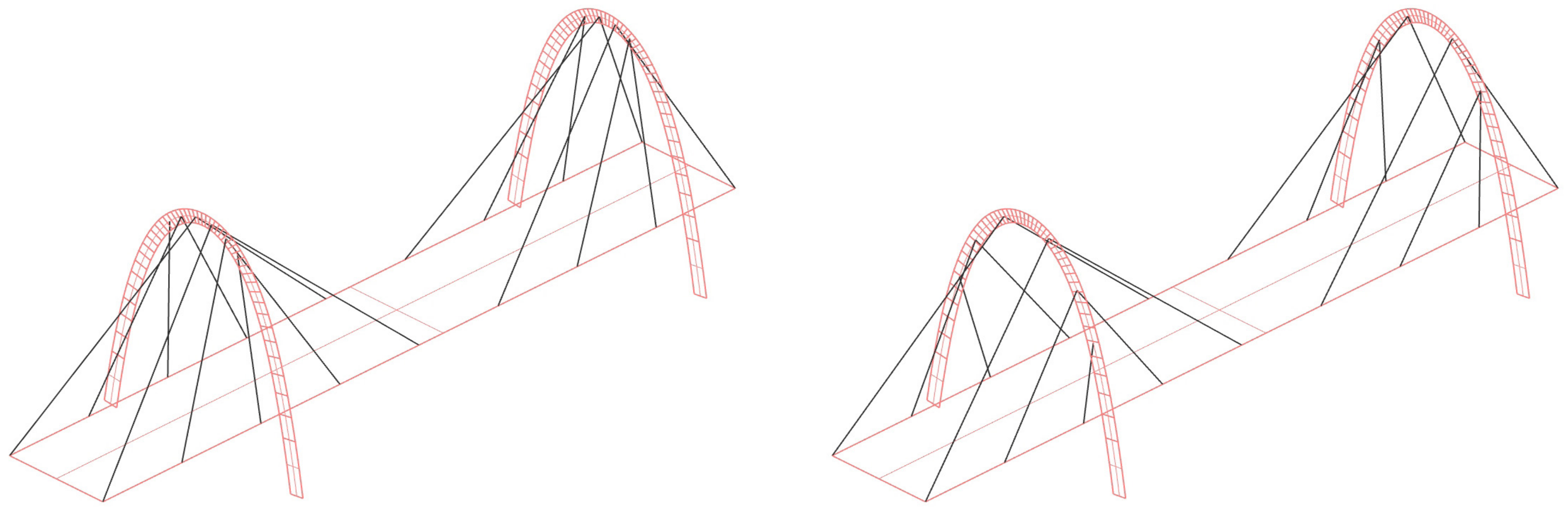
- **Pylon's inclination**



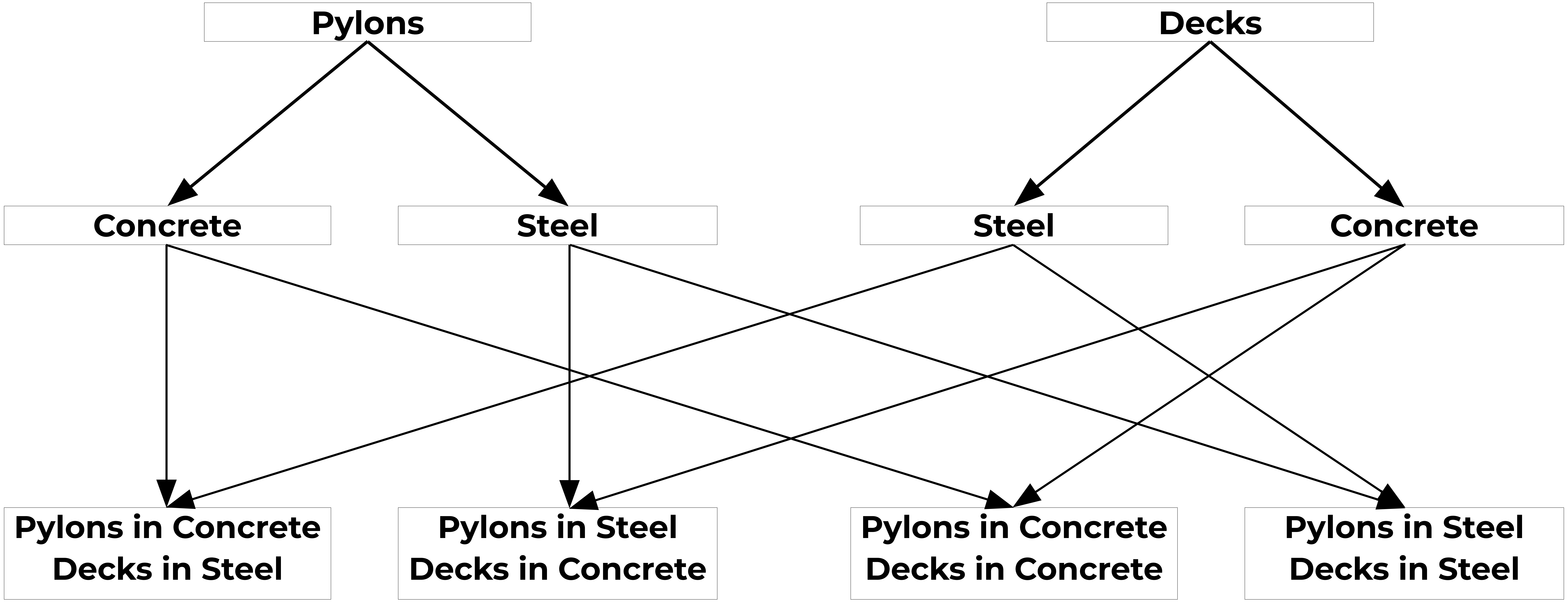
- **Number of cables**



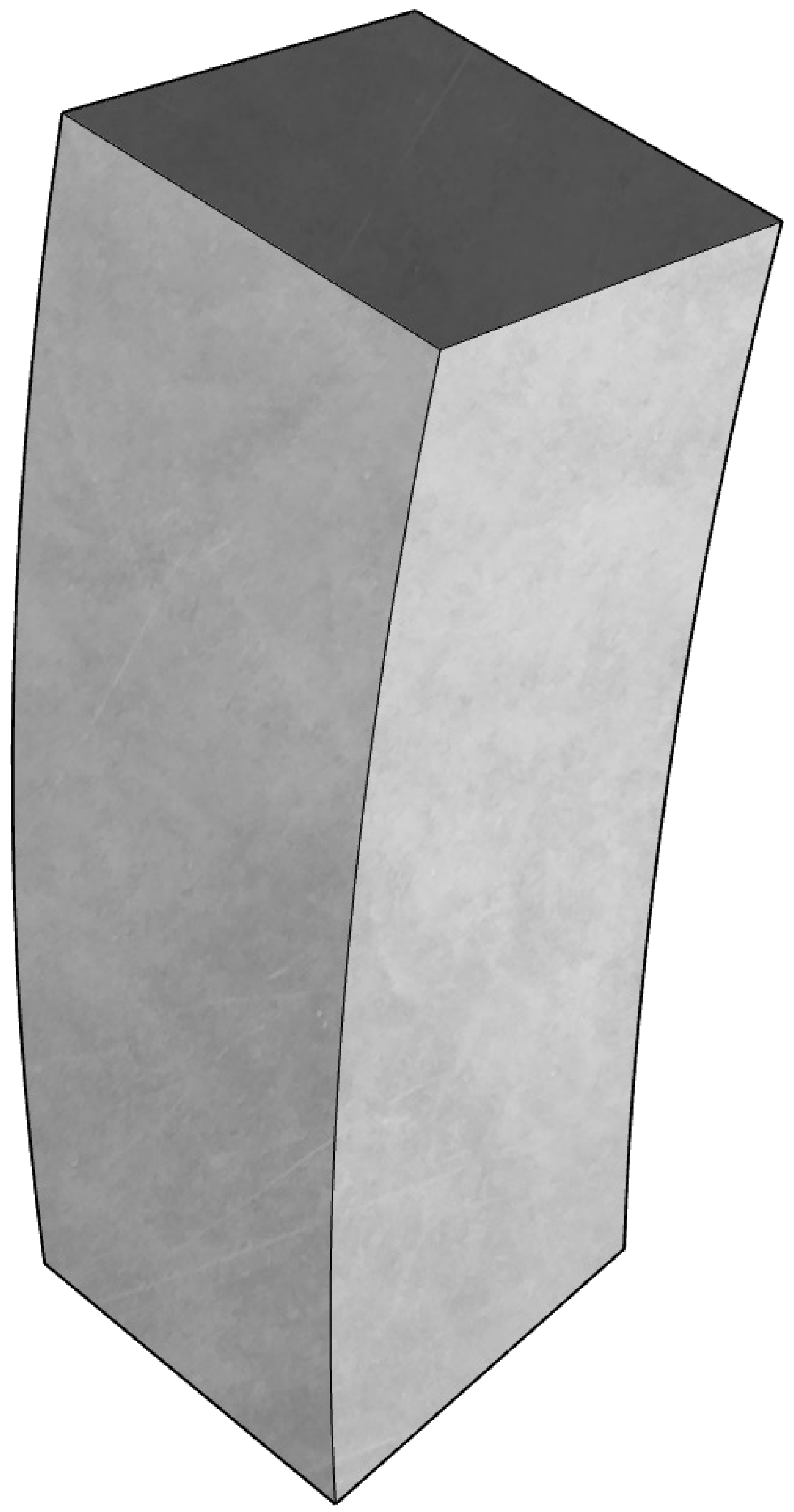
- **Distance between cables**



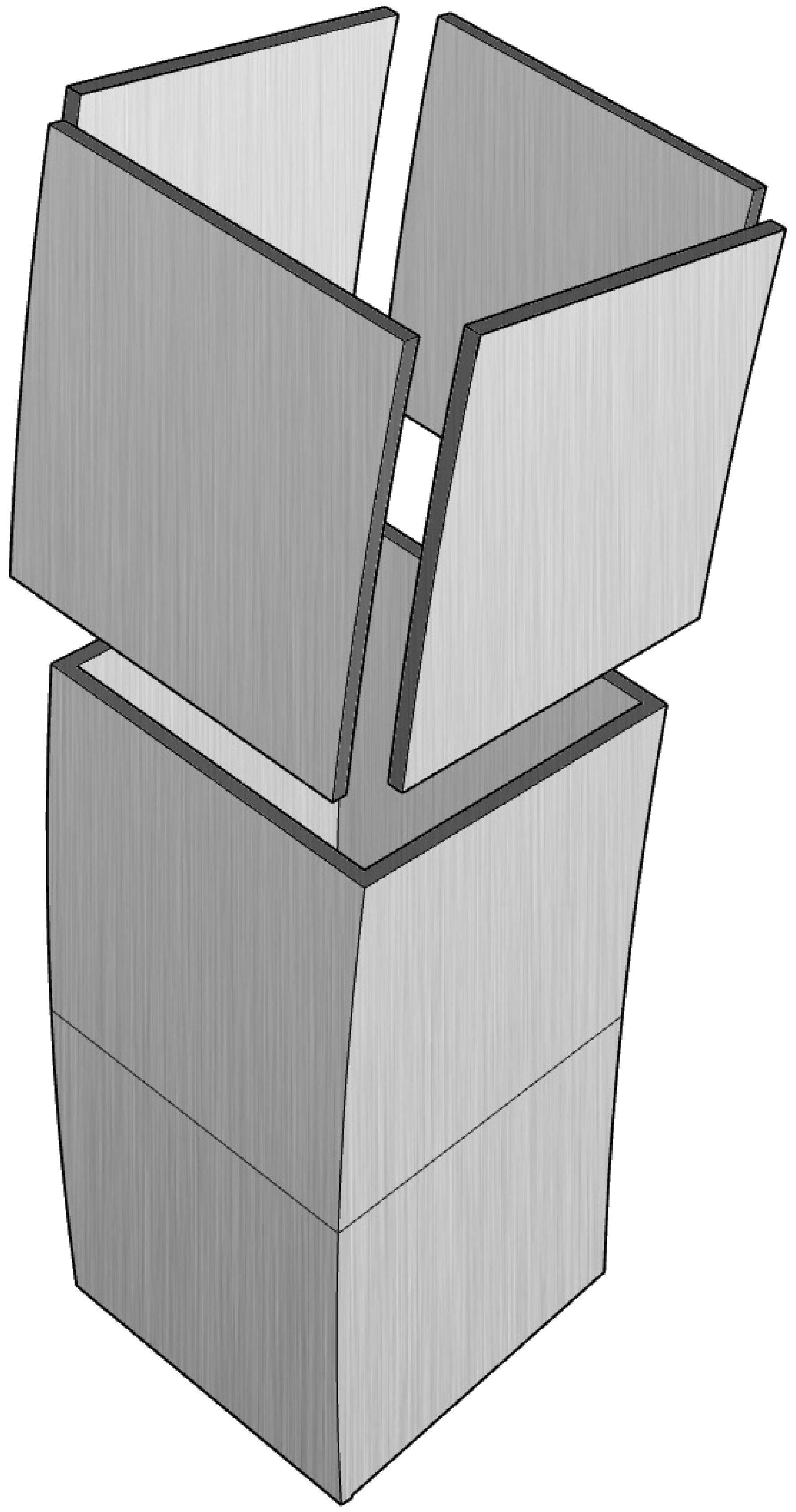
# Materials


Pylons
Decks
Concrete
Steel
Steel
Concrete
Pylons in Concrete
Decks in Steel
Pylons in Steel
Decks in Concrete
Pylons in Concrete
Decks in Concrete
Pylons in Steel
Decks in Steel

# Pylon

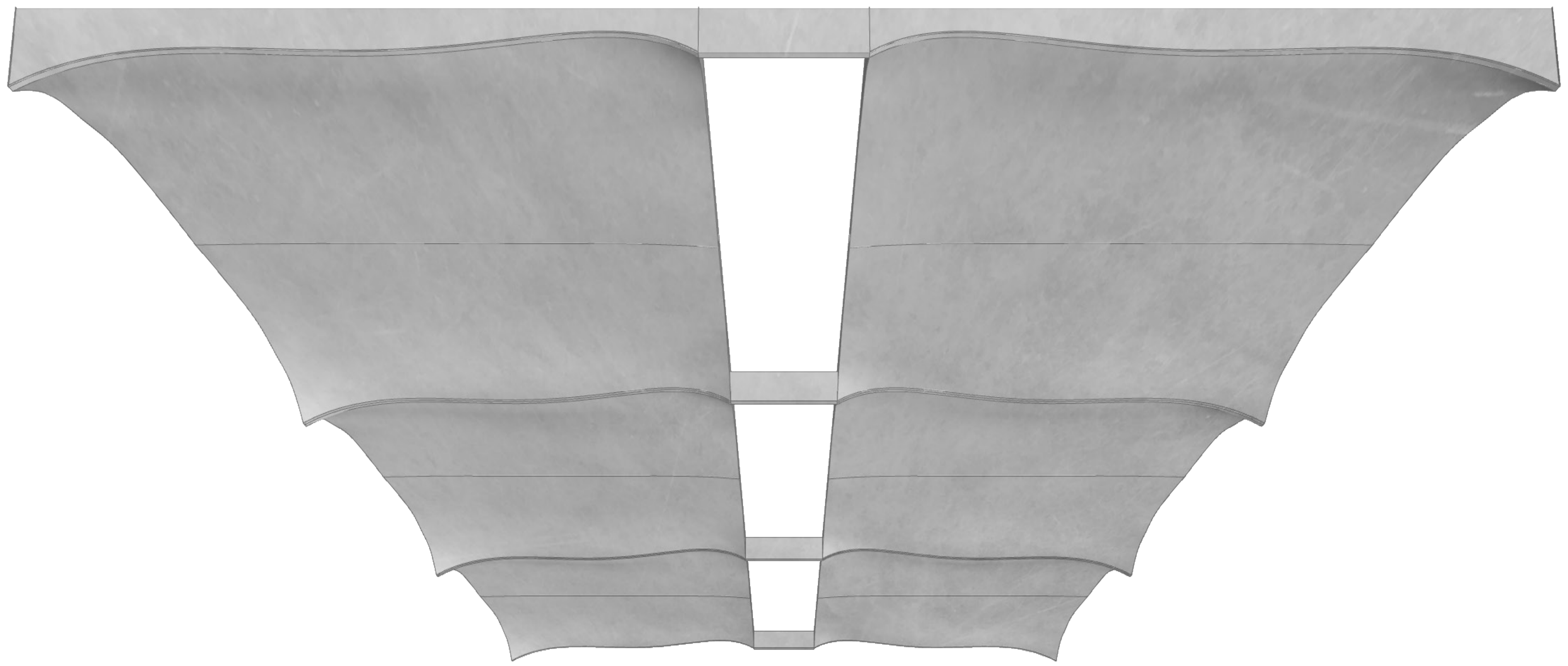


- **Concrete**

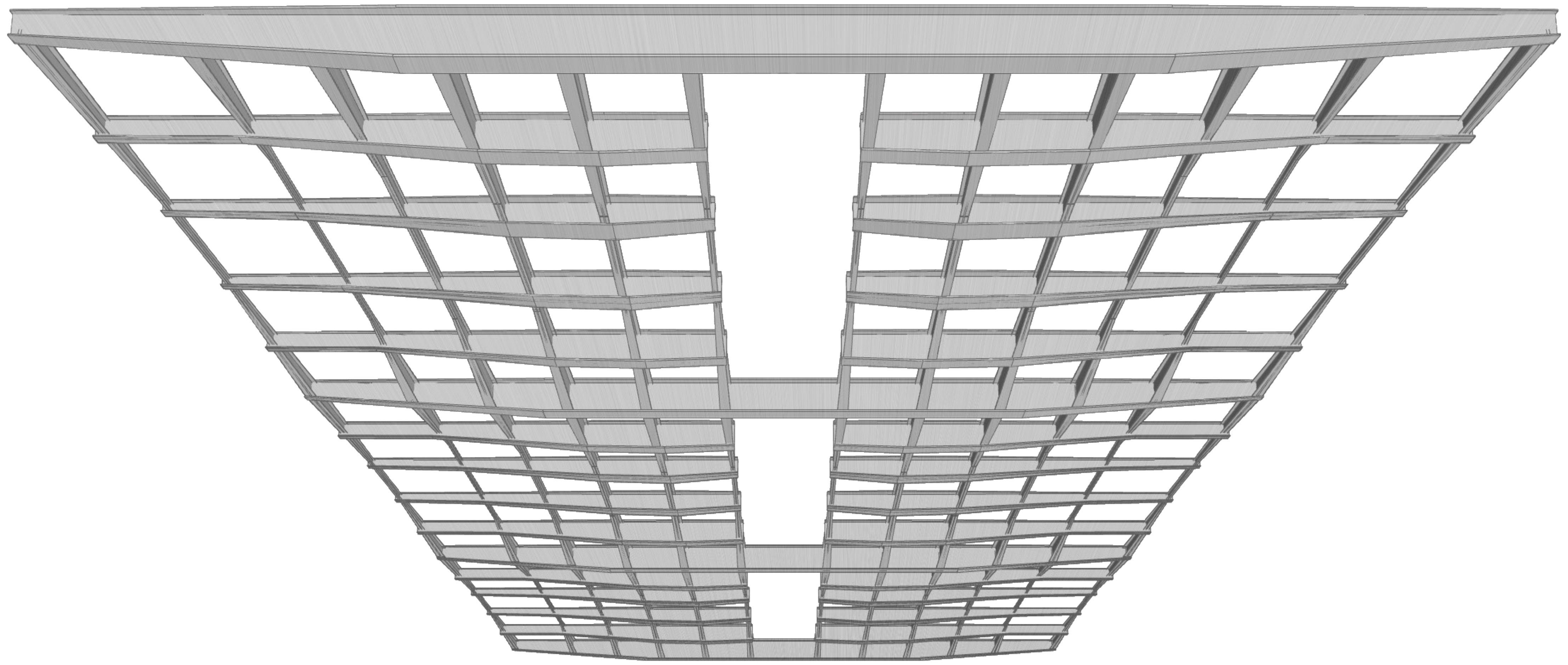


- **Steel**

# Deck

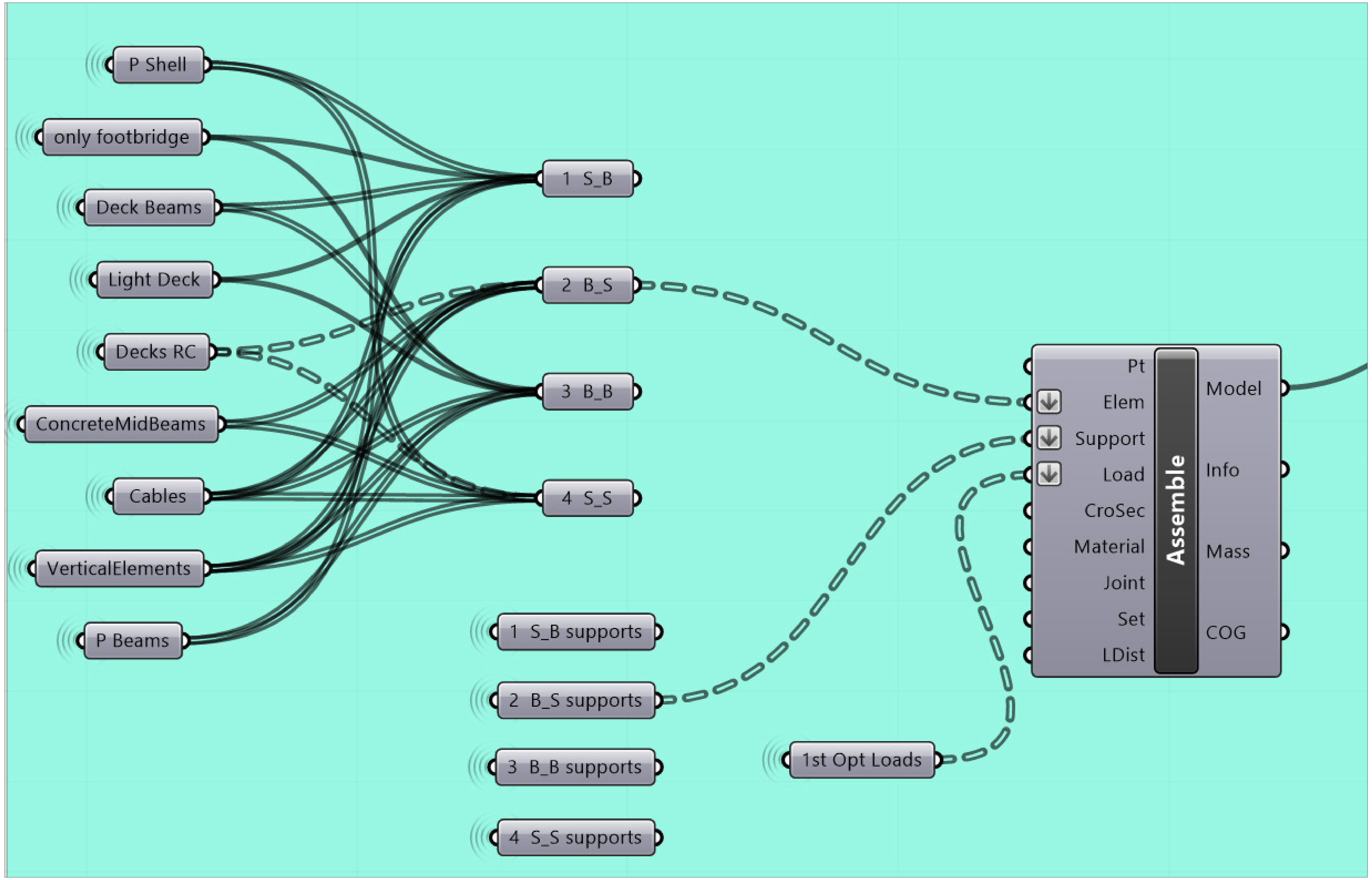


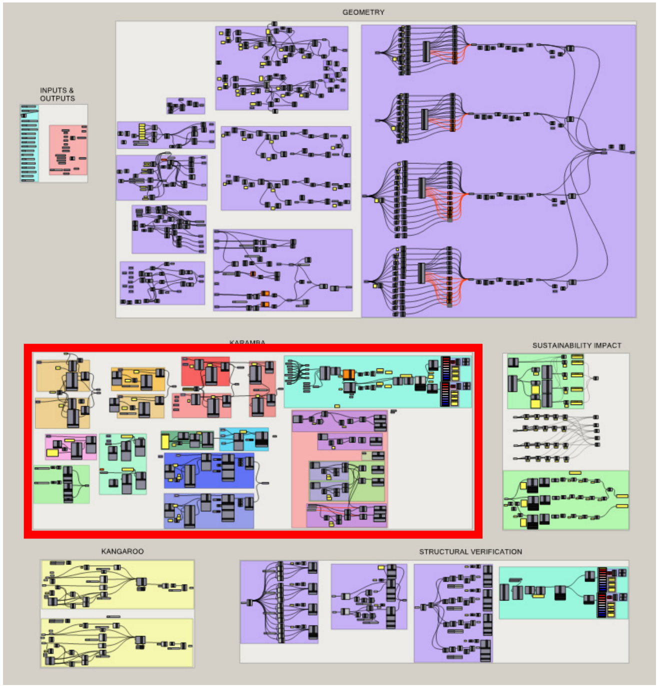
• **Concrete**



• **Steel**

# Model assembly (Karamba)



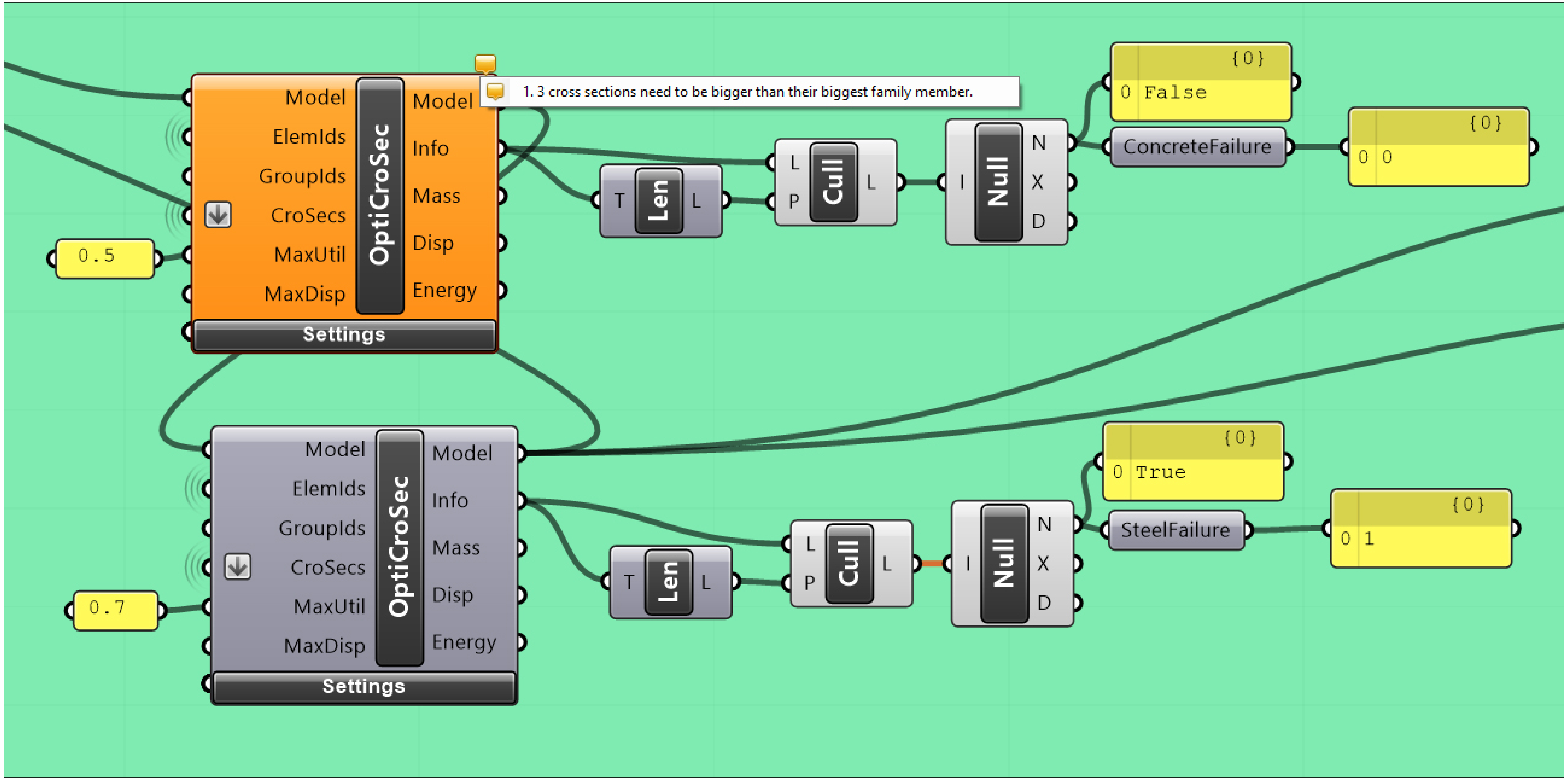



# Loads (optimisation)

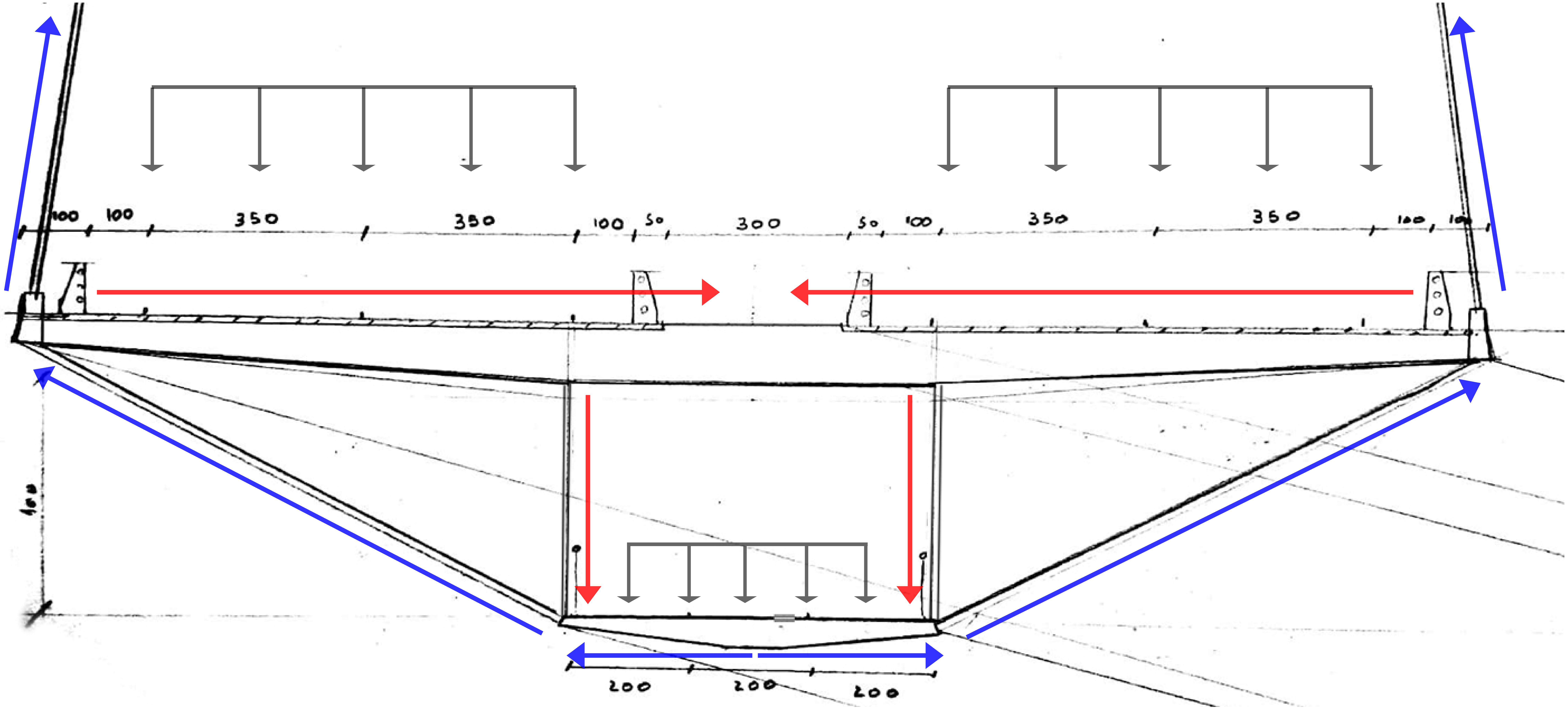
- **Dead load = mass X gravity**
- **Car traffic uniformly distributed load = 9 KN/m²**
- **Footbridge uniformly distributed load = 5 KN/m²**

# Cross-sections optimisation

- **Concrete elements**
- **Steel elements**



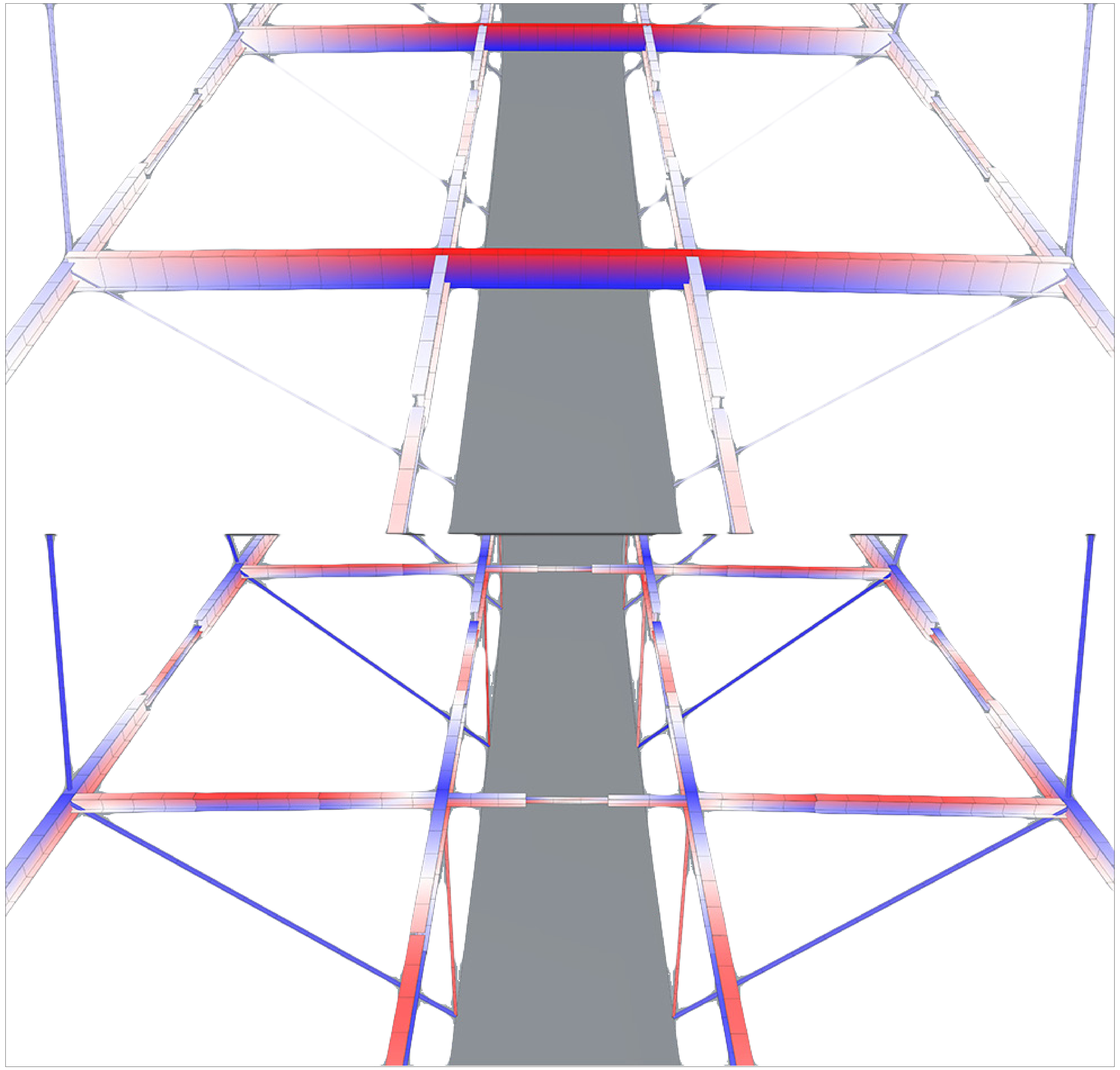
# Flow of forces in the deck



# Footbridge supports influence

- **Without vertical supports**

- **With vertical supports**



# Sustainability indicators

- **Environmental impact**
- **Economic impact**

# Environmental impact

It has been assessed evaluating the amount of materials needed in relation to their environmental profile. Data is retrieved from the **QuartzProject database**, which applies a "cradle-to-gate" analysis in order to consider the impact of all the processes involved in the realization of different building components and their transportation to the construction site.

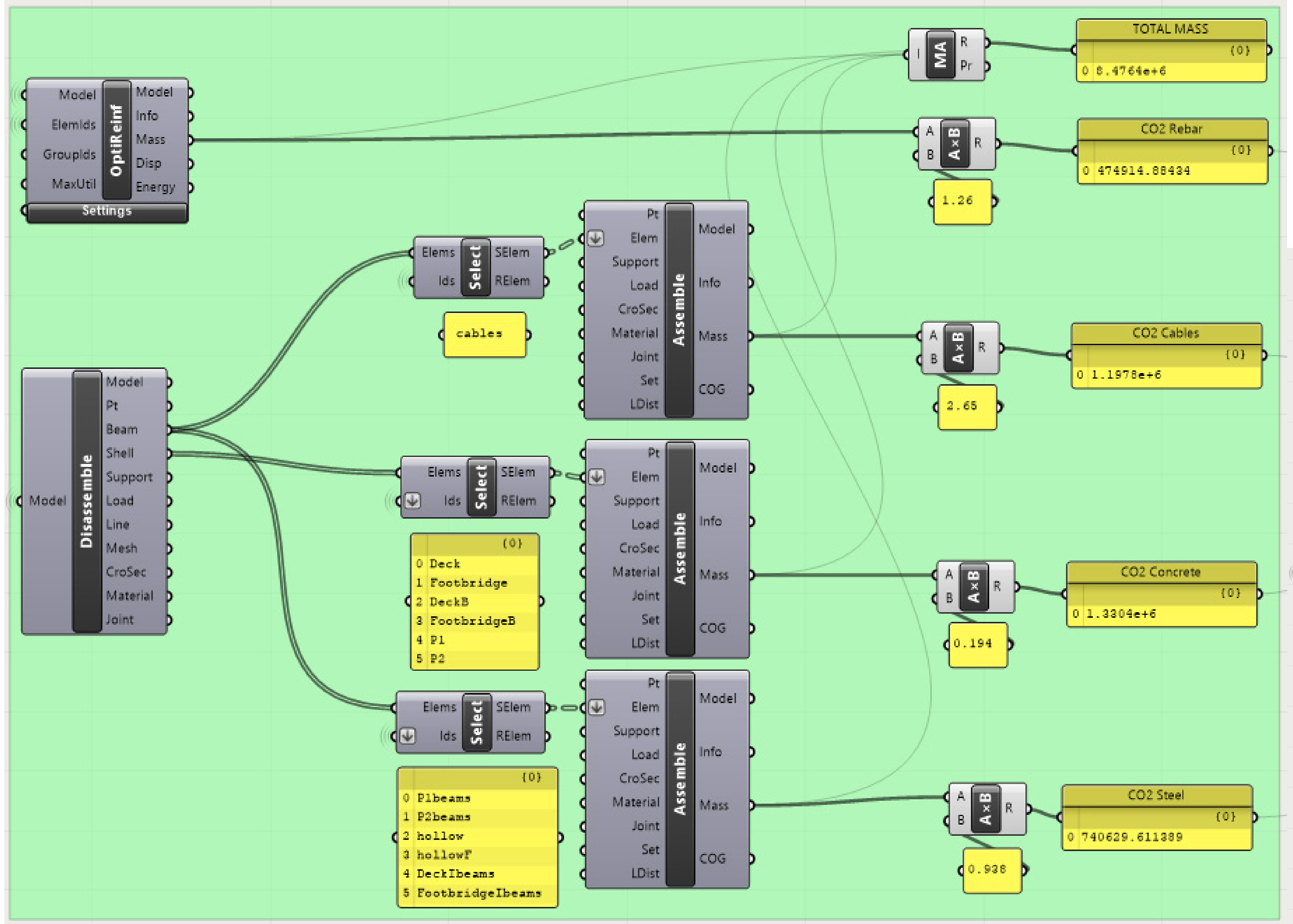
$$\text{Evaluation} = \text{Weight of the material} \times \text{Kg } CO_2 \text{ emission}$$

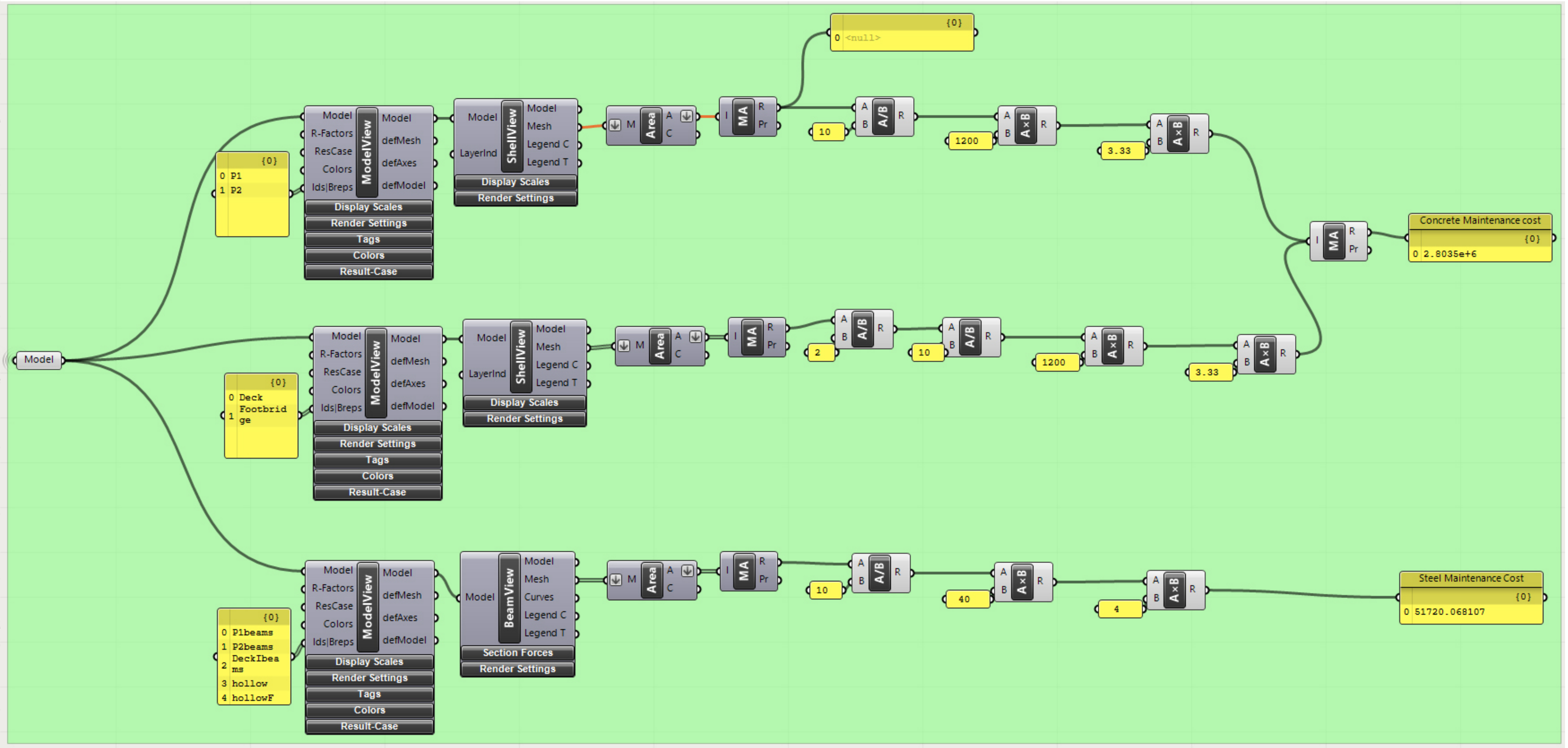
# Economic impact

It has been assessed evaluating both the amount of materials needed in relation to their cost (€/kg), and the cost of maintenance required over the bridge lifetime (€/m^2).
The cost of the materials has been retrieved from the **CES database**.
The cost of maintenance has been calculated according to the **SASS methodology**'s estimation, which considers the type of maintenance work, the extent of work, and the number of interventions.

Evaluation = (Weight of the material × Cost) +
(Surface in need of maintenance × Cost × number of interventions)

# Sustainability assessment




- **Environmental impact**
- **Economic impact**

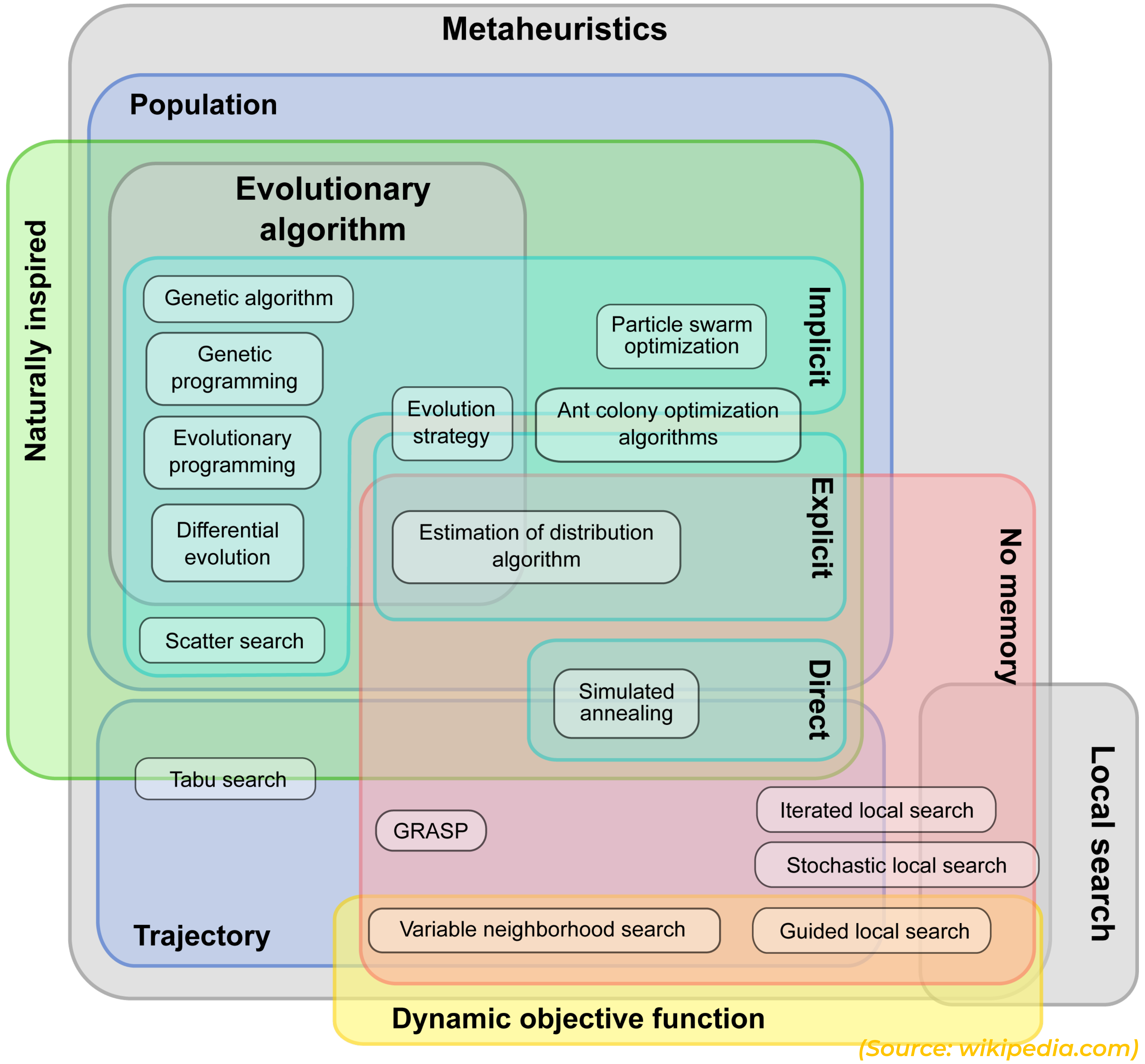
# Optimisation

# Multi objective optimisation

Within this research, it is required to consider numerous variables to fulfill more than one objective, with criteria that may conflict with each other. For this reason, a Multi-Objective Optimisation will be considered to obtain a **pool of optimal alternatives**.

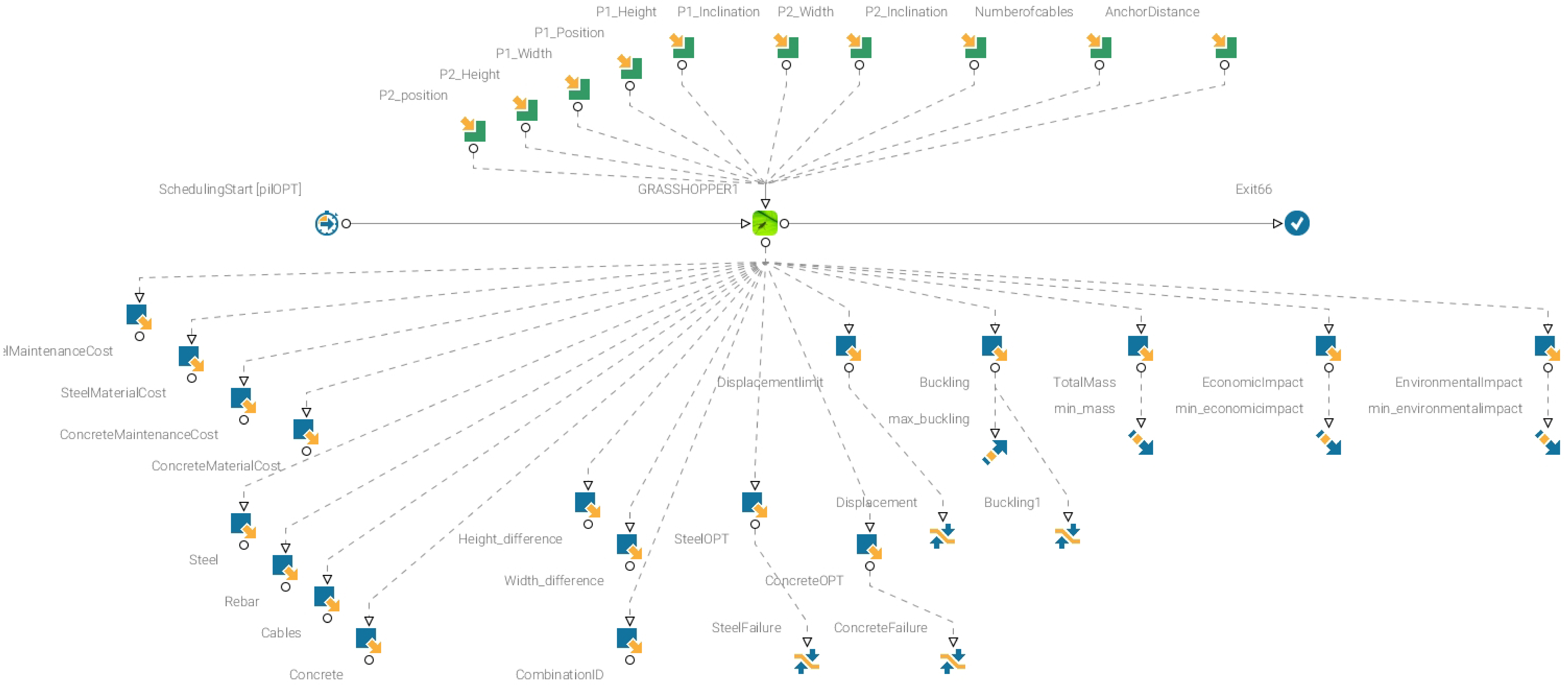
Metaheuristic algorithms and, in particular, population-based and evolutionary algorithms are preferred for the proven success in design.

The **pilOPT** algorithm developed by ESTECO was used within the software for the optimisation search chosen: **modeFRONTIER**



(Source: wikipedia.com)

# Optimisation workflow



# Optimisation workflow

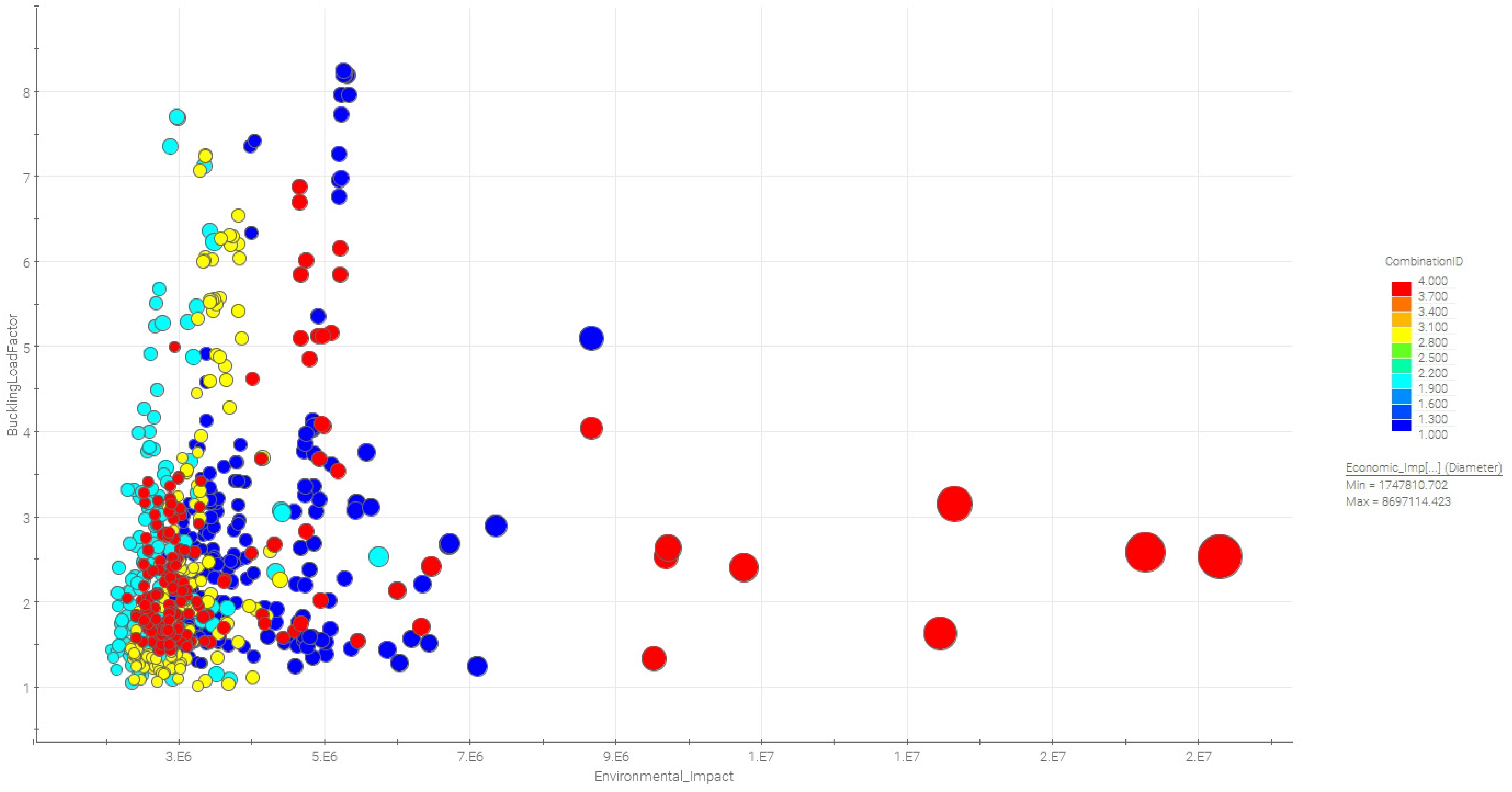
**Inputs:**
- **Geometry variables**

**Constraints:**
- **Cross-sections failure**
- **Buckling load factor > 1**

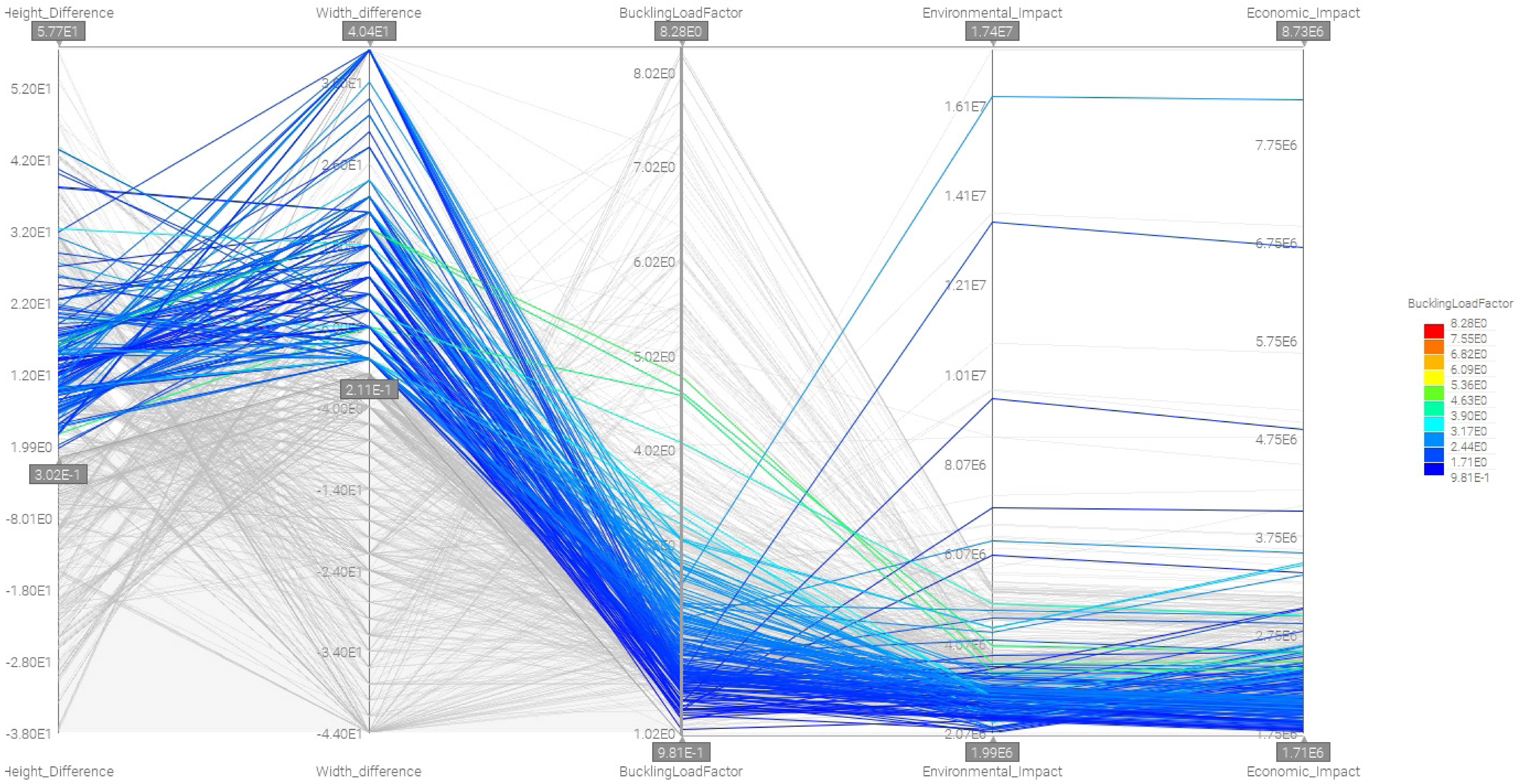
**Objectives:**
- **Minimize environmental impact**
- **Minimize economic impact**
- **Maximise buckling load factor**

**Extra Outputs:**
- **Height difference between pylons**
- **Width difference between pylons**
- **Material combination ID**

# Results

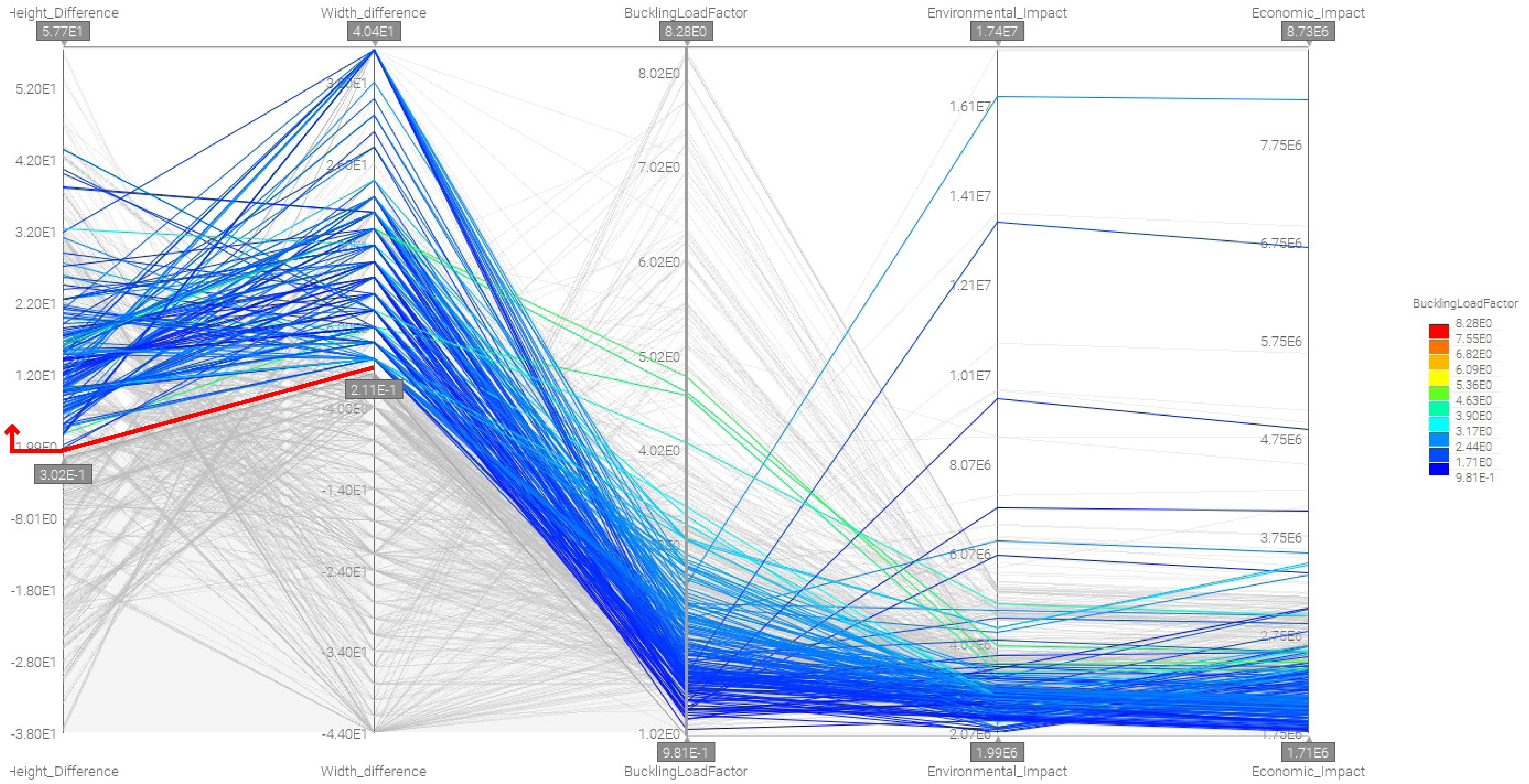

BucklingLoadFactor
Environmental_Impact
3.E6
5.E6
7.E6
9.E6
1.E7
1.E7
2.E7
2.E7
CombinationID
4.000
3.700
3.400
3.100
2.800
2.500
2.200
1.900
1.600
1.300
1.000
Economic_Imp[...] (Diameter)
Min = 1747810.702
Max = 8697114.423

# Height & width influence on objectives

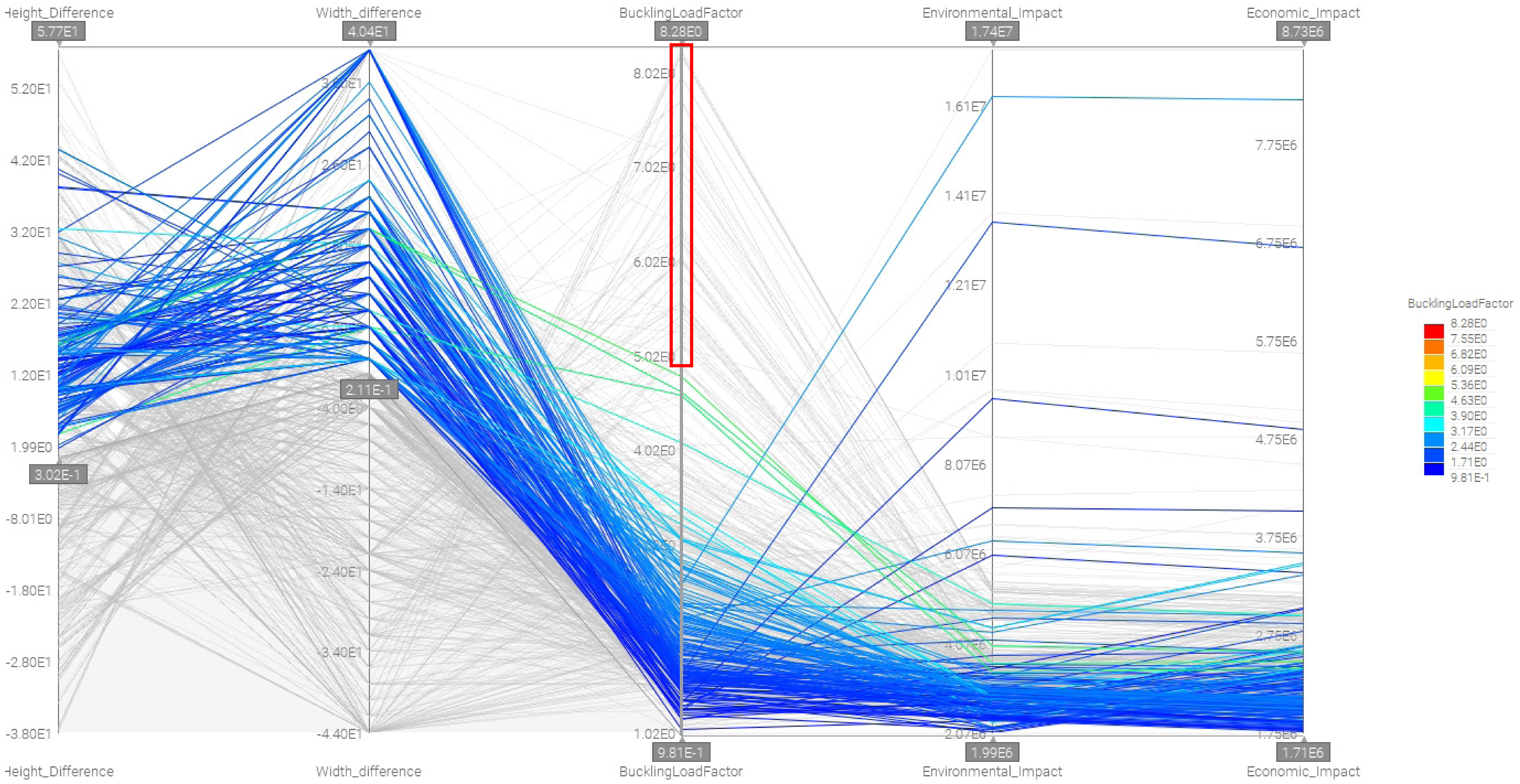


# Height & width influence on objectives

- 1st arch taller and wider than the 2nd



# Height & width influence on objectives

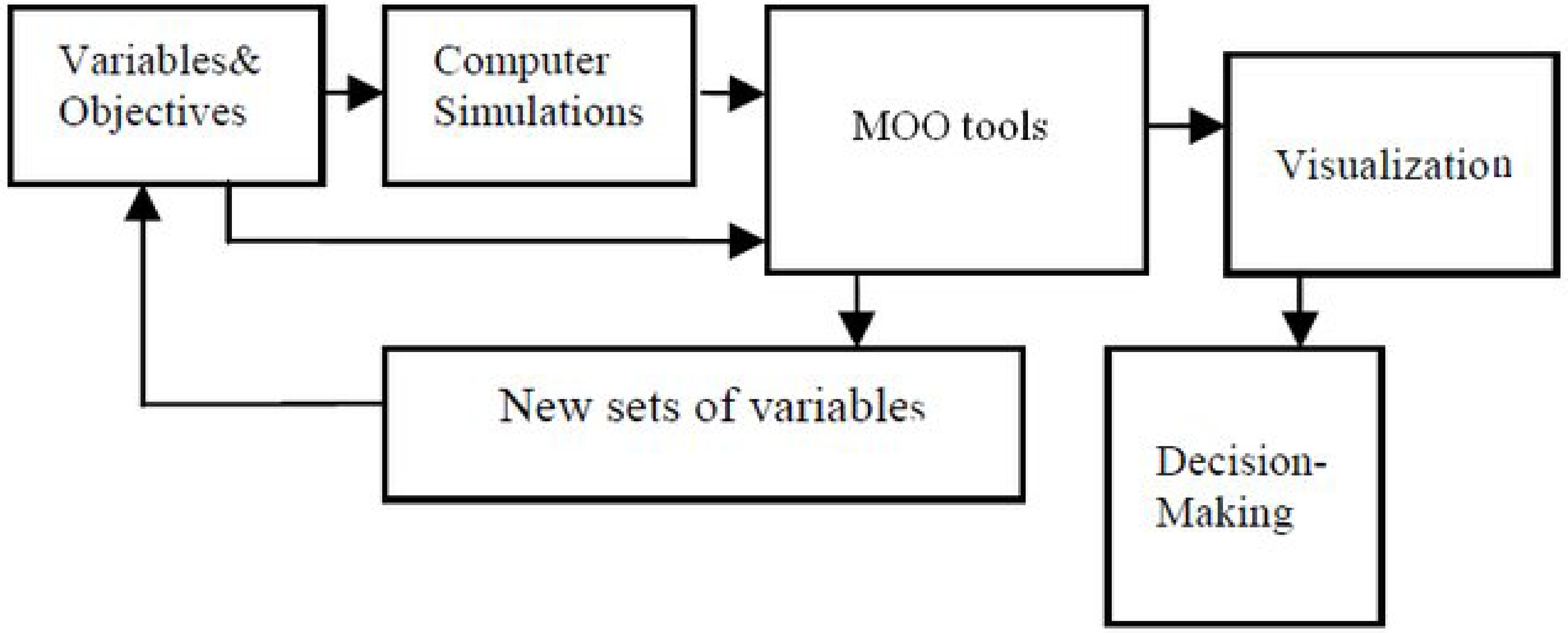



- **Solutions with high BLF values are excluded**

# MCDM methods

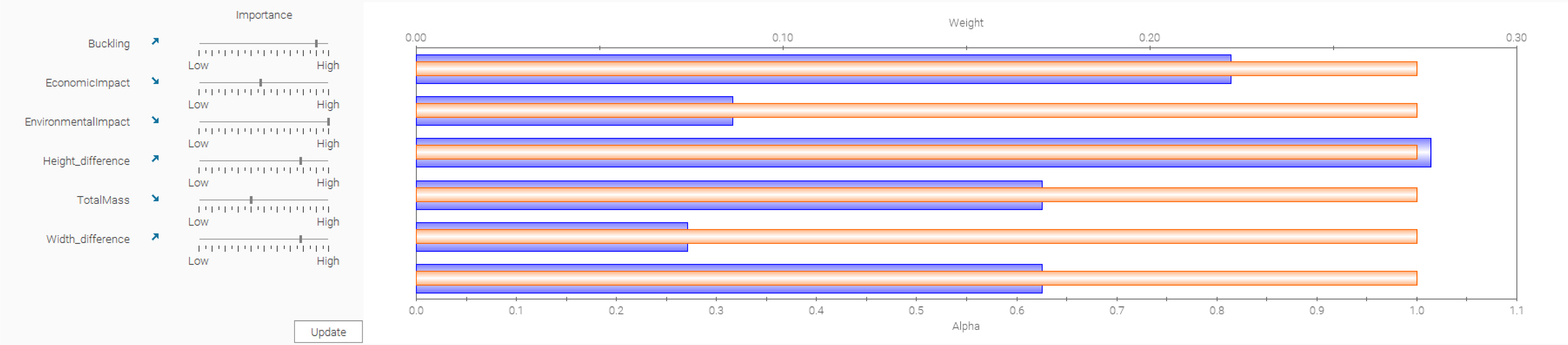
The choice that has to be made from the set of Pareto-optimal solutions must be guided by an understanding of the trade-offs of the different solutions. Multi-Criteria Decision-Making models can be used to maximize the performance obtained by the optimisation process applying **weights** to the different criteria returning a **ranking** of the solutions.

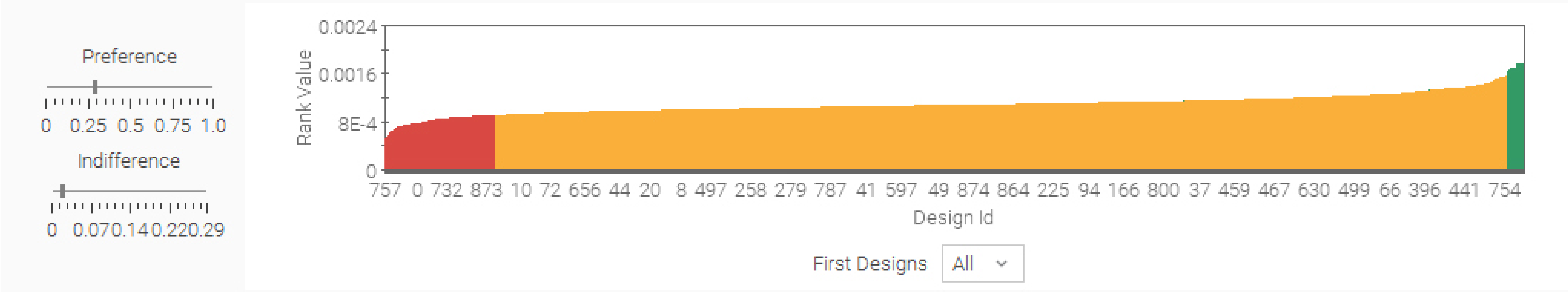
Among the methodologies used in the engineering field, **Analytical Hierarchy Process** (AHP) has the most significant impact on the optimisation of choice, and it was used for this research.




*(Source: Mosavi, 2001)*

# MCDM

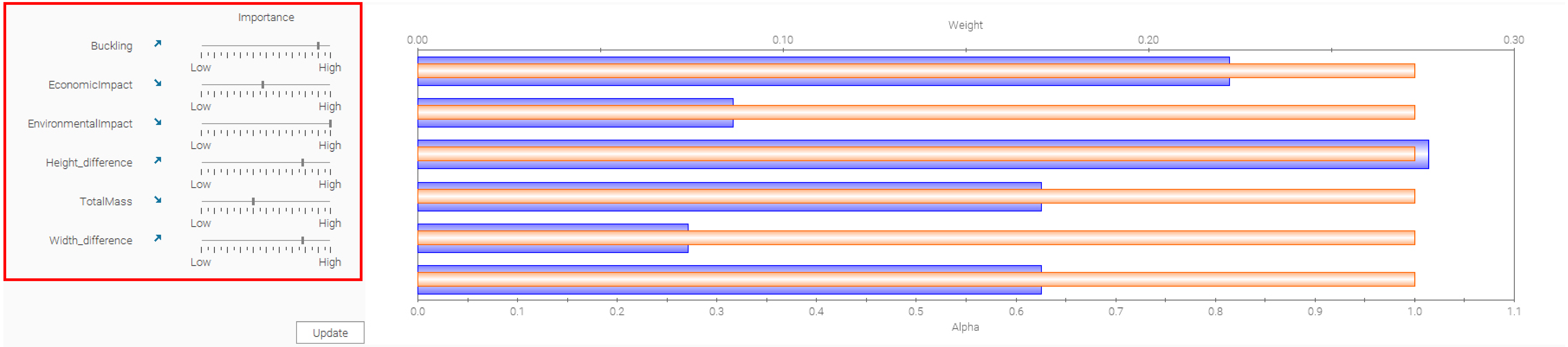


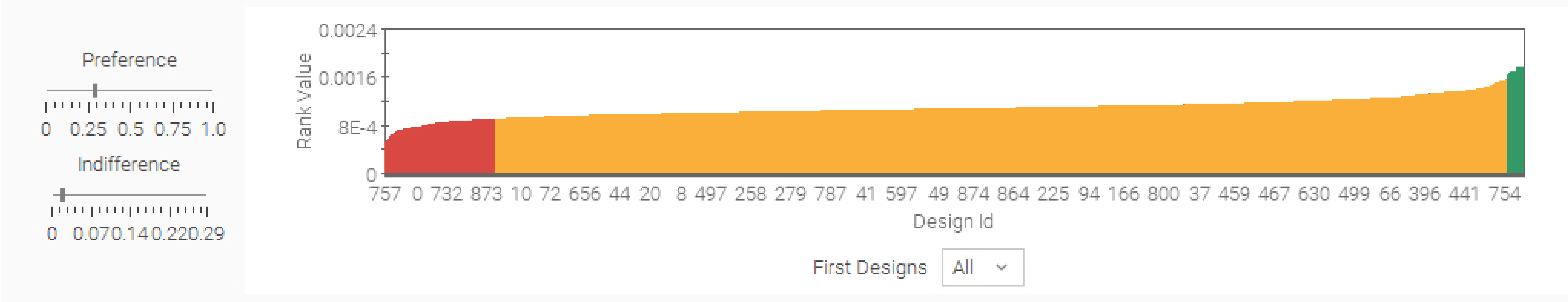




Ranking Table

| ID | Buckling | EconomicImpact | EnvironmentalImpact | Height_difference | TotalMass | Width_difference | Rank Value |
|---|---|---|---|---|---|---|---|
| 286 | 7.9666E0 | 3.1299E6 | 5.3253E6 | 3.1522E1 | 1.1001E7 | -4.4000E1 | 0.002 |
| 238 | 8.1880E0 | 3.1222E6 | 5.3004E6 | 3.1172E1 | 1.0948E7 | -4.4000E1 | 0.002 |
| 46 | 8.1908E0 | 3.1273E6 | 5.3129E6 | 3.1202E1 | 1.0968E7 | -4.4000E1 | 0.002 |
| 340 | 8.1956E0 | 3.0954E6 | 5.2474E6 | 3.0161E1 | 1.0852E7 | -4.2000E1 | 0.002 |
| 285 | 8.2005E0 | 3.1027E6 | 5.2615E6 | 3.0192E1 | 1.0874E7 | -4.2000E1 | 0.002 |
| 283 | 8.2329E0 | 3.1039E6 | 5.2630E6 | 2.9747E1 | 1.0878E7 | -4.0000E1 | 0.002 |
| 348 | 8.2462E0 | 3.0888E6 | 5.2551E6 | 2.9221E1 | 1.0808E7 | -4.0000E1 | 0.002 |
| 468 | 7.1232E0 | 3.0560E6 | 3.3425E6 | -2.6076E1 | 8.5445E6 | 4.0000E1 | 0.002 |

# Assigned weights




Ranking Table

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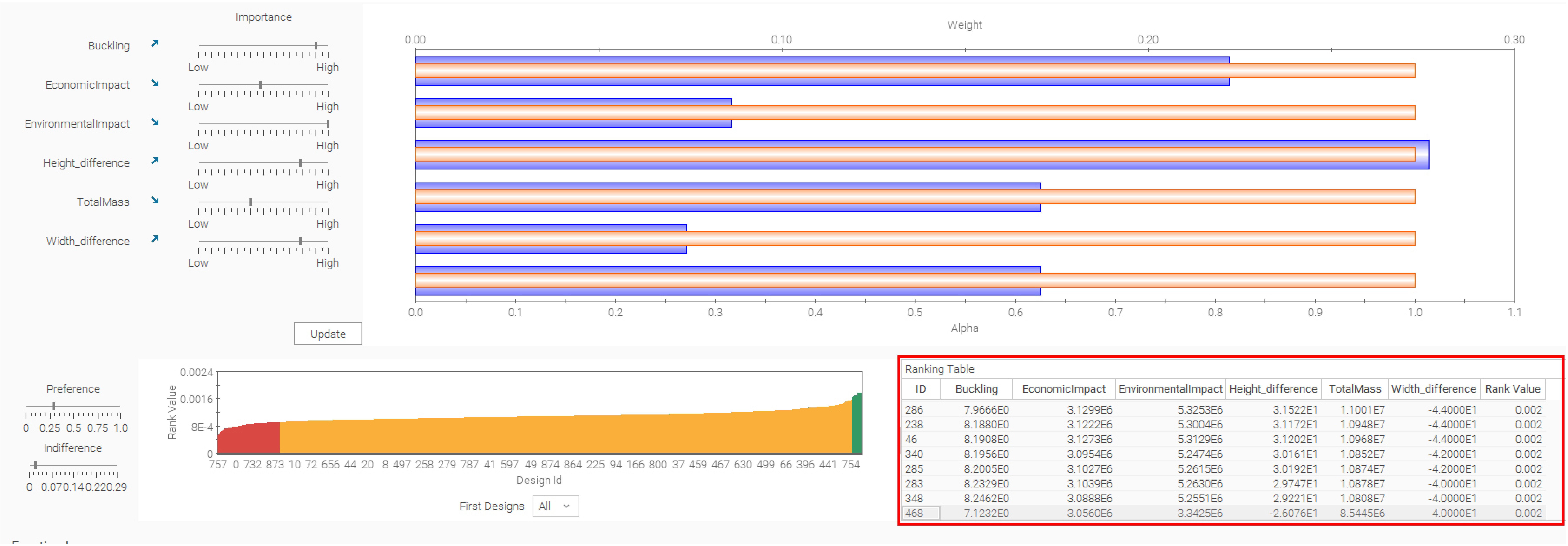
| 286 | 7.9666E0 | 3.1299E6 | 5.3253E6 | 3.1522E1 | 1.1001E7 | -4.4000E1 | 0.002 |
| 238 | 8.1880E0 | 3.1222E6 | 5.3004E6 | 3.1172E1 | 1.0948E7 | -4.4000E1 | 0.002 |
| 46 | 8.1908E0 | 3.1273E6 | 5.3129E6 | 3.1202E1 | 1.0968E7 | -4.4000E1 | 0.002 |
| 340 | 8.1956E0 | 3.0954E6 | 5.2474E6 | 3.0161E1 | 1.0852E7 | -4.2000E1 | 0.002 |
| 285 | 8.2005E0 | 3.1027E6 | 5.2615E6 | 3.0192E1 | 1.0874E7 | -4.2000E1 | 0.002 |
| 283 | 8.2329E0 | 3.1039E6 | 5.2630E6 | 2.9747E1 | 1.0878E7 | -4.0000E1 | 0.002 |
| 348 | 8.2462E0 | 3.0888E6 | 5.2551E6 | 2.9221E1 | 1.0808E7 | -4.0000E1 | 0.002 |
| 468 | 7.1232E0 | 3.0560E6 | 3.3425E6 | -2.6076E1 | 8.5445E6 | 4.0000E1 | 0.002 |

# Assigned weights

| | |
|---|---|
| • Minimum environmental impact | 1 |
| • Maximum buckling load factor | 0.9 |
| • 1st arch taller than 2nd | 0.8 |
| • 1st arch wider than 2nd | 0.8 |
| • Minimum economic impact | 0.5 |

# Ranking




Ranking Table

| ID | Buckling | EconomicImpact | EnvironmentalImpact | Height_difference | TotalMass | Width_difference | Rank Value |
|---|---|---|---|---|---|---|---|
| 286 | 7.9666E0 | 3.1299E6 | 5.3253E6 | 3.1522E1 | 1.1001E7 | -4.4000E1 | 0.002 |
| 238 | 8.1880E0 | 3.1222E6 | 5.3004E6 | 3.1172E1 | 1.0948E7 | -4.4000E1 | 0.002 |
| 46 | 8.1908E0 | 3.1273E6 | 5.3129E6 | 3.1202E1 | 1.0968E7 | -4.4000E1 | 0.002 |
| 340 | 8.1956E0 | 3.0954E6 | 5.2474E6 | 3.0161E1 | 1.0852E7 | -4.2000E1 | 0.002 |
| 285 | 8.2005E0 | 3.1027E6 | 5.2615E6 | 3.0192E1 | 1.0874E7 | -4.2000E1 | 0.002 |
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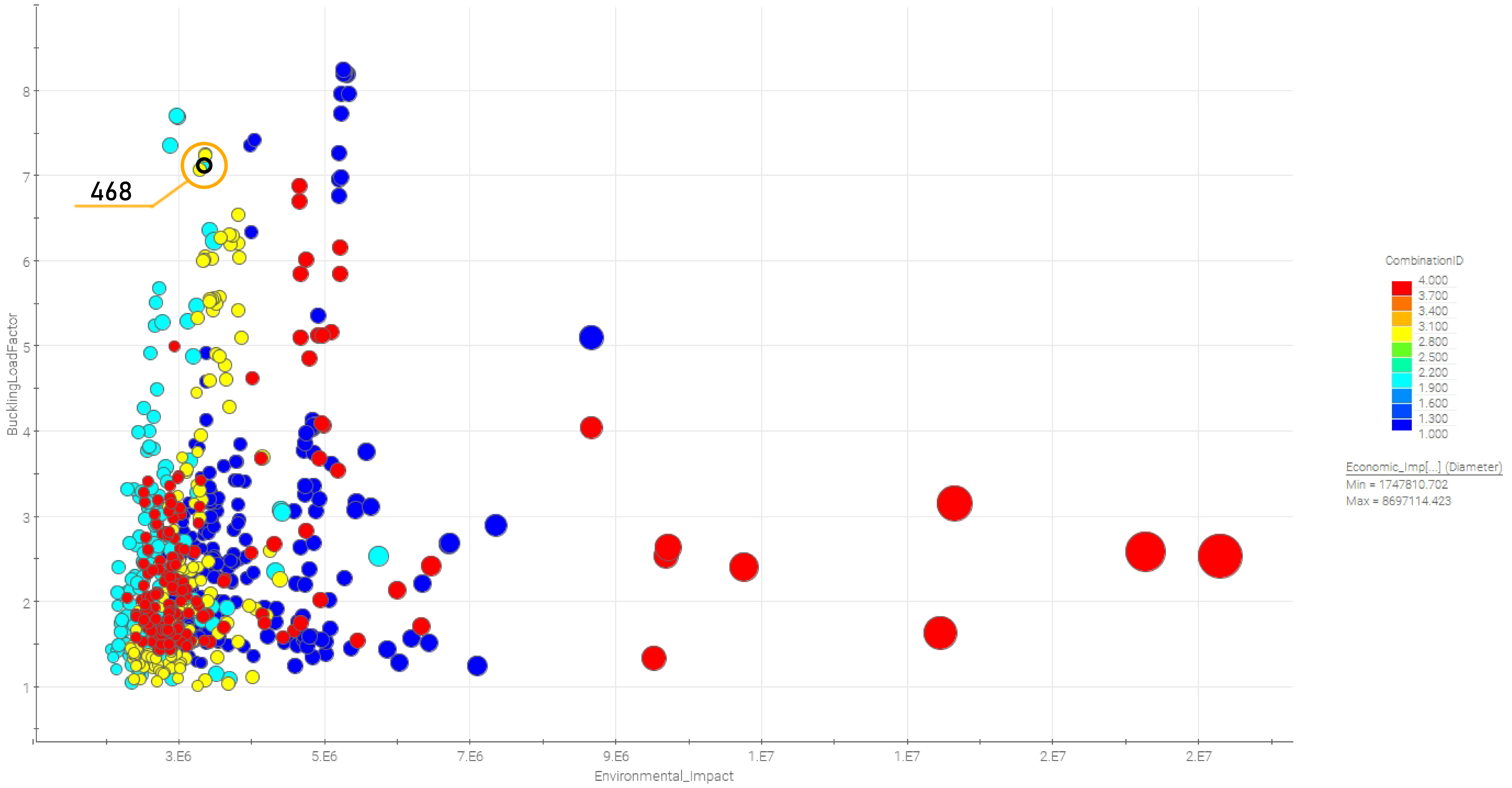
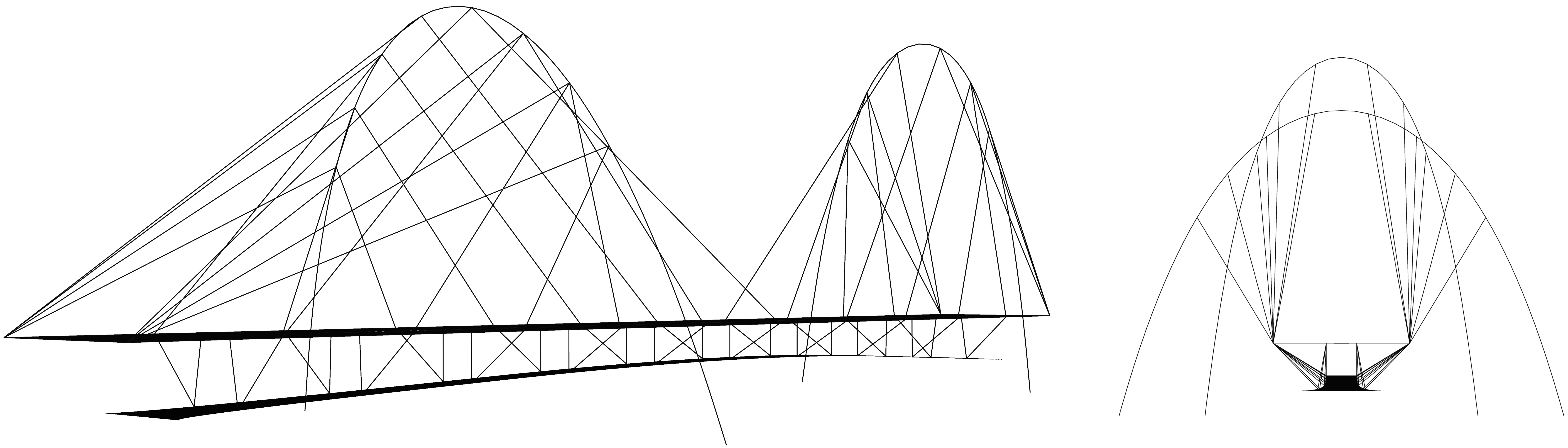
| 468 | 7.1232E0 | 3.0560E6 | 3.3425E6 | -2.6076E1 | 8.5445E6 | 4.0000E1 | 0.002 |

# 1st ranked solution



# Chosen solution

- **Steel pylons and reinforced concrete decks**

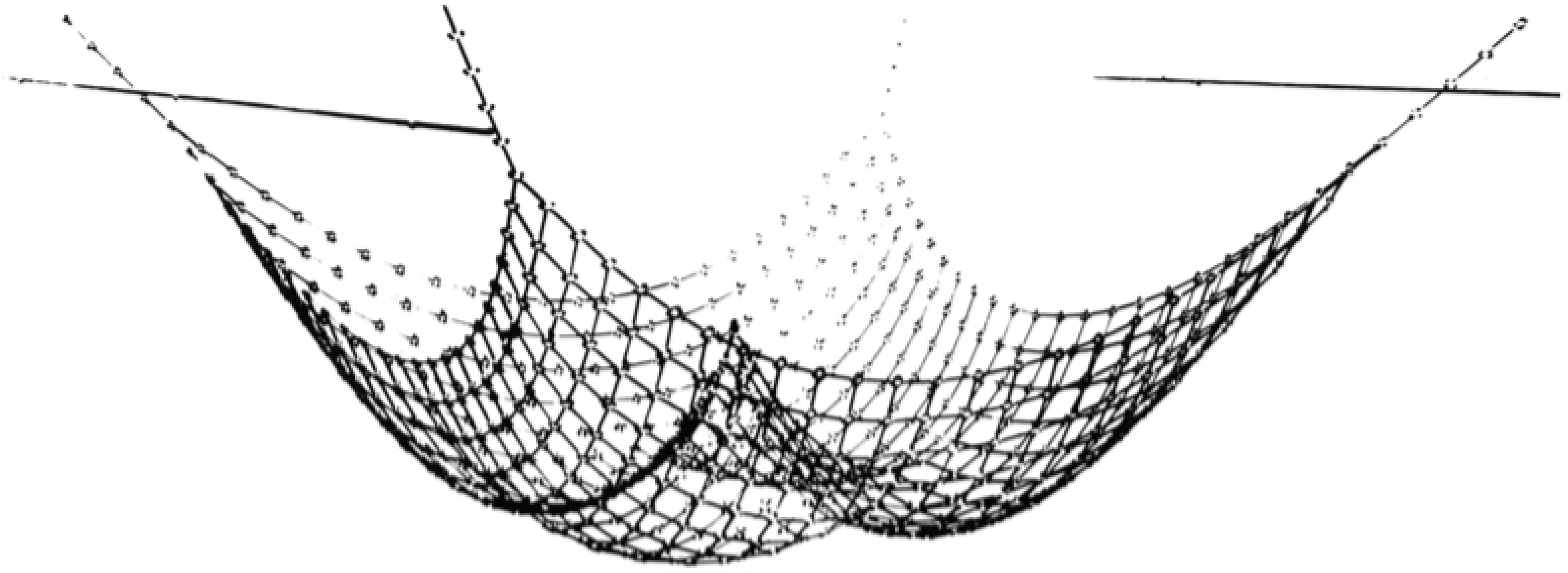


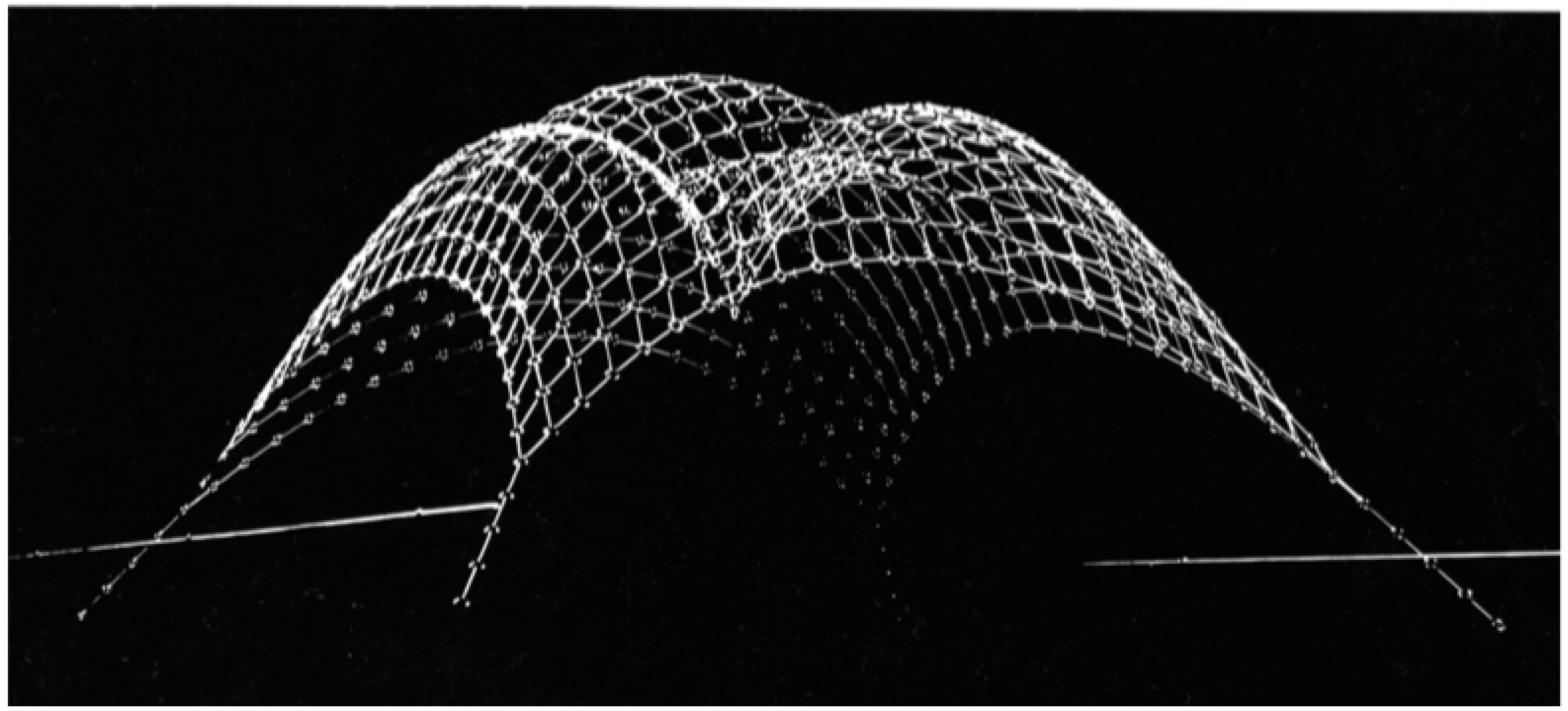
# Form-finding

The form-finding method used to optimise the shape of the arches is based on the **particle-spring system** using the Kangaroo physical engine.

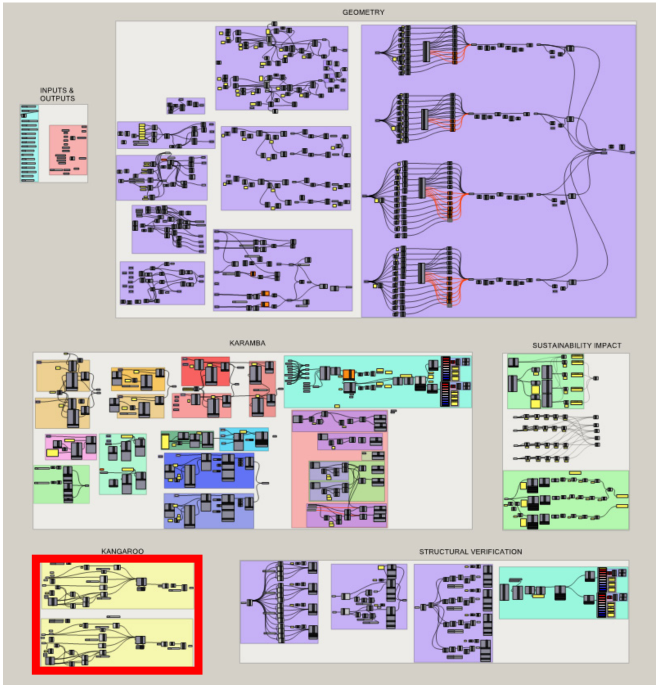
The **resultant forces of the cables** were applied on their anchor point on the pylons.

The simulation will show an arch in tension due to the opposite direction assigned to the forces, in reality, the tension of the elements resembles the compression to which the arches are subjected.



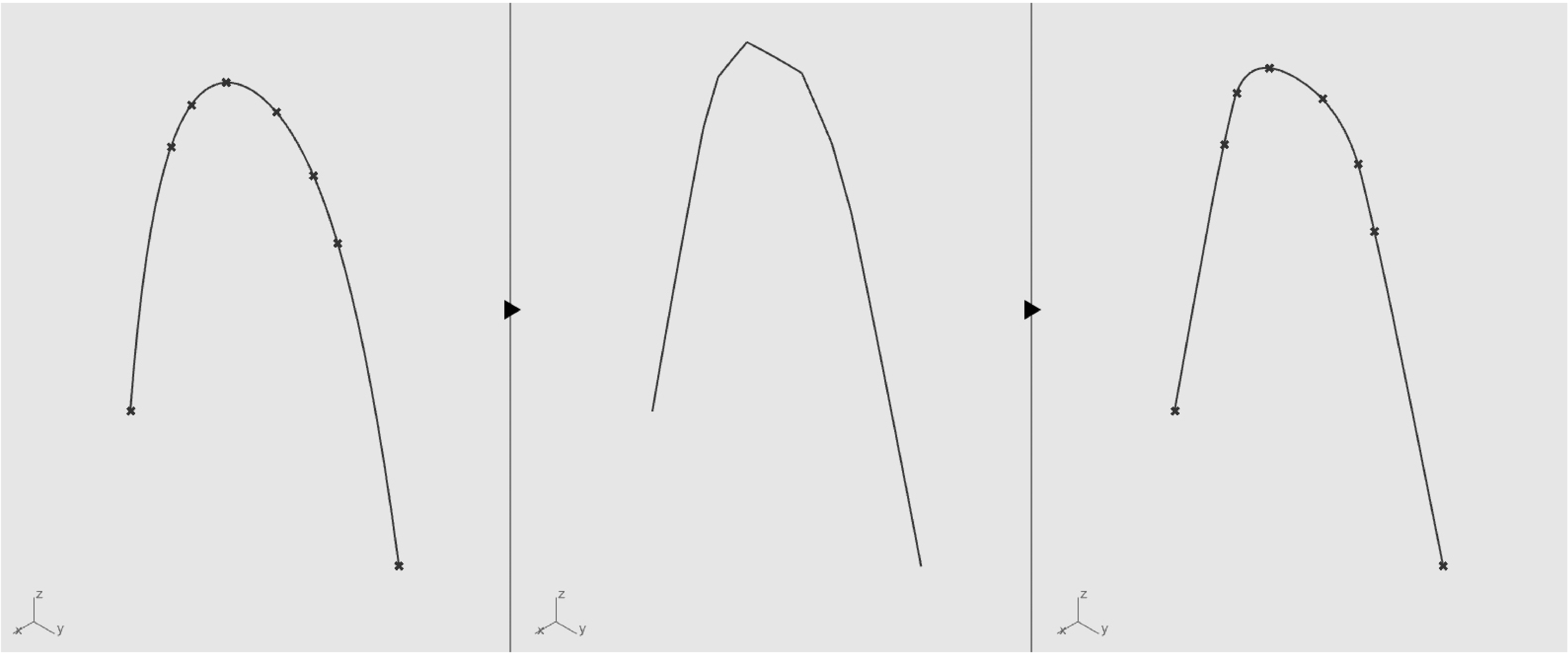


*(Source: math-art.eu)*



# Pylon’s shape optimisation

- Cables resultant forces applied to the arches
- Curve smoothed
- Structural analysis

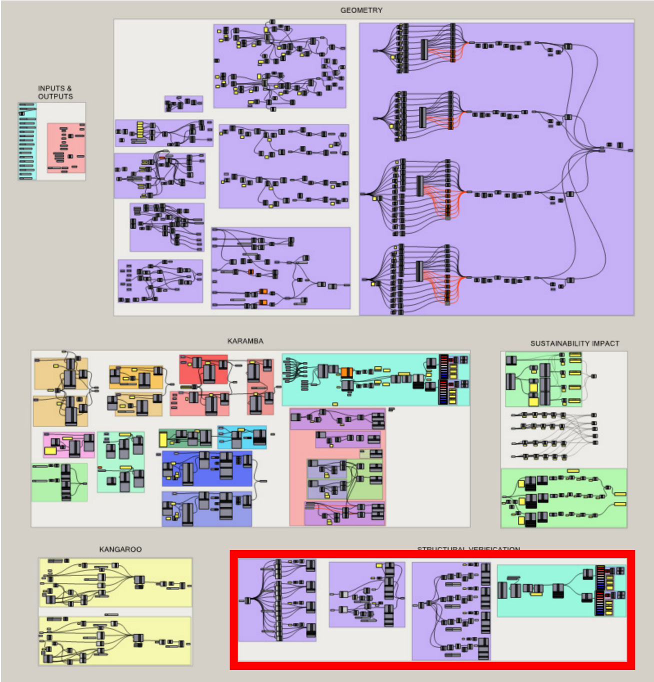


# Pylon's shape refinement

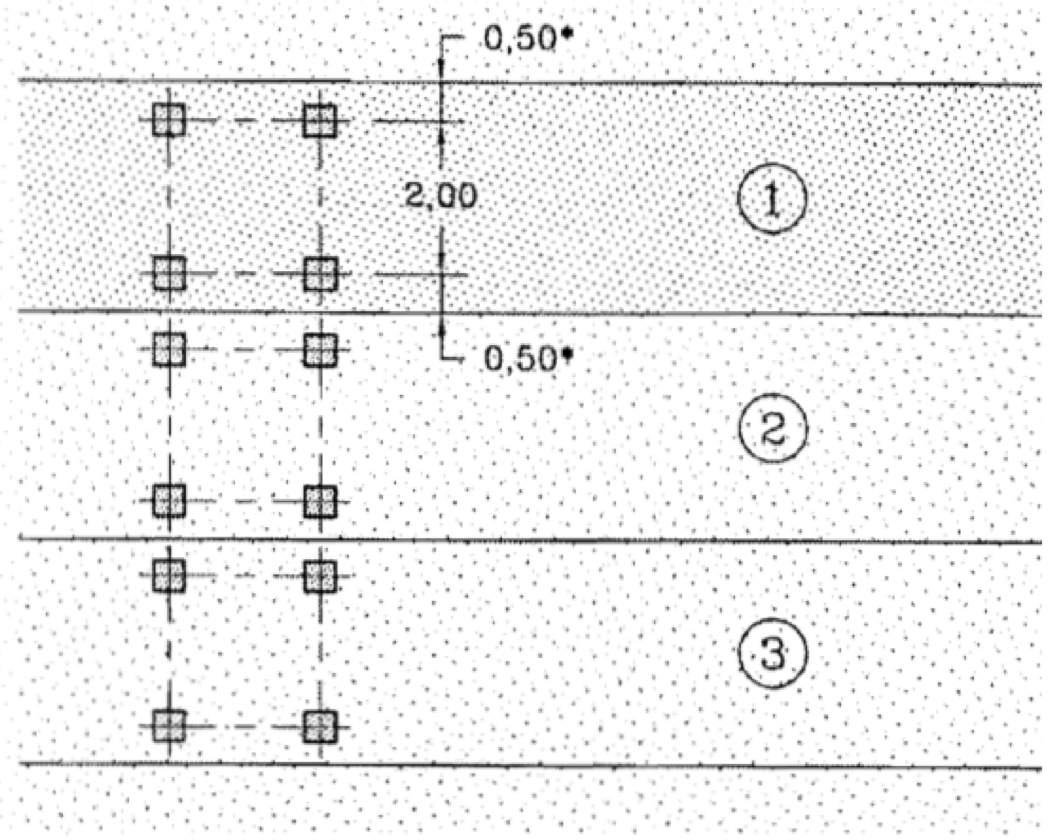
• **Form-founded arch**

• **Refined arch**

# Loads (structural verification)



- **Dead load = mass X gravity**
- **Car traffic uniformly distributed load = 9-2.5-2.5-2.5 KN/m²**
- **Footbridge uniformly distributed load = 5 KN/m²**
- **Car traffic point loads = 300-200-100-100 KN**
- **Wind load = 0.87 KN/m²**

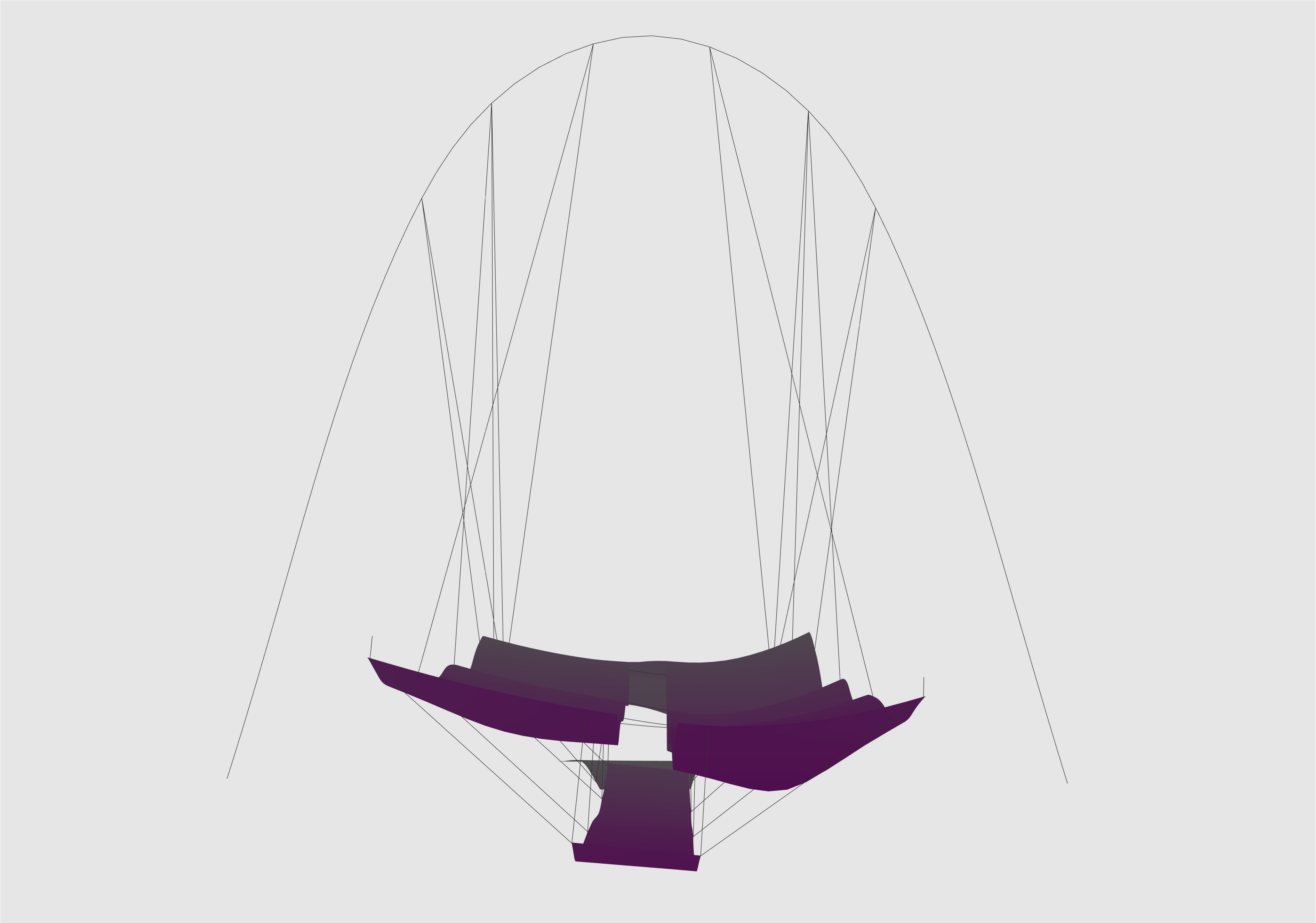



| Location | Tandem system *TS* | *UDL* system |
|---|---|---|
| | Axle loads $Q_{ik}$ (kN) | AC1 $q_{ik}$ (or $q_{rk}$) (kN/m$^2$) AC1 |
| Lane Number 1 | 300 | 9 |
| Lane Number 2 | 200 | 2,5 |
| Lane Number 3 | 100 | 2,5 |
| Other lanes | 0 | 2,5 |
| Remaining area ( $q_{rk}$ ) | 0 | 2,5 |

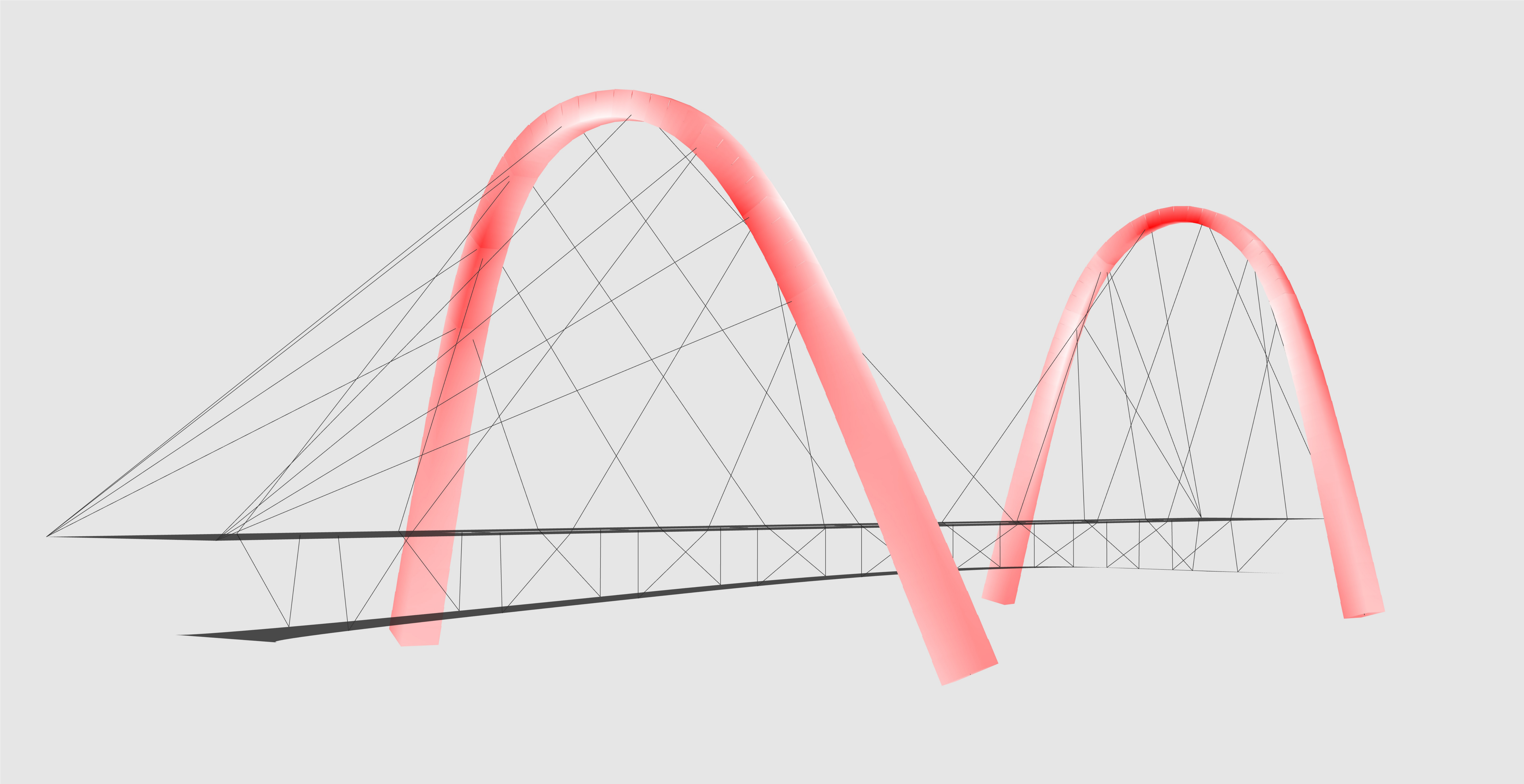
*(Source: Eurocode)*

# Deformation

- **Asymmetrical loads**
- **Displacement = 28cm -> 46cm**
- **BLF = 7.1 -> 5.6**

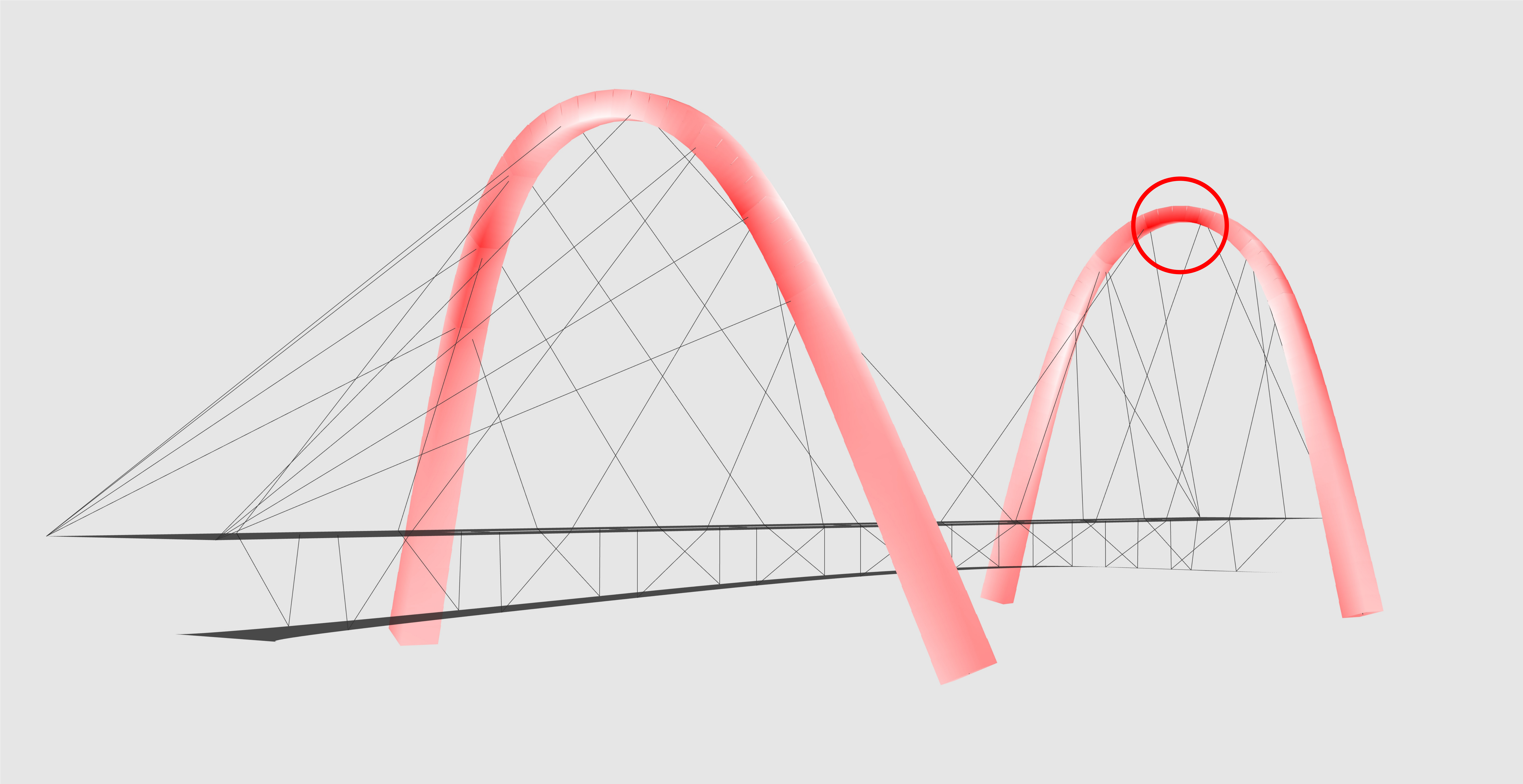


# Material utilisation distribution



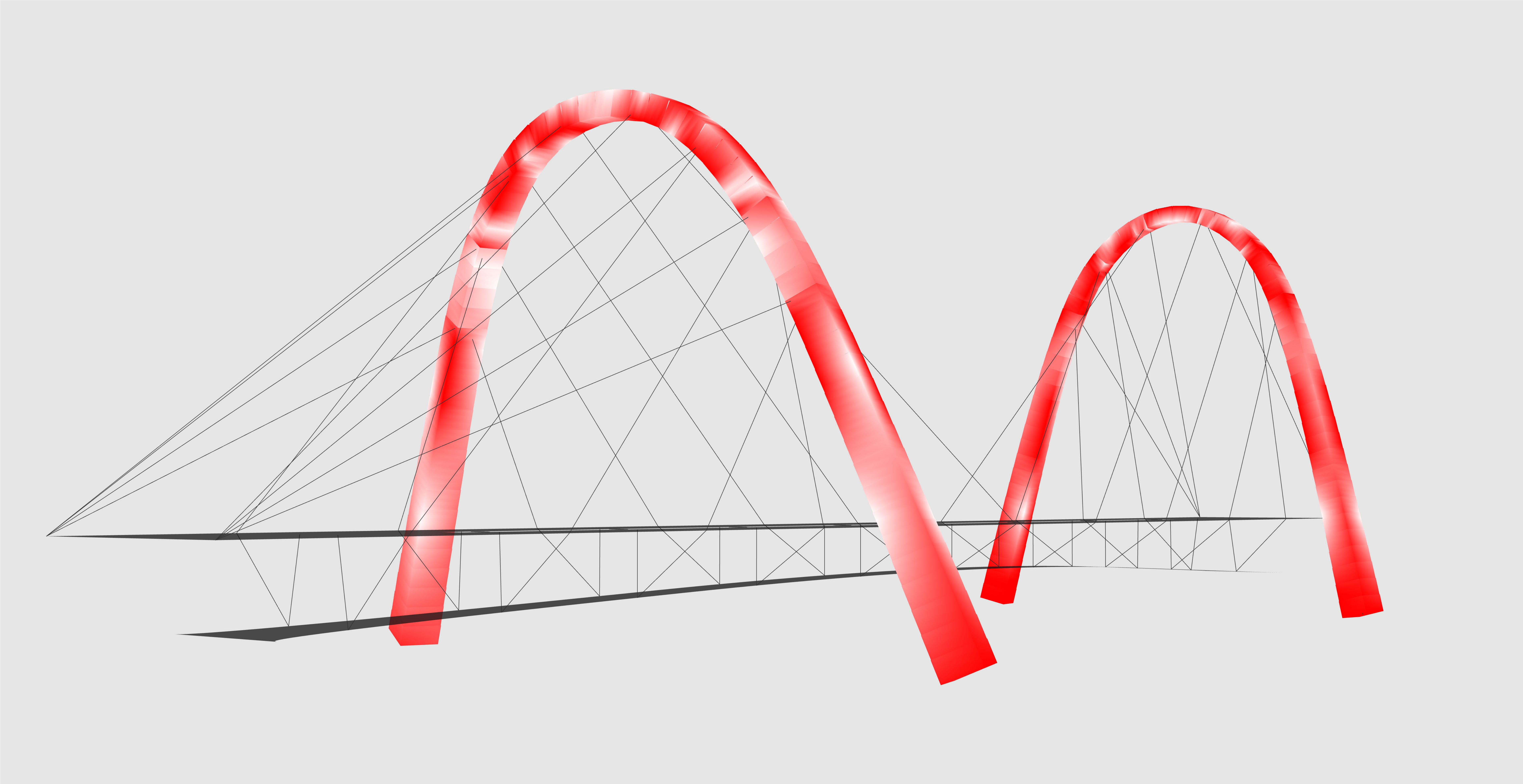
- **Before further thickness optimisation**

# Material utilisation distribution



- **Before further thickness optimisation**

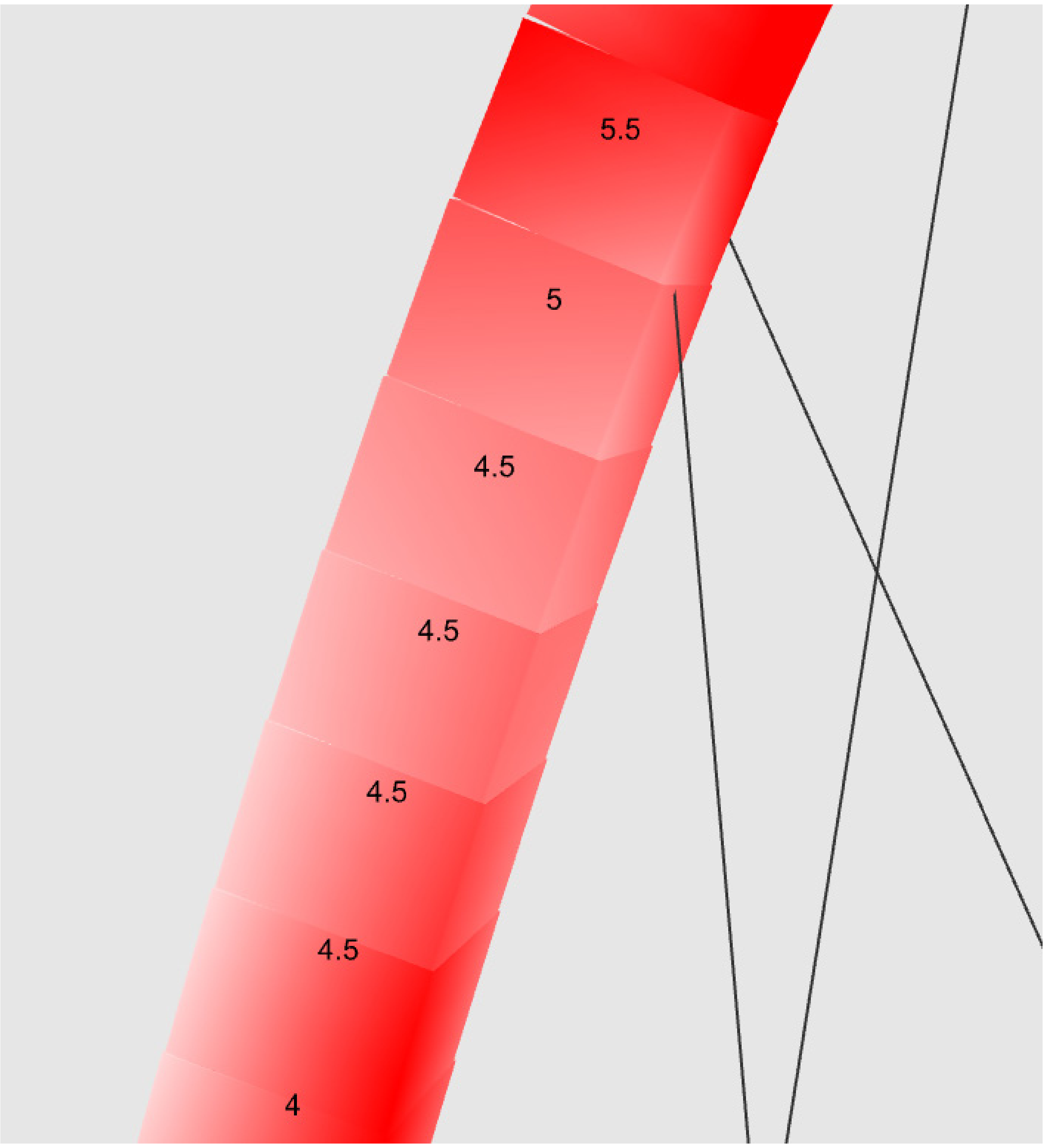
# Material utilisation distribution



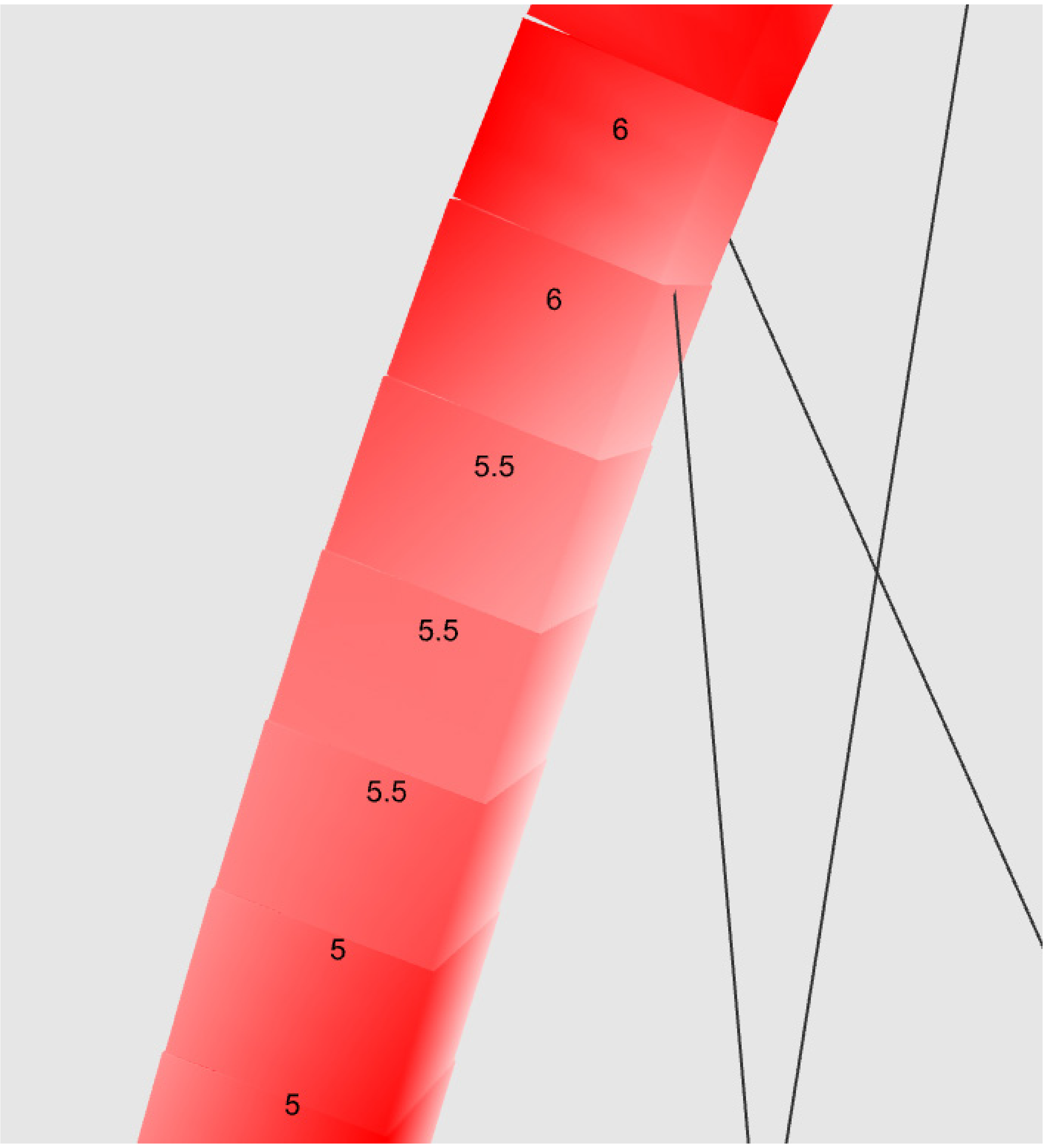
- **After thickness optimisation**

# Thickness refinement

- **BLF = 6.9**
- **Max utilisation = 70%**

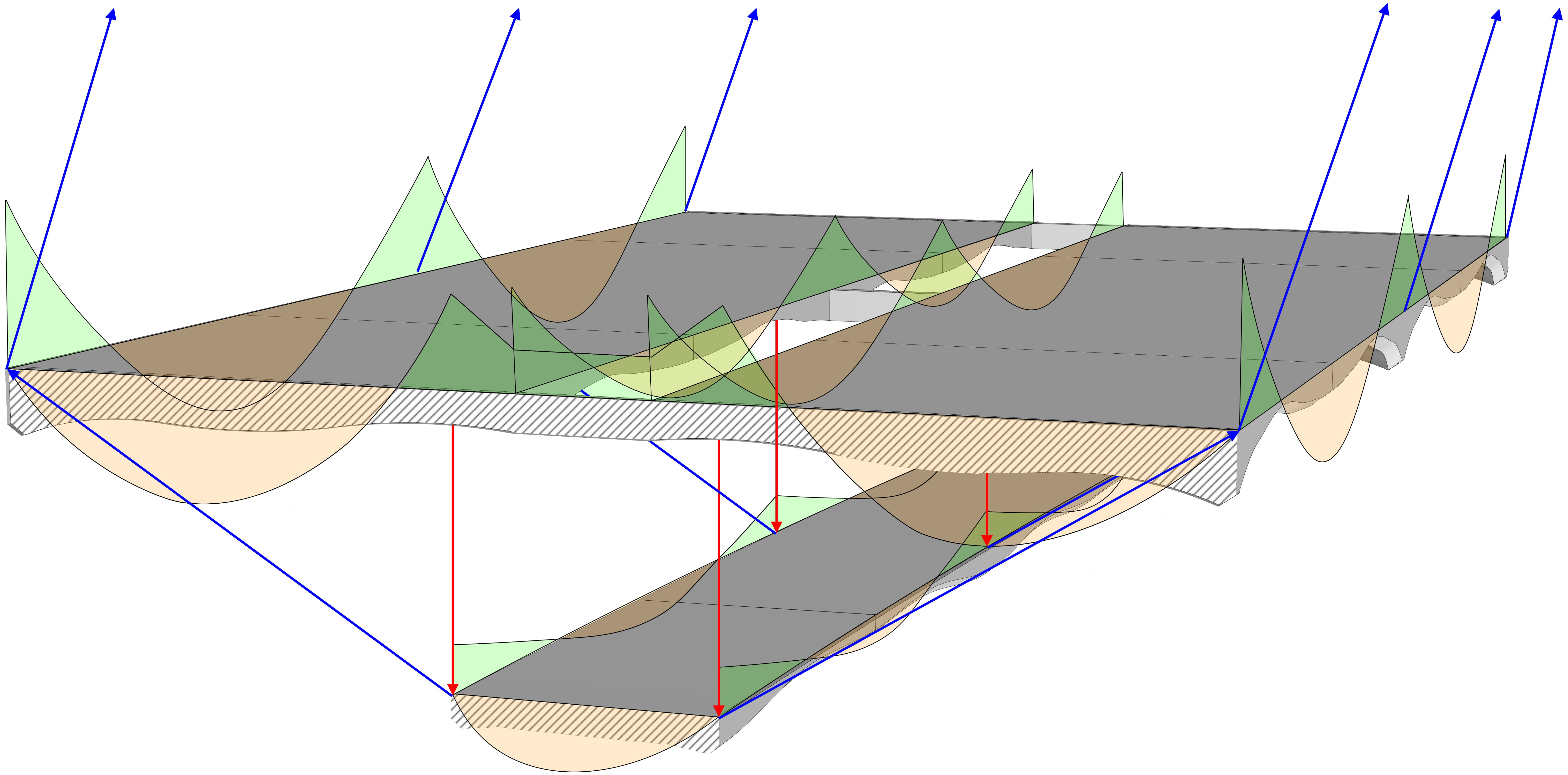



- **Before**



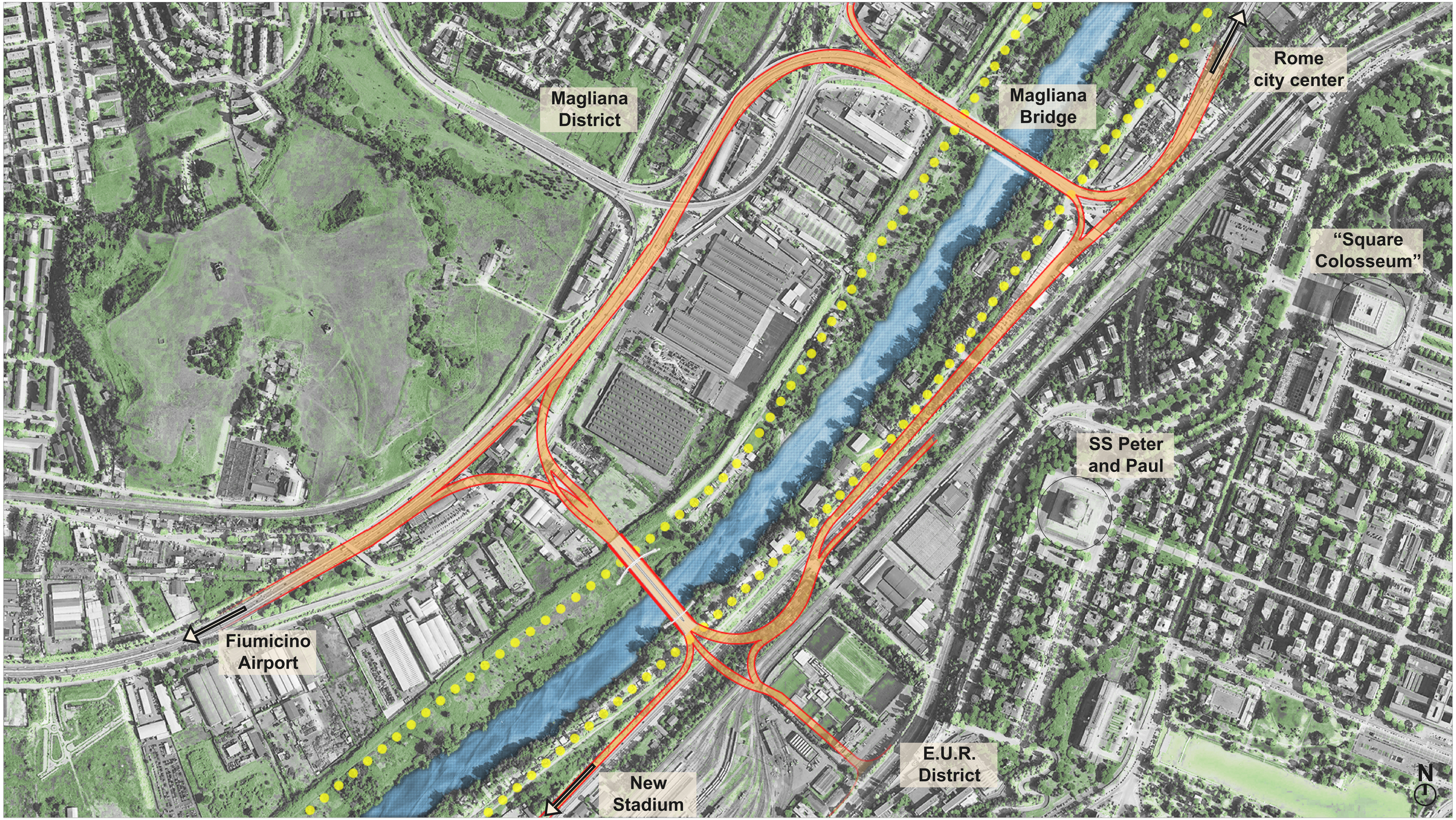

- **After**

# Deck edges and surface refinement



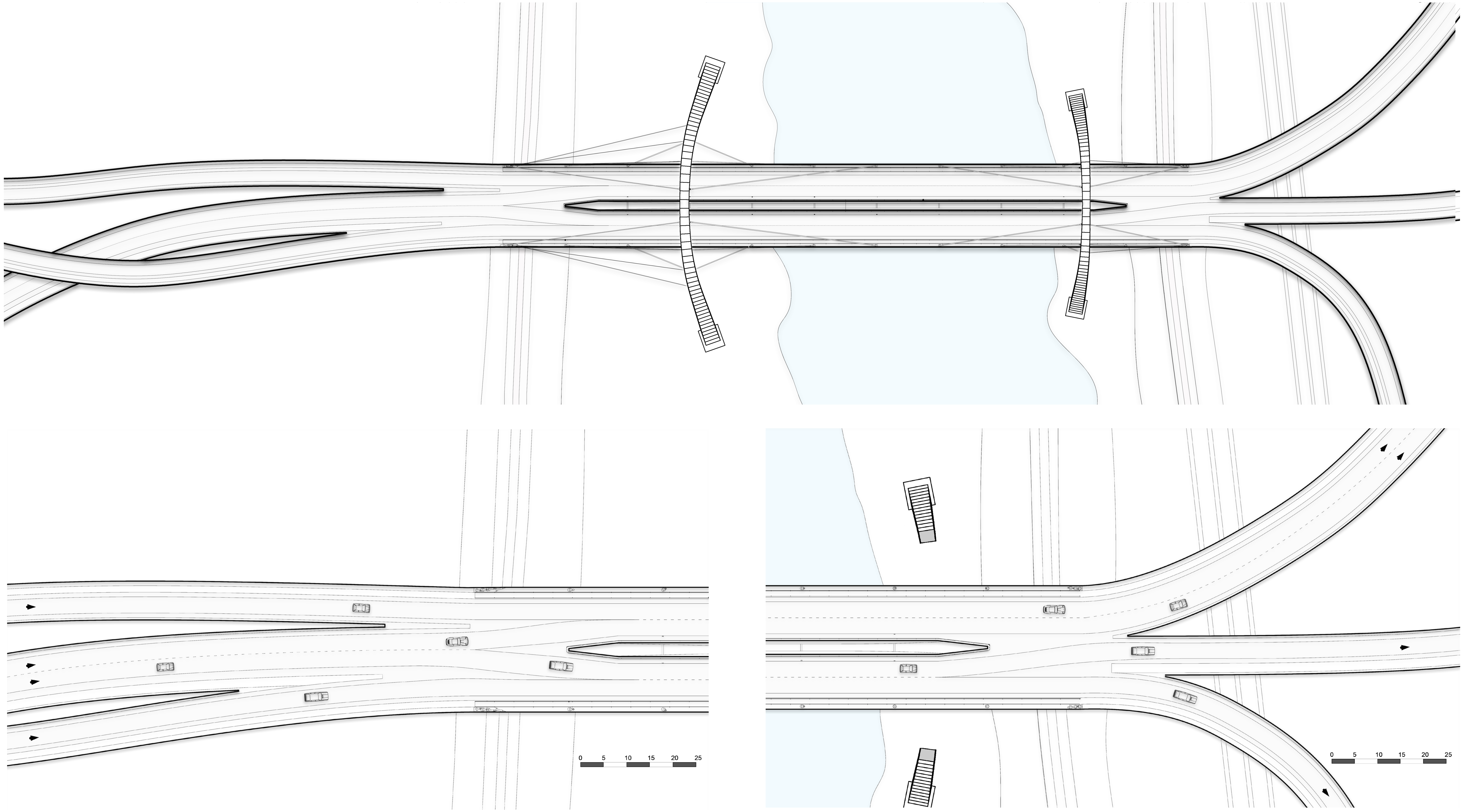
- **Simplified bending moment**

# Final Design

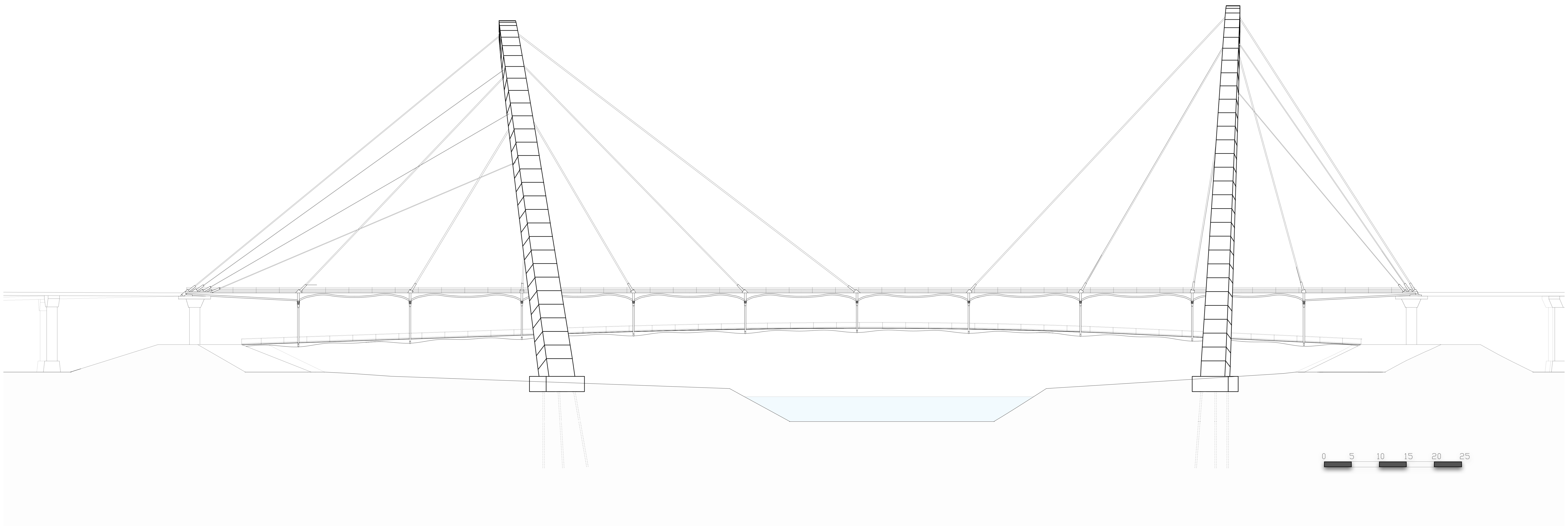

Magliana
District
Magliana
Bridge
Rome
city center
"Square
Colosseum"
SS Peter
and Paul
Fiumicino
Airport
New
Stadium
E.U.R.
District
N

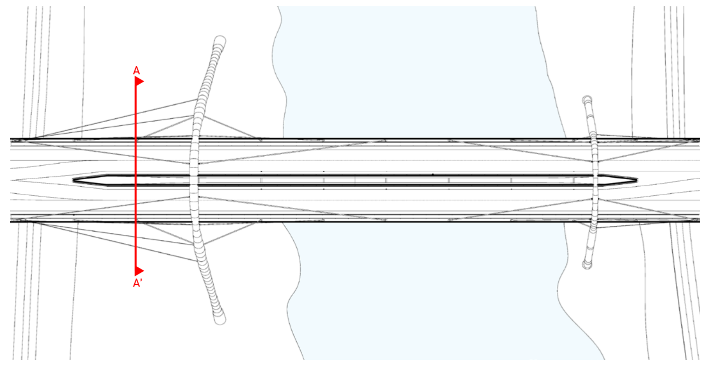

Magliana
District
Magliana
Bridge
Rome
city center
"Square
Colosseum"
SS Peter
and Paul
Fiumicino
Airport
New
Stadium
E.U.R.
District
N

# Plan

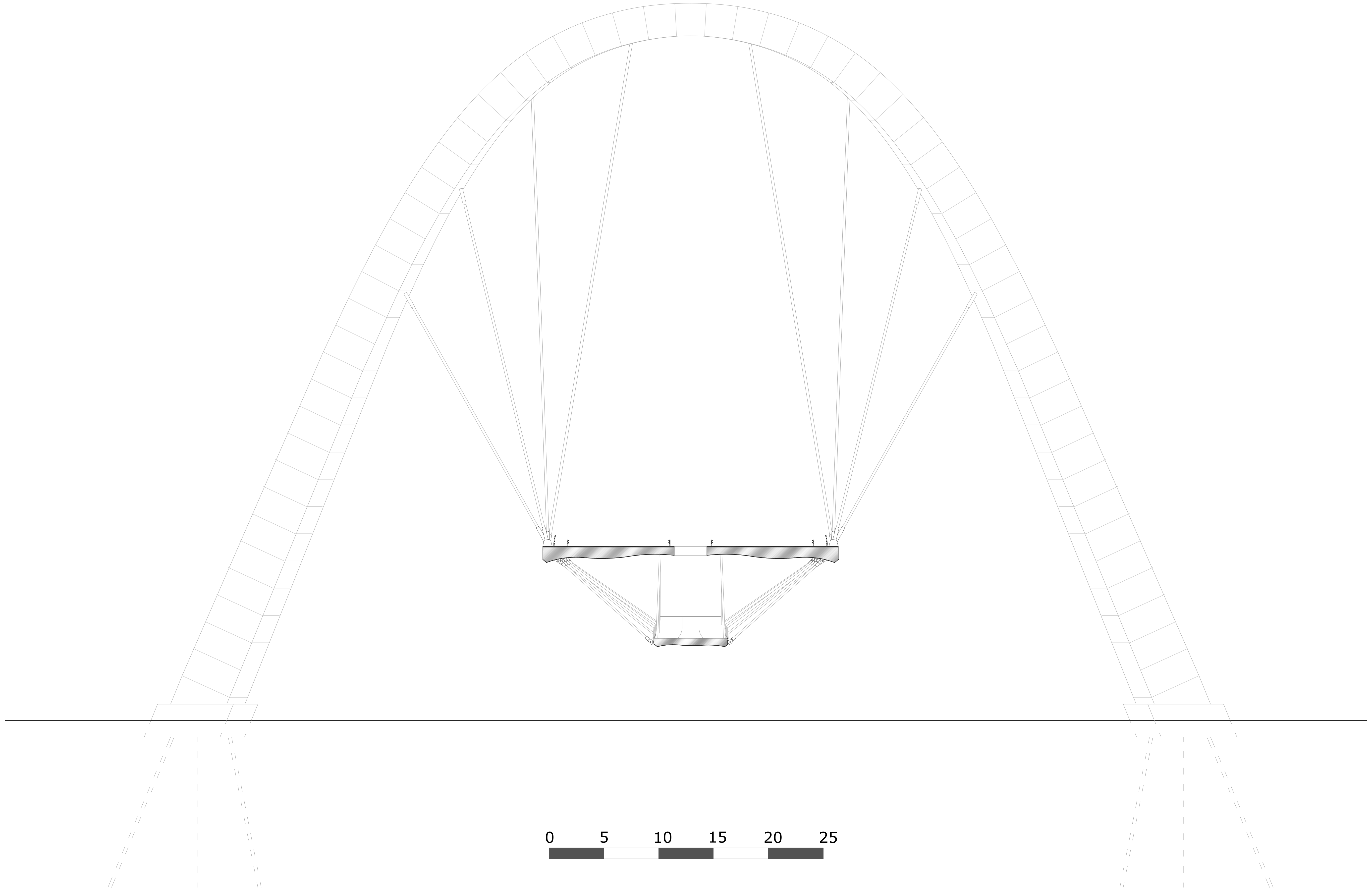


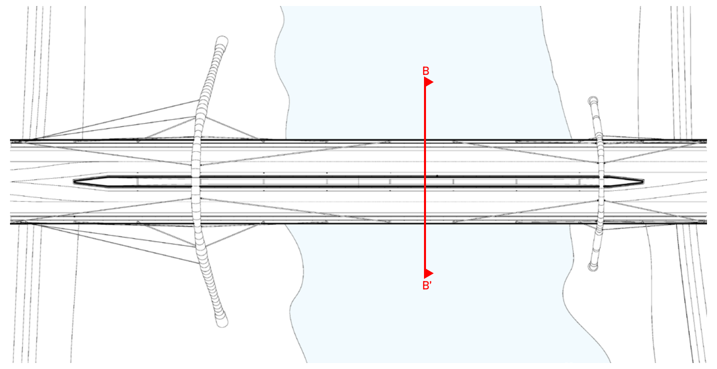
# Elevation



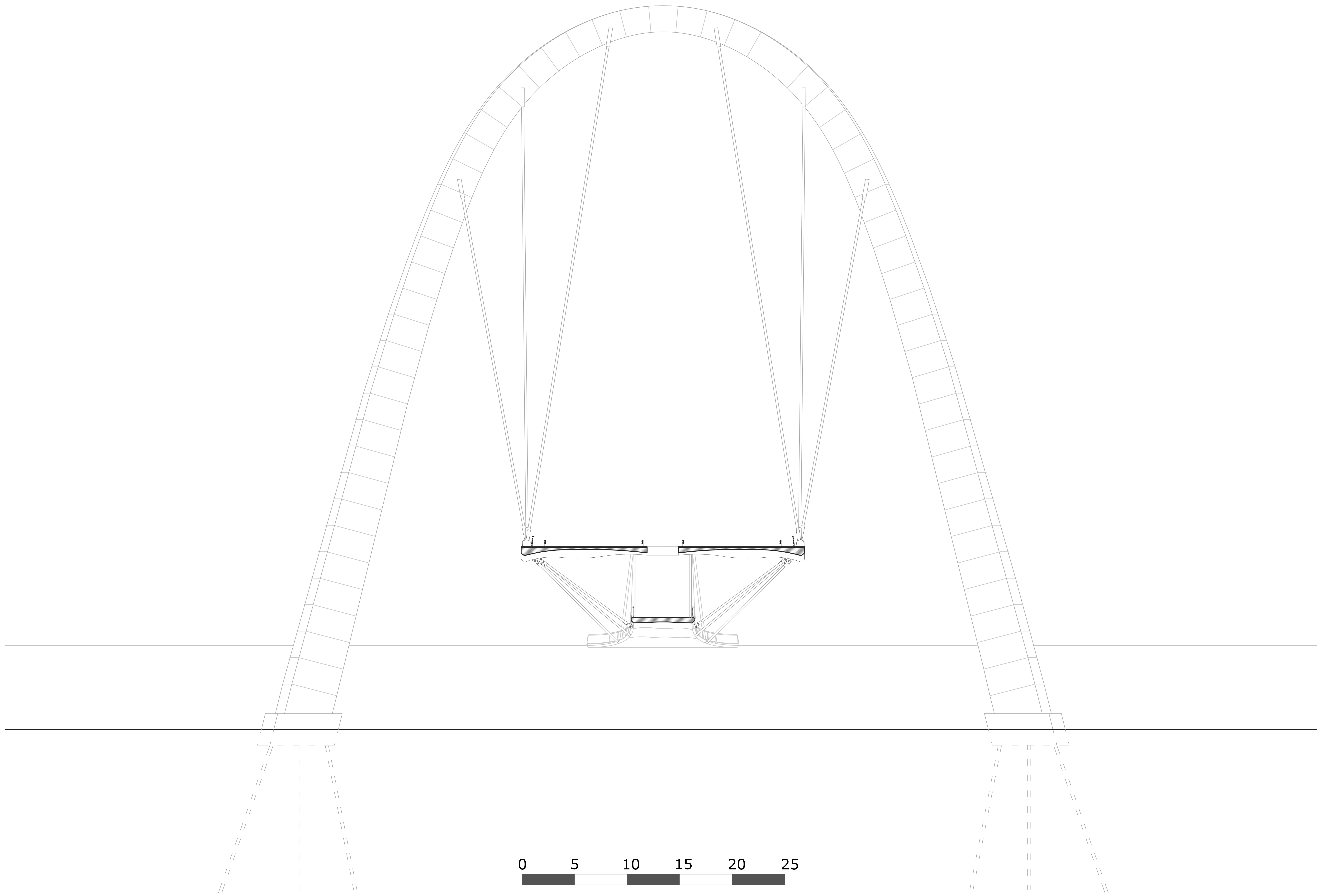


# Section A-A’ (1st arch)

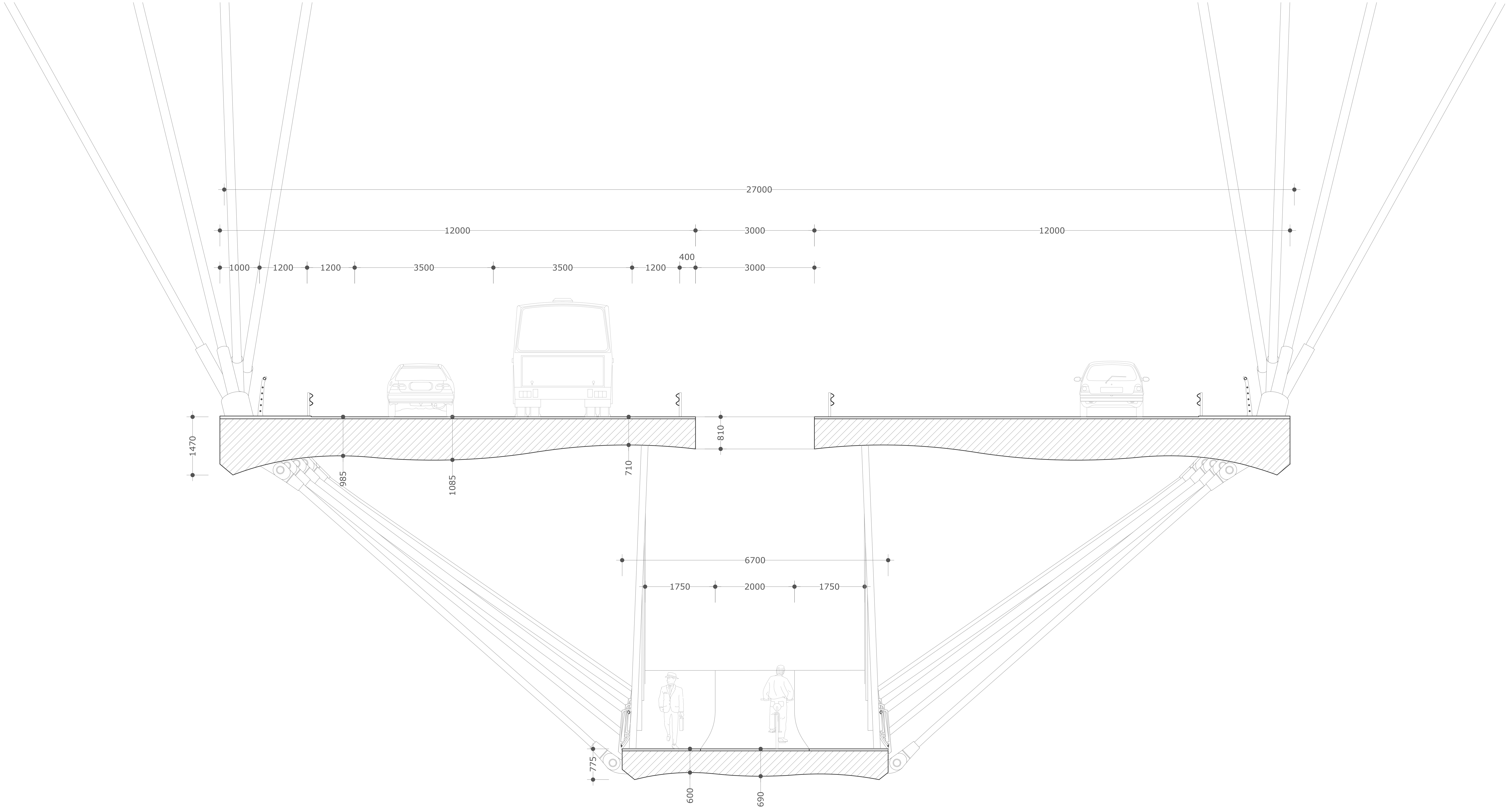




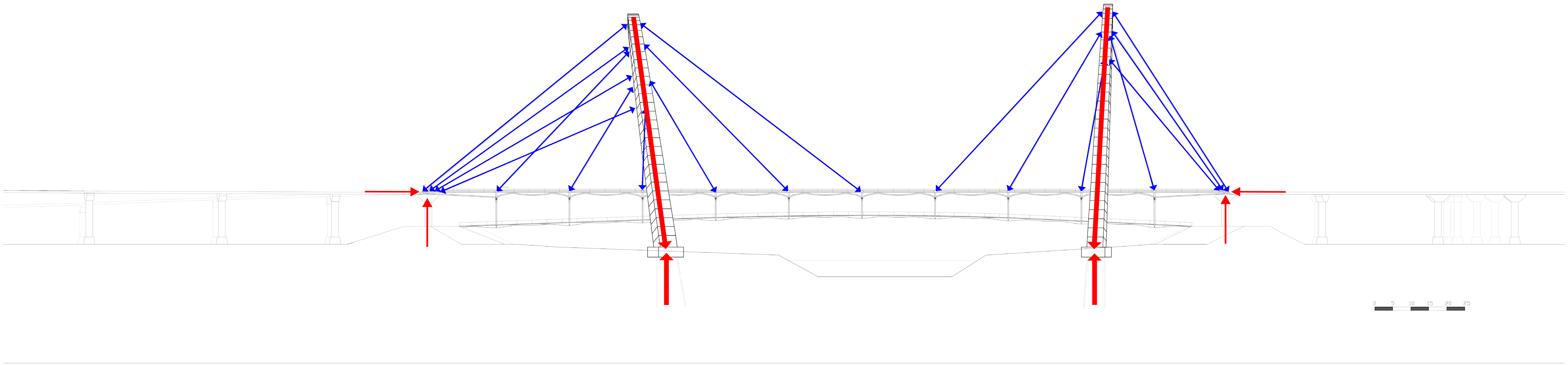
# Section B-B’ (2nd arch)



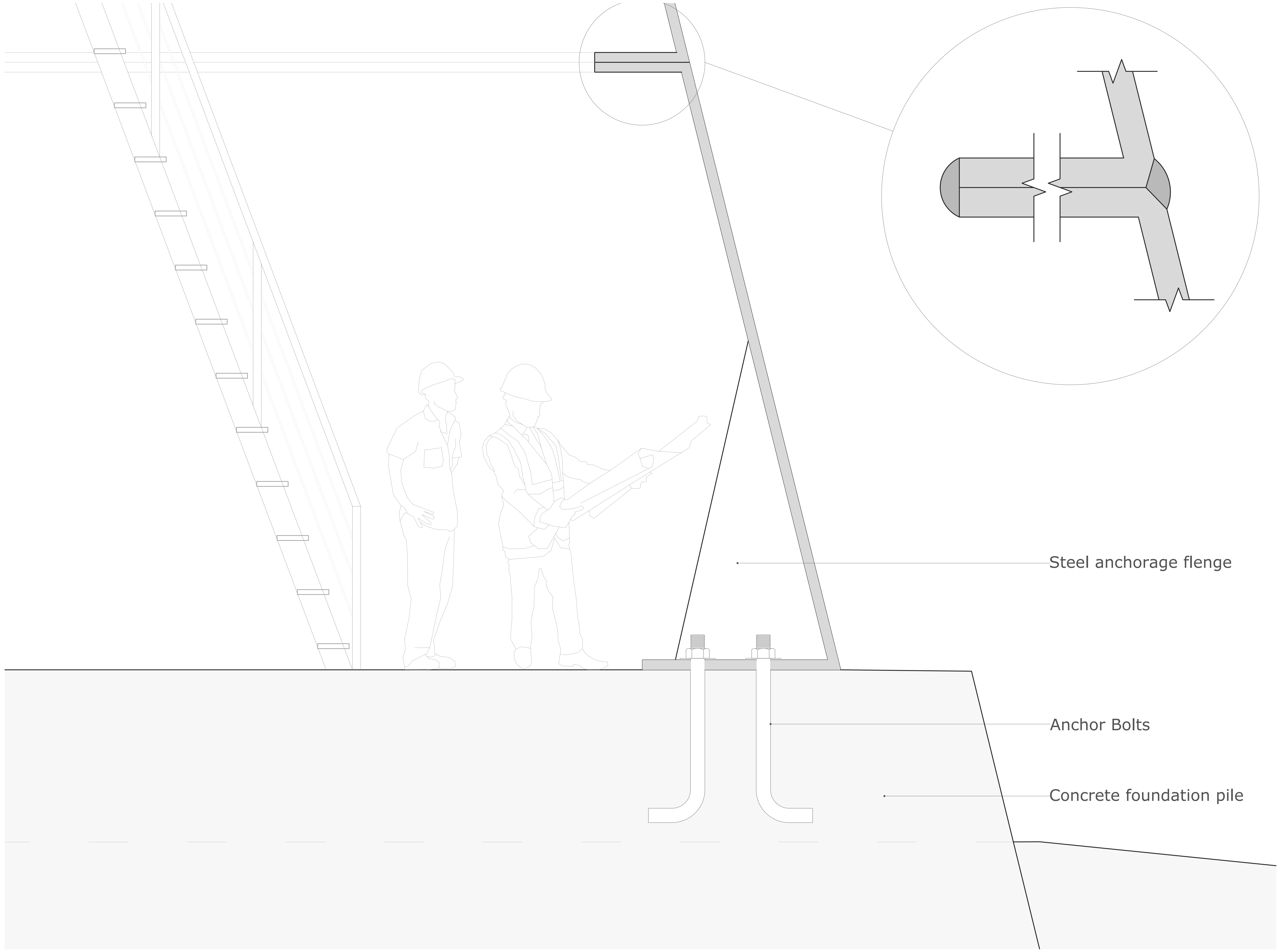
# Section A-A’


27000
12000
3000
12000
400
1000
1200
1200
3500
3500
1200
3000
1470
810
985
1085
710
6700
1750
2000
1750
775
600
690

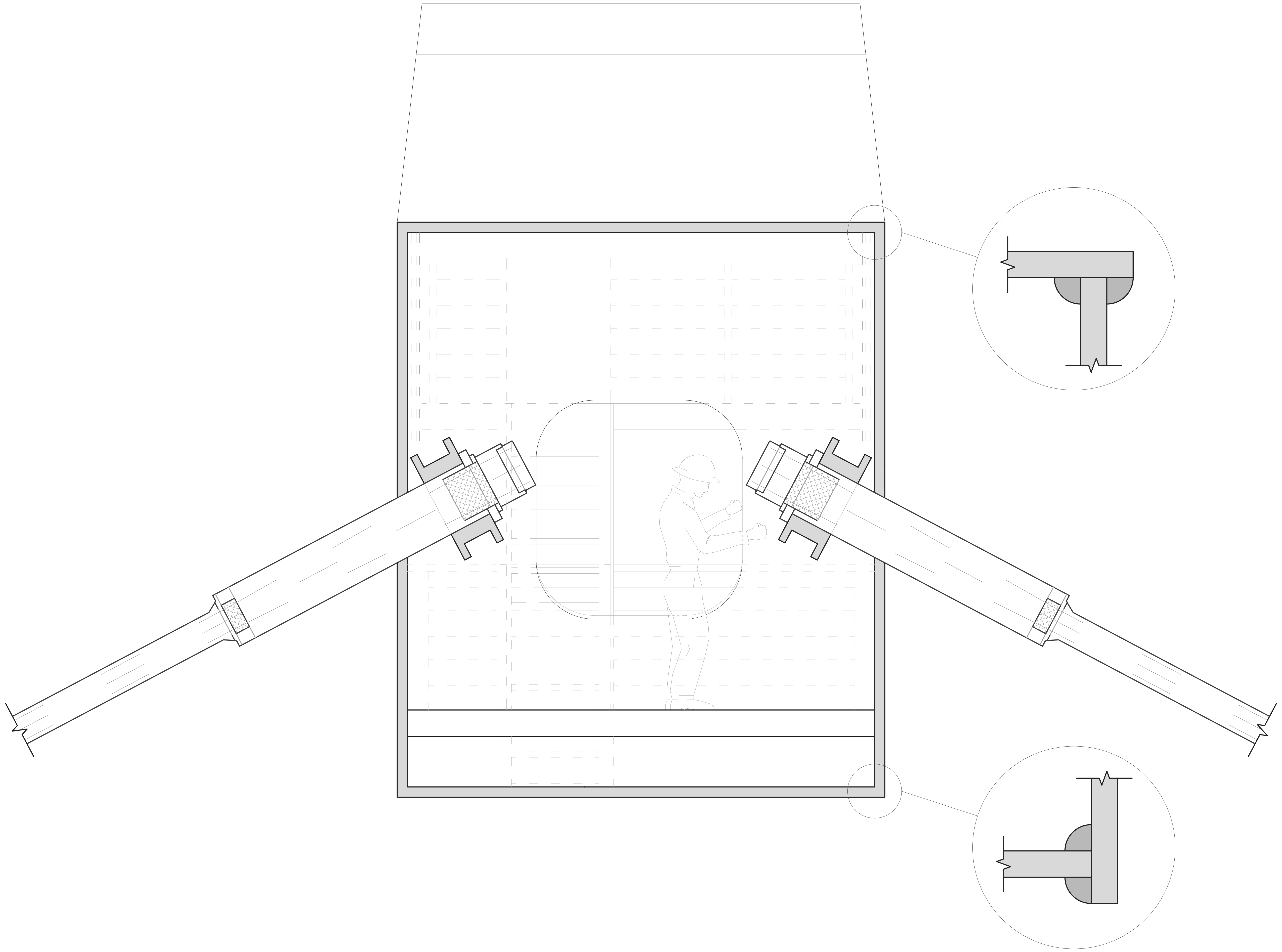
# Flow of forces



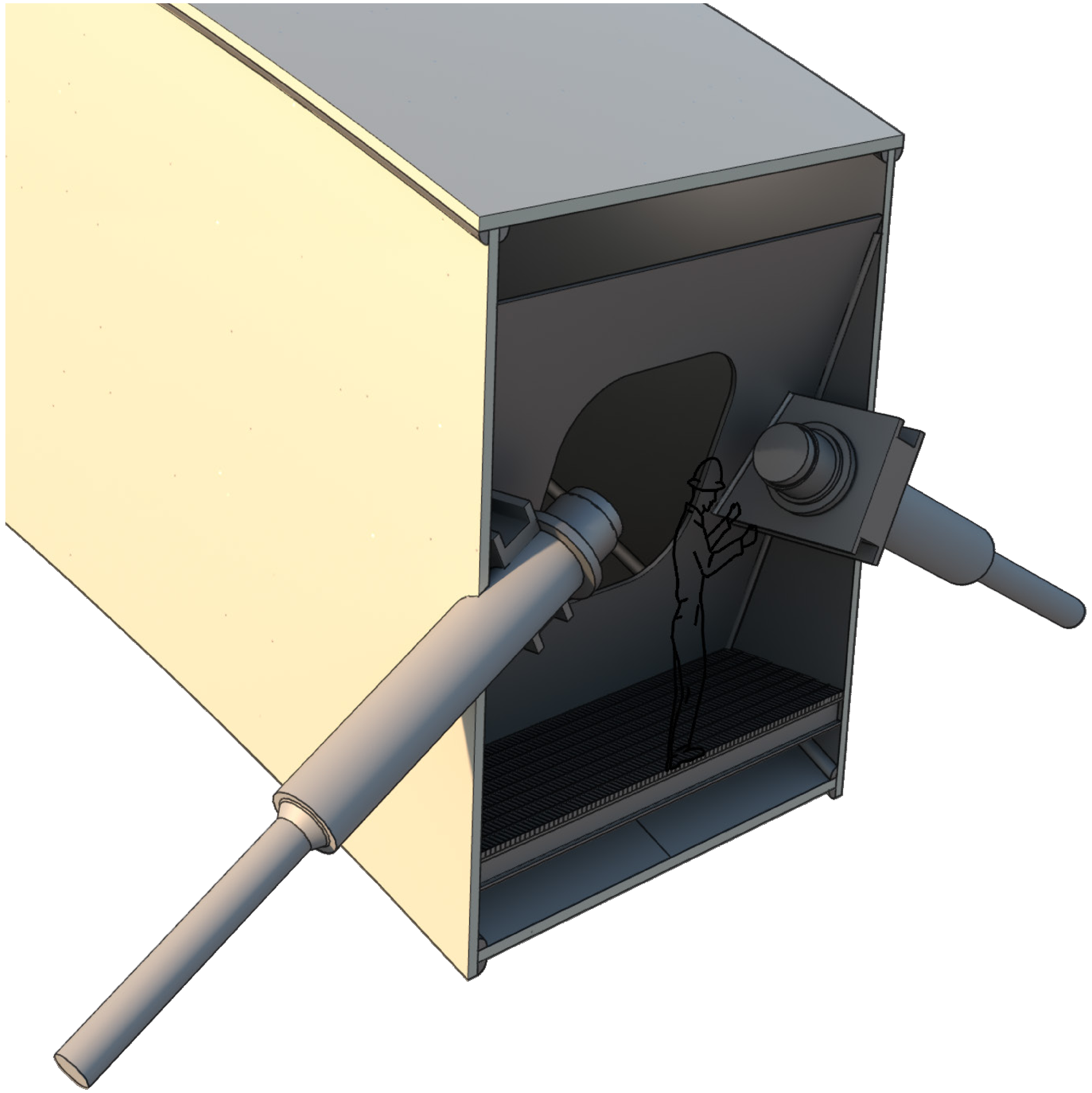
# Pylon’s connection to foundation



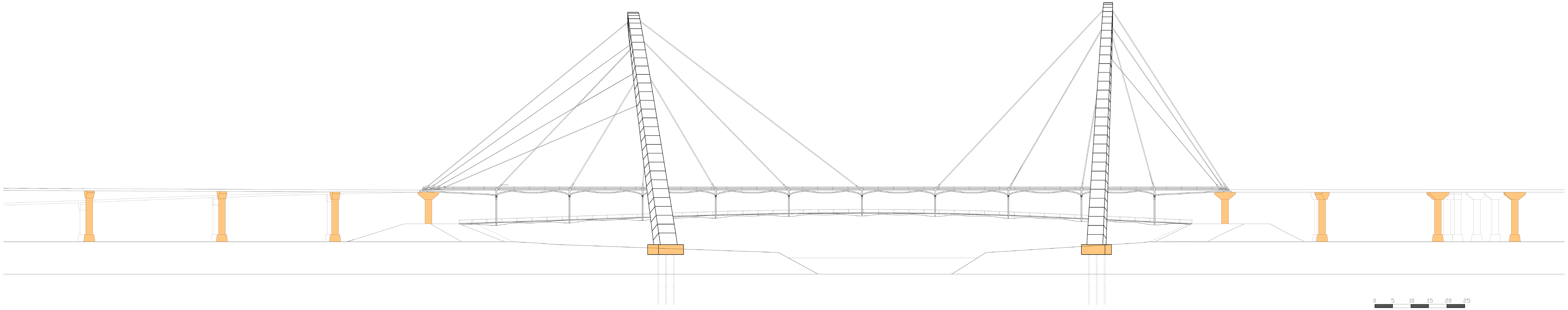
# Cables' anchorage on pylon



# Cables’ anchorage on pylon

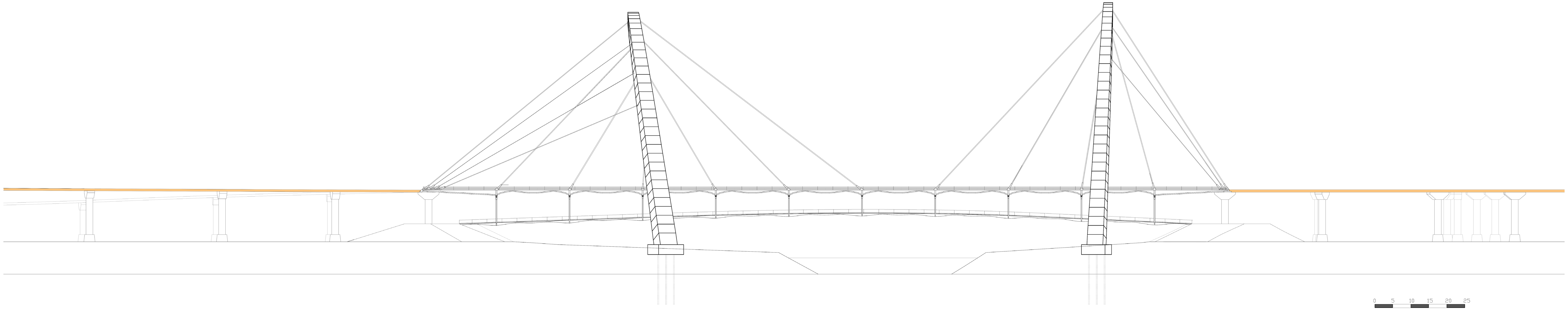


# Building sequence



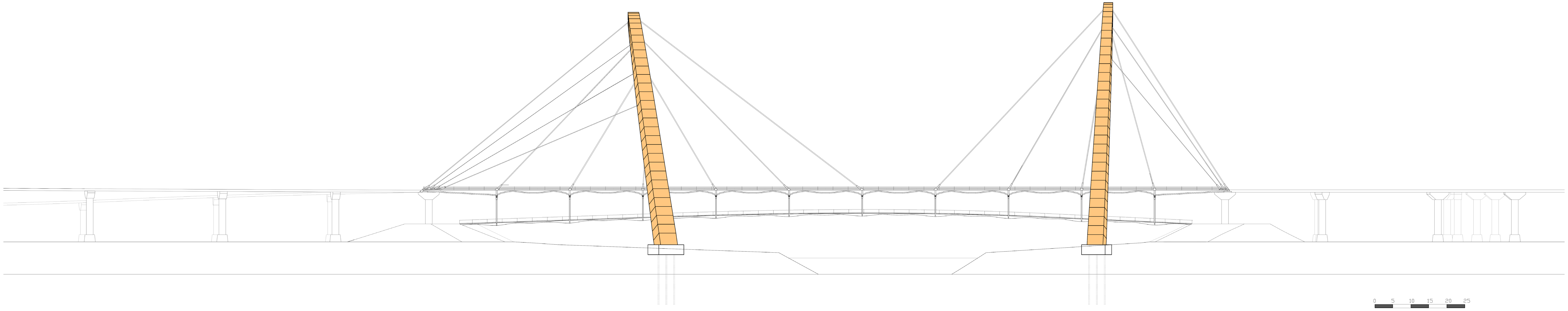
• **Foundations and road supports**

# Building sequence



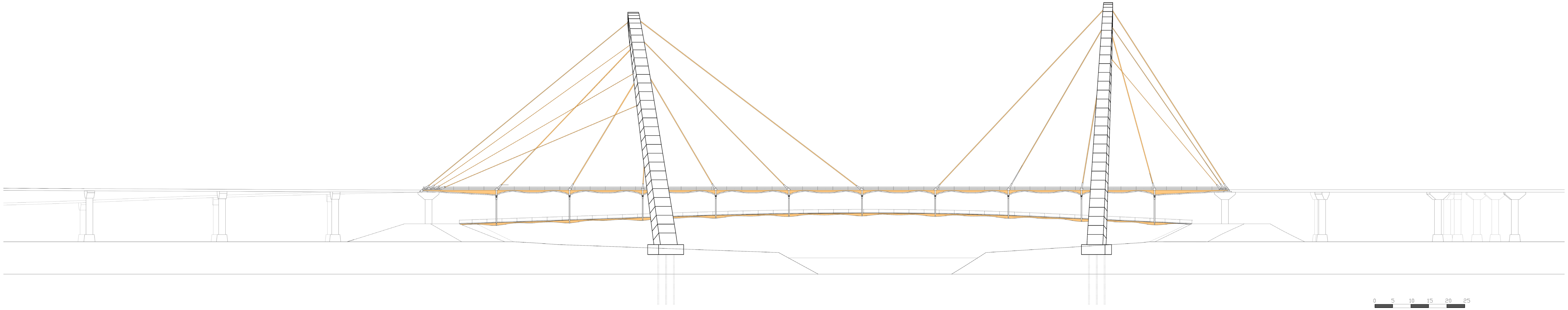

- **Approaching roads**

# Building sequence



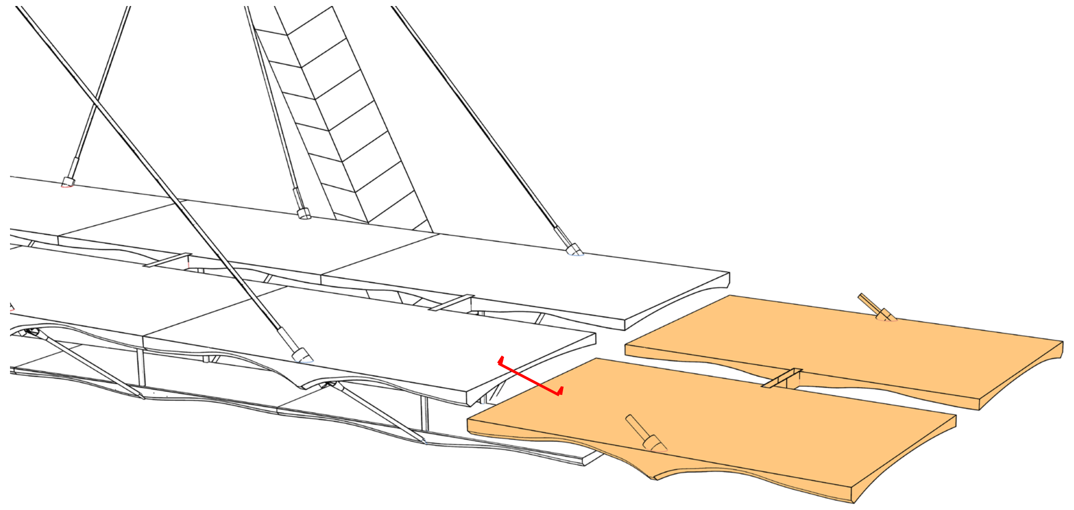
- **Pylons construction**

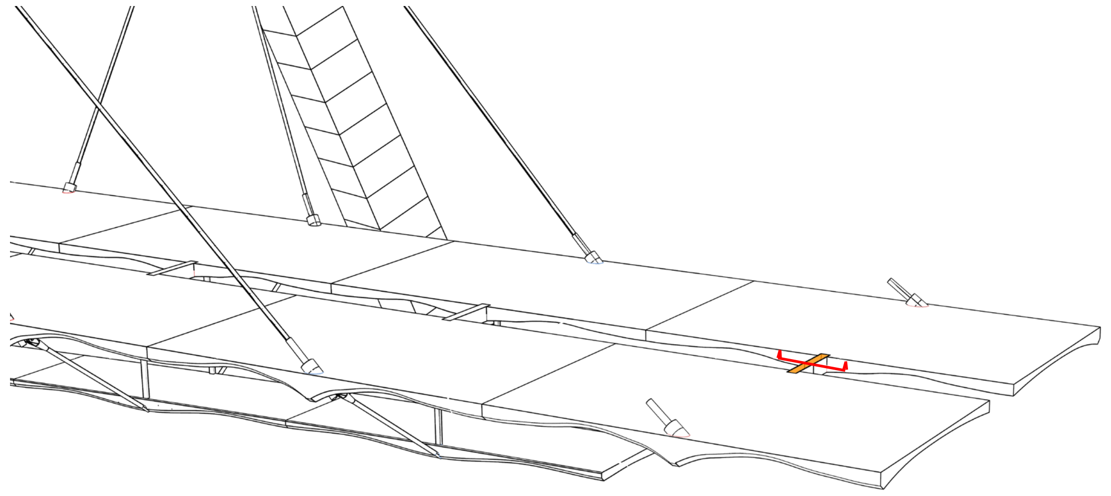
# Building sequence

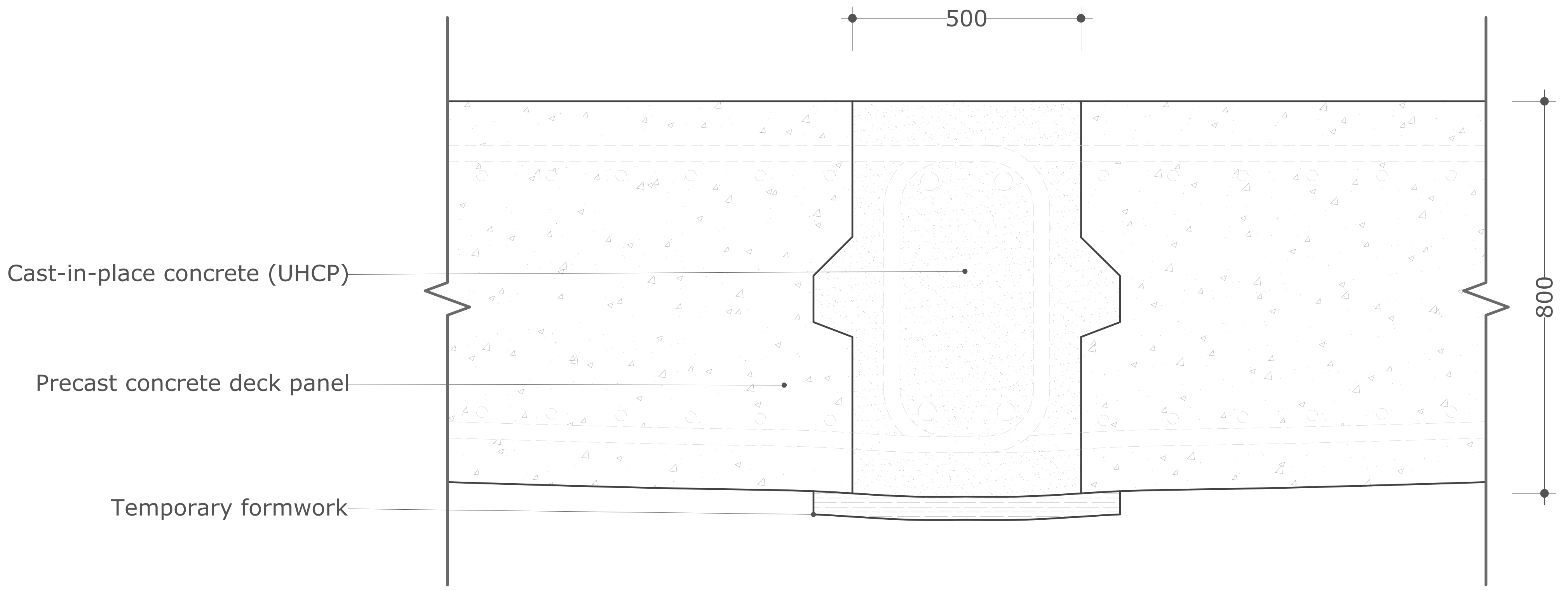


- **Deck segments and cables**

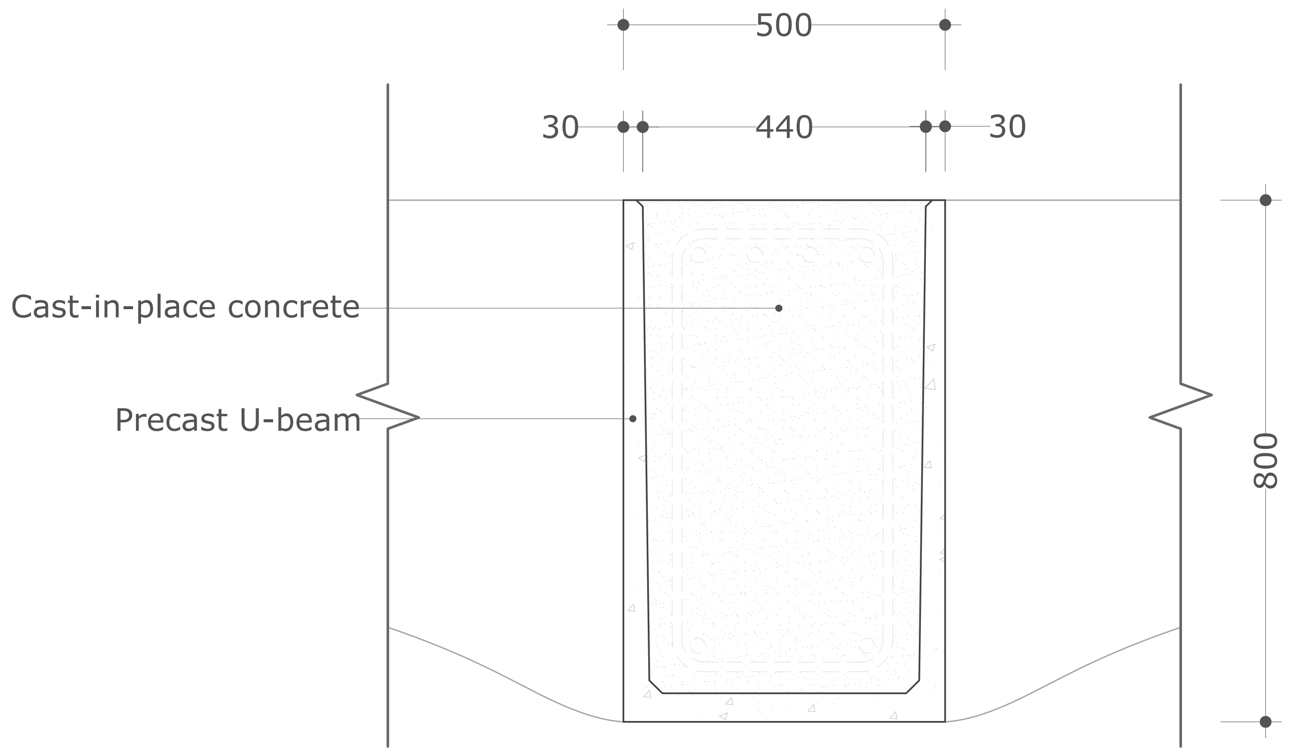
# Deck segments connection





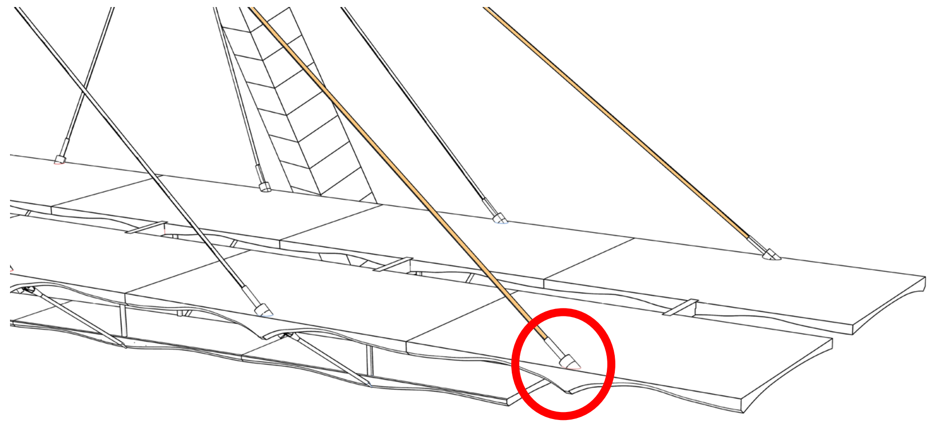


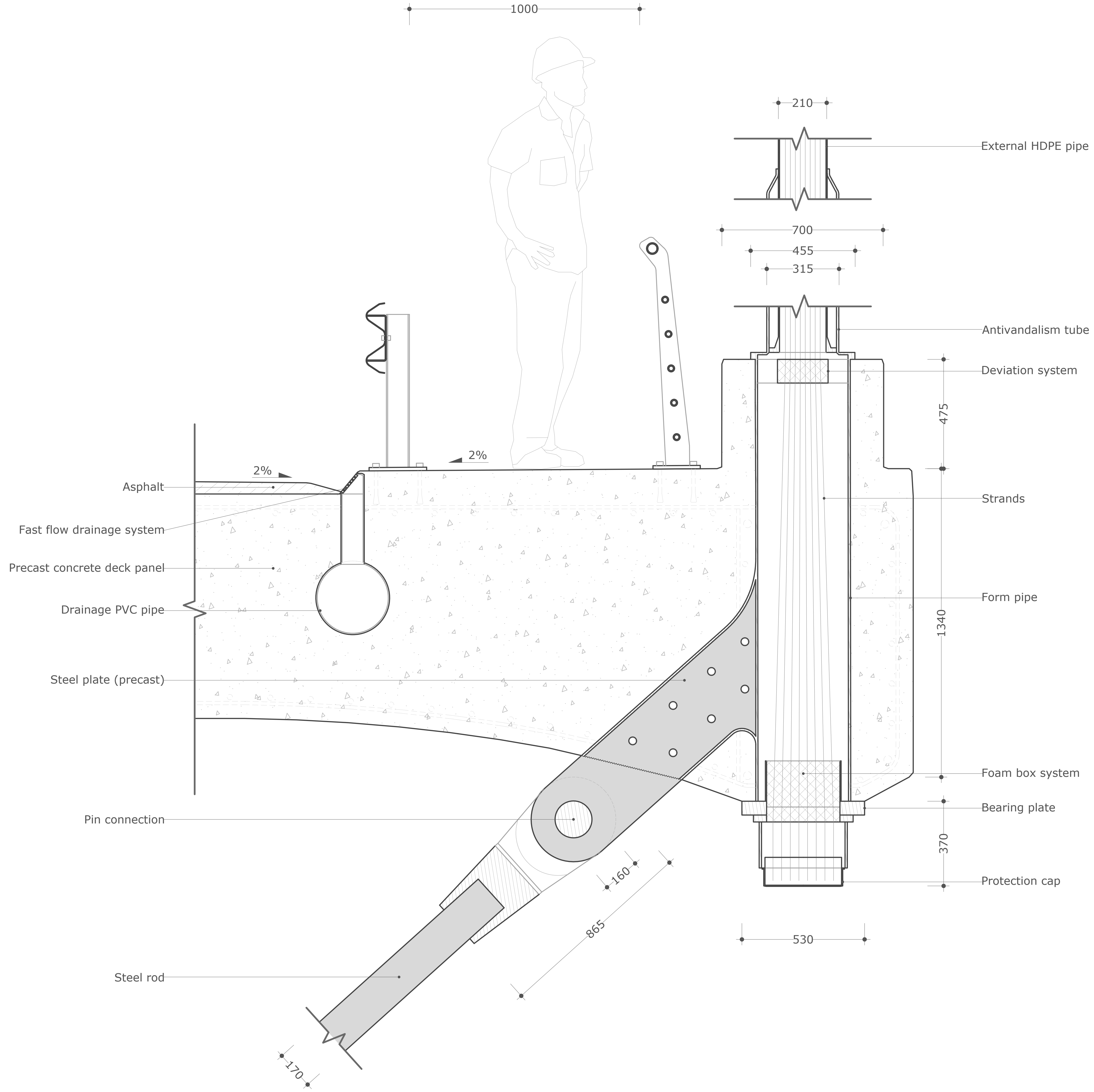

**Deck segments connection**

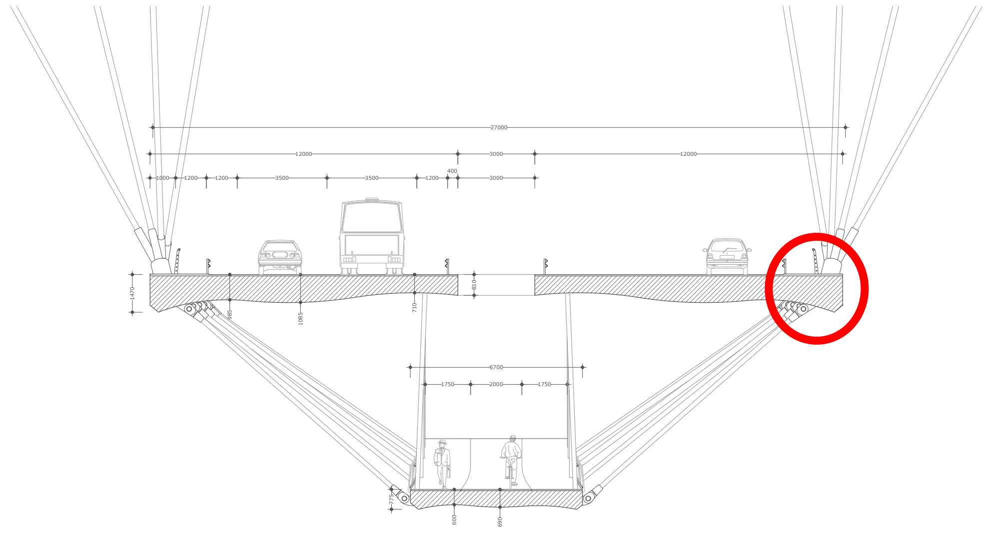


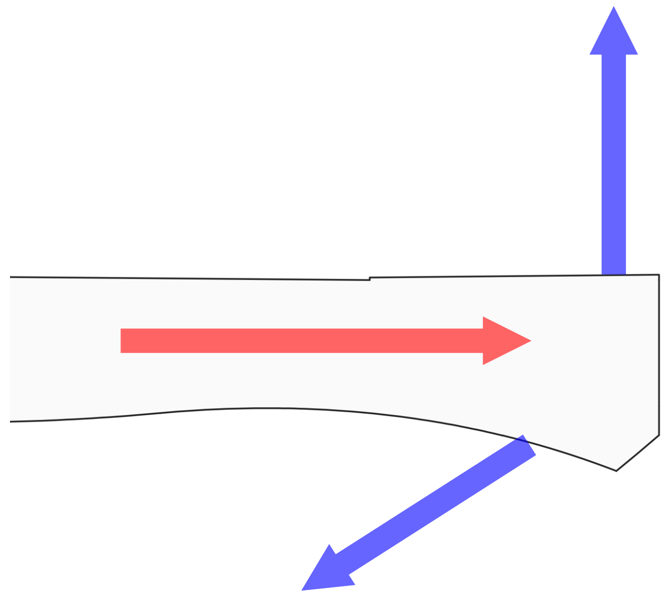

**Crossbeam transversal section**

# Cables' anchorage on deck

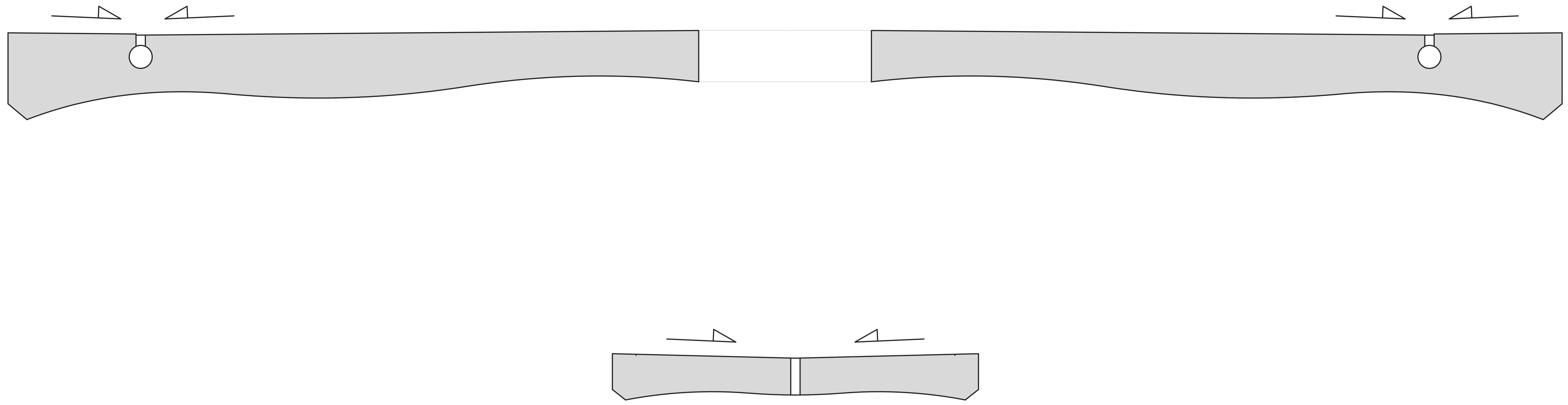


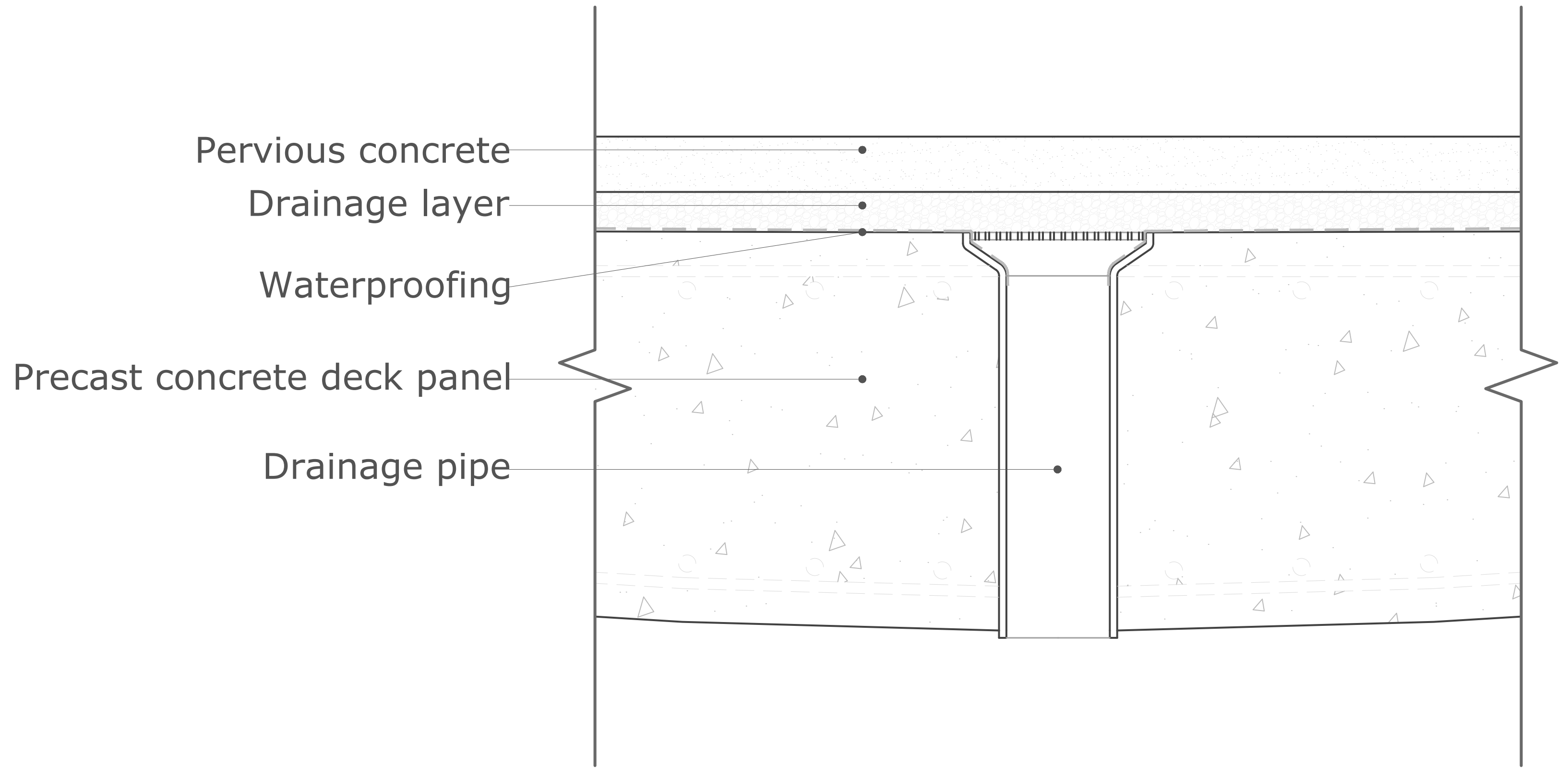




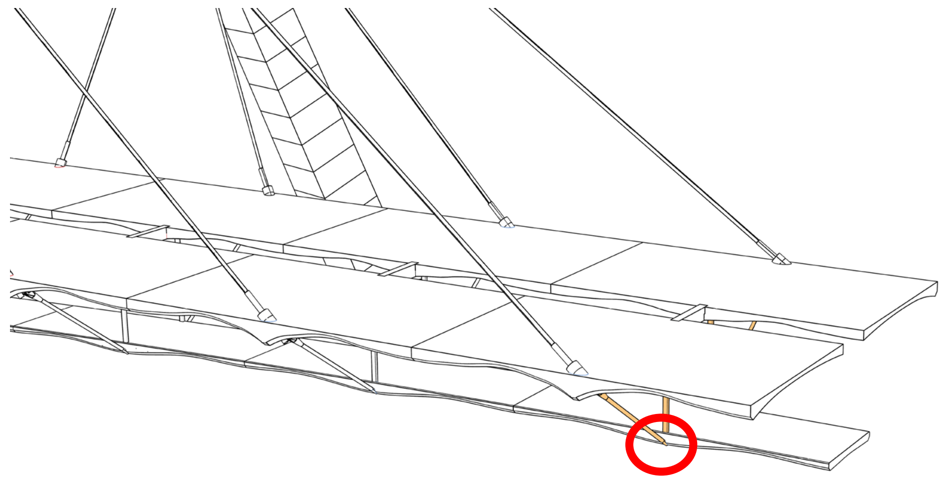
# Water drainage scheme

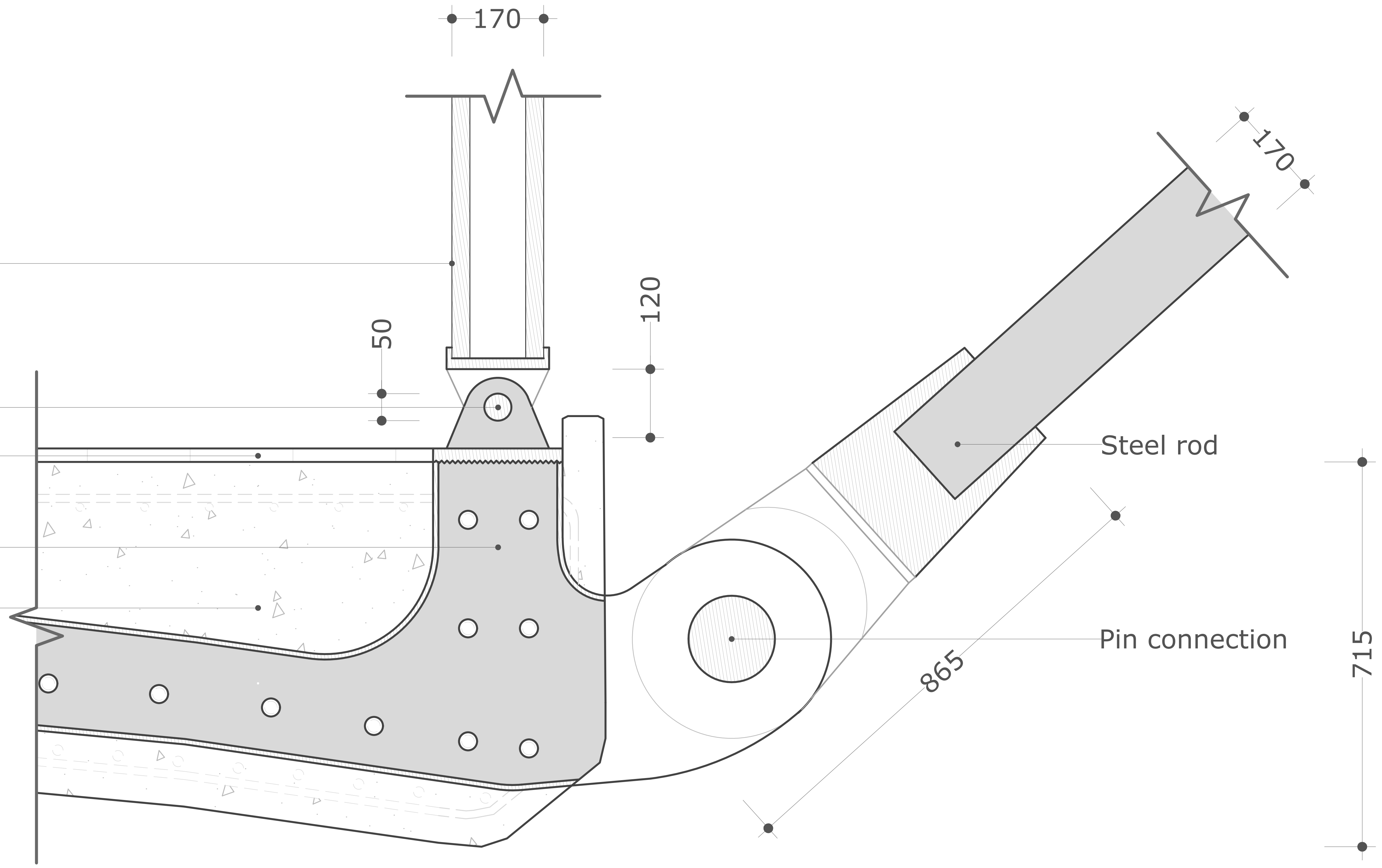


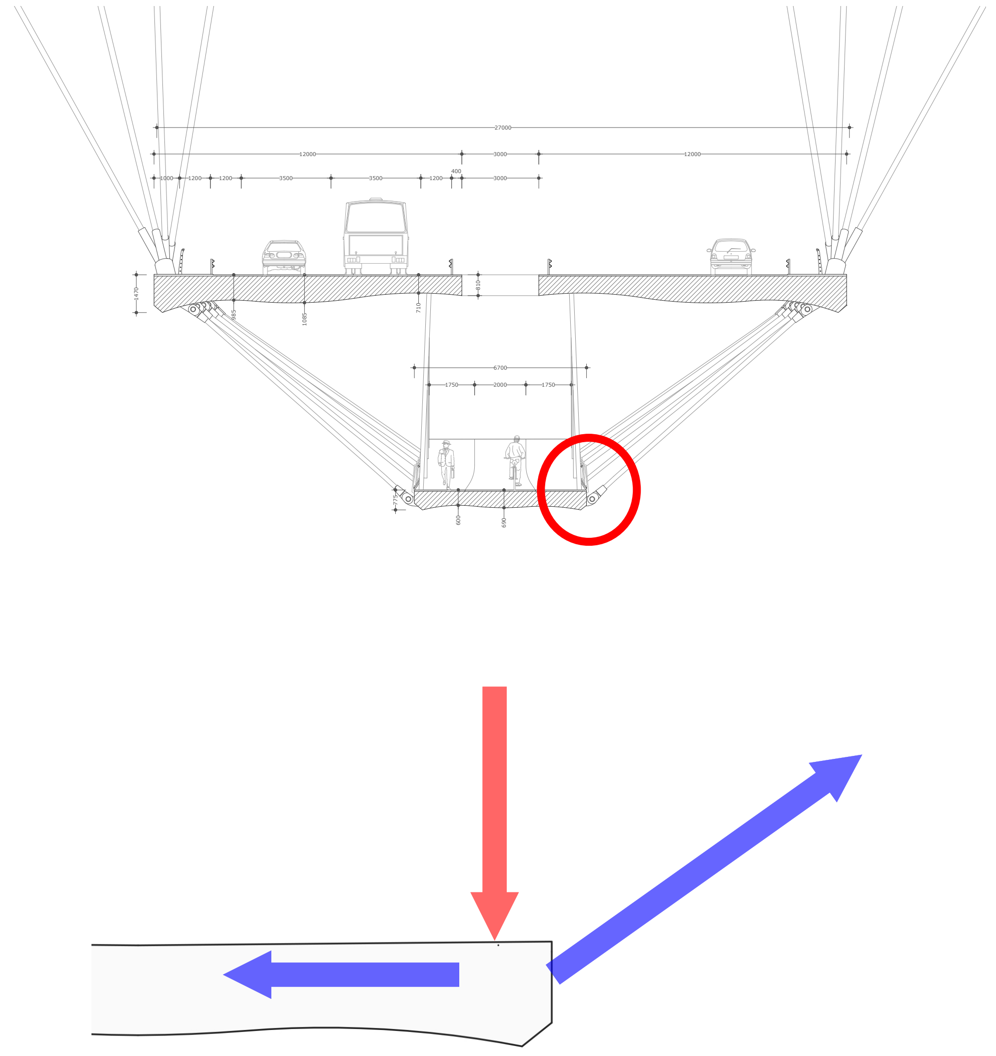



**Water drainage on footbridge**

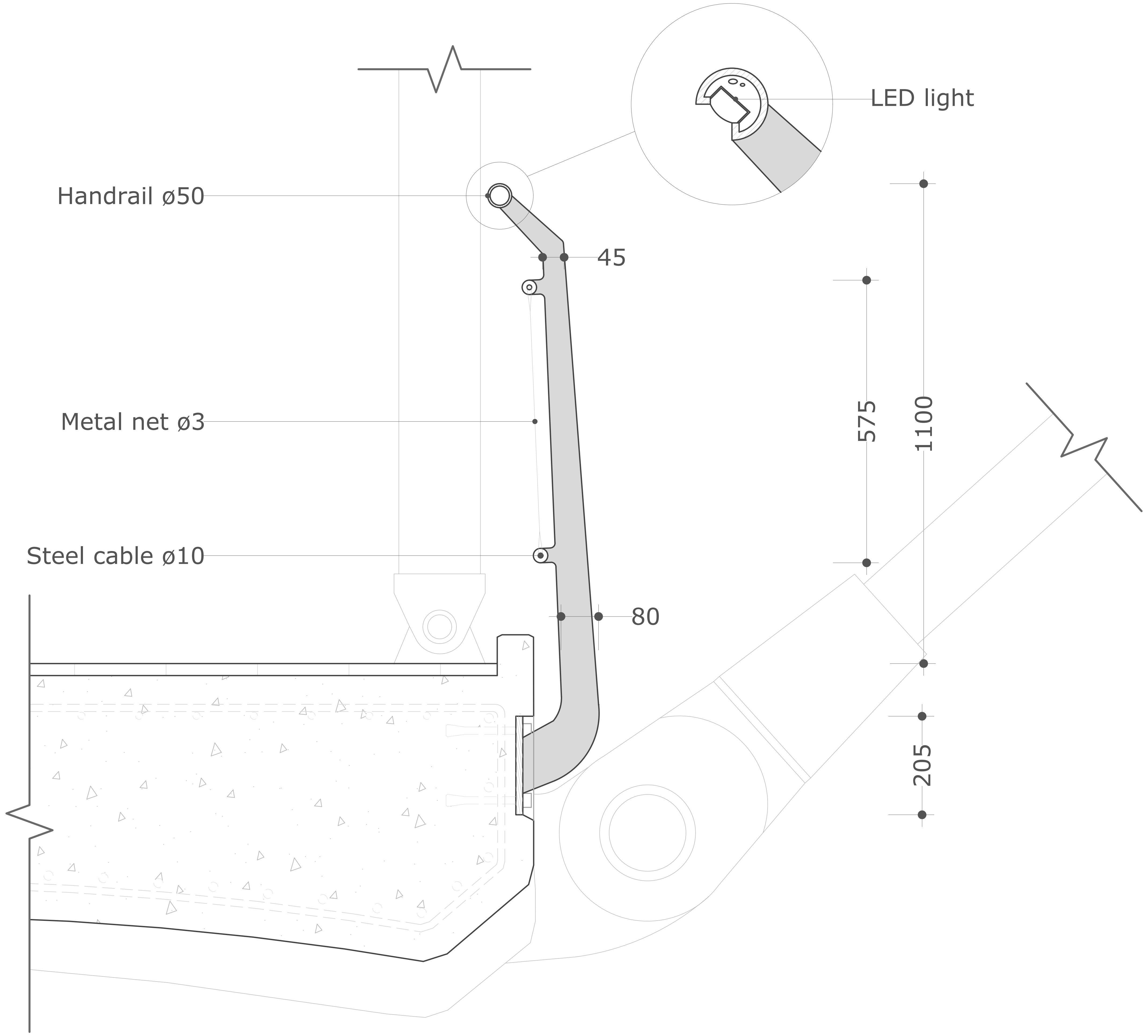
# Footbridge supports anchorage



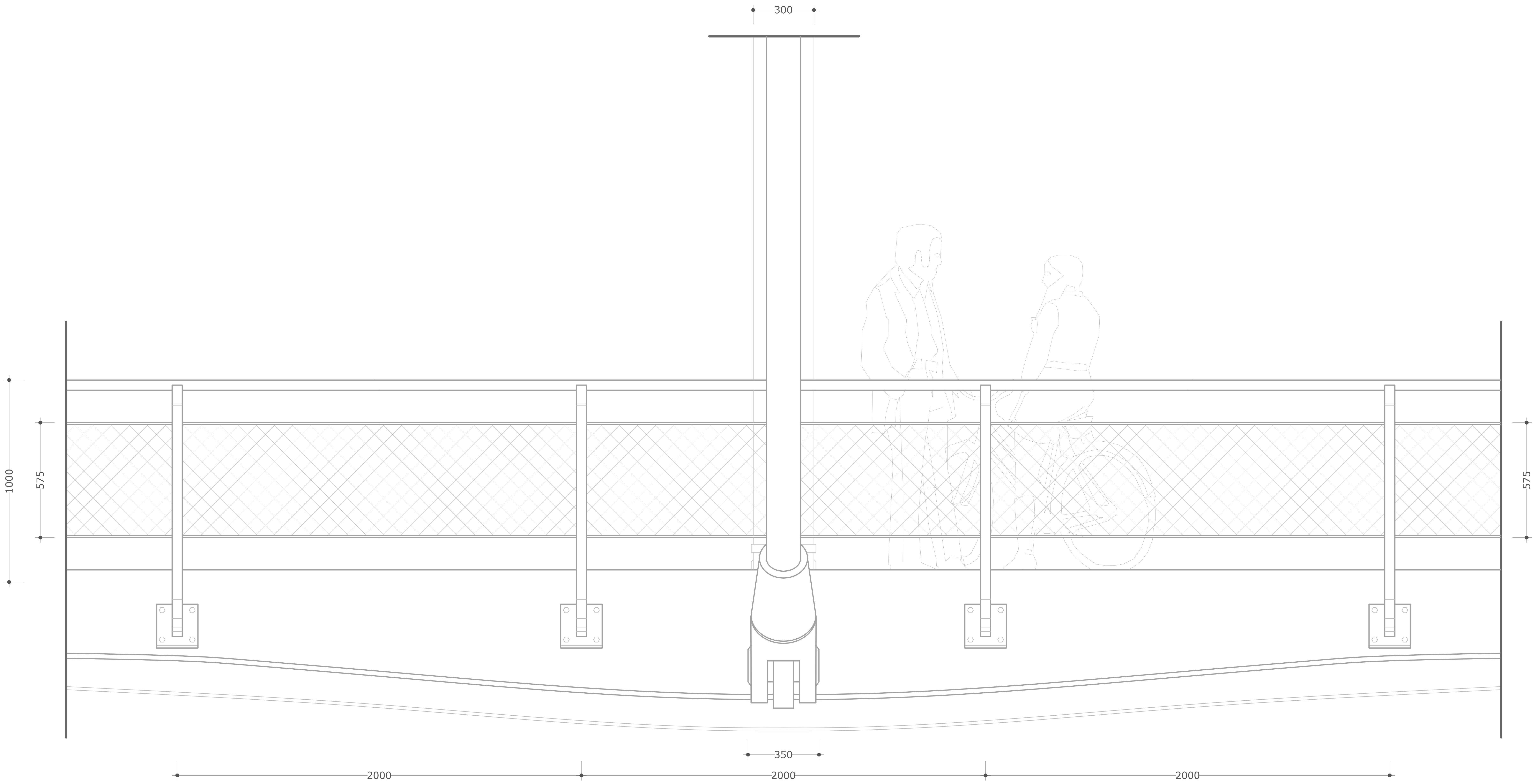


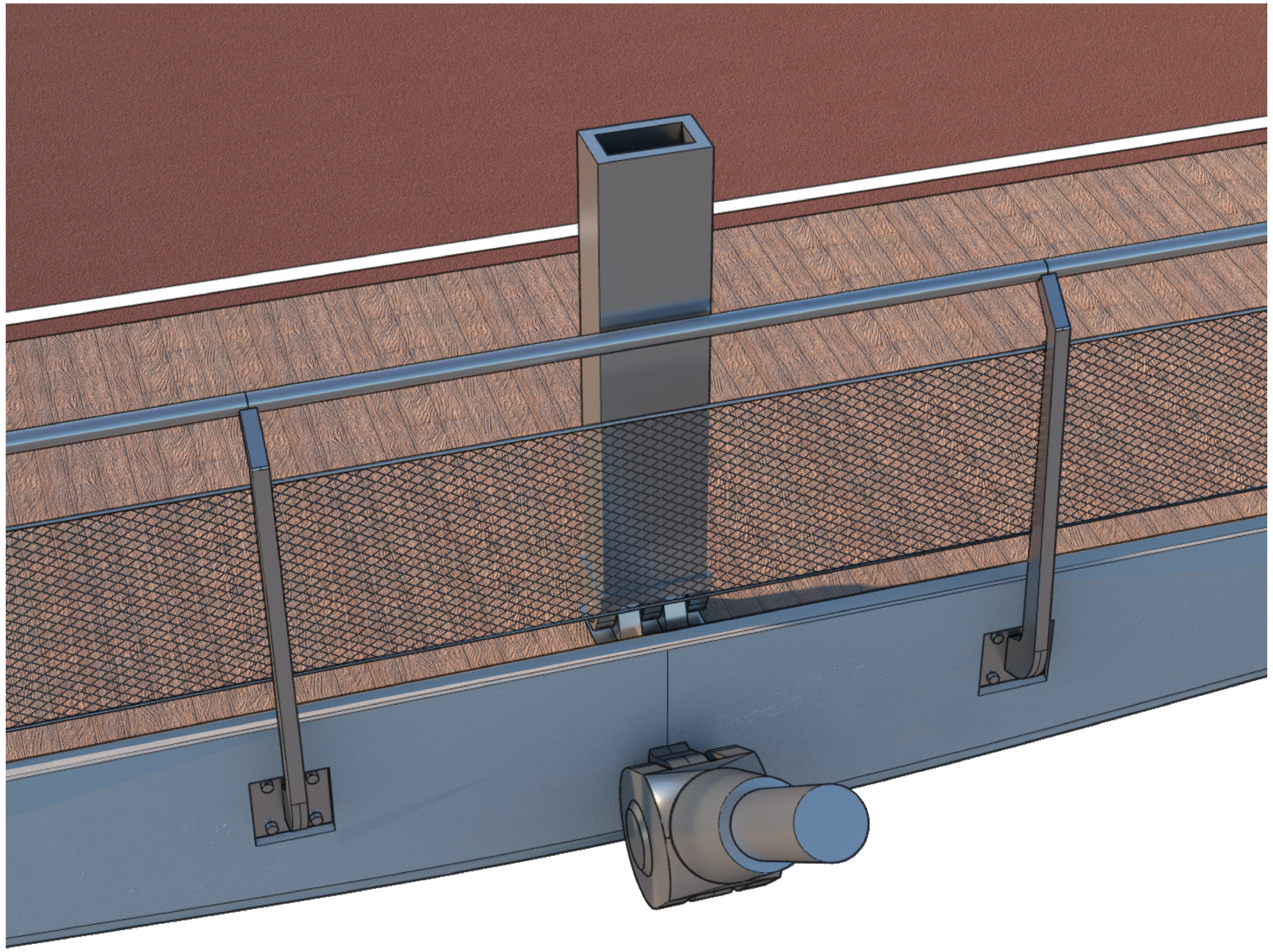
# Footbridge railing

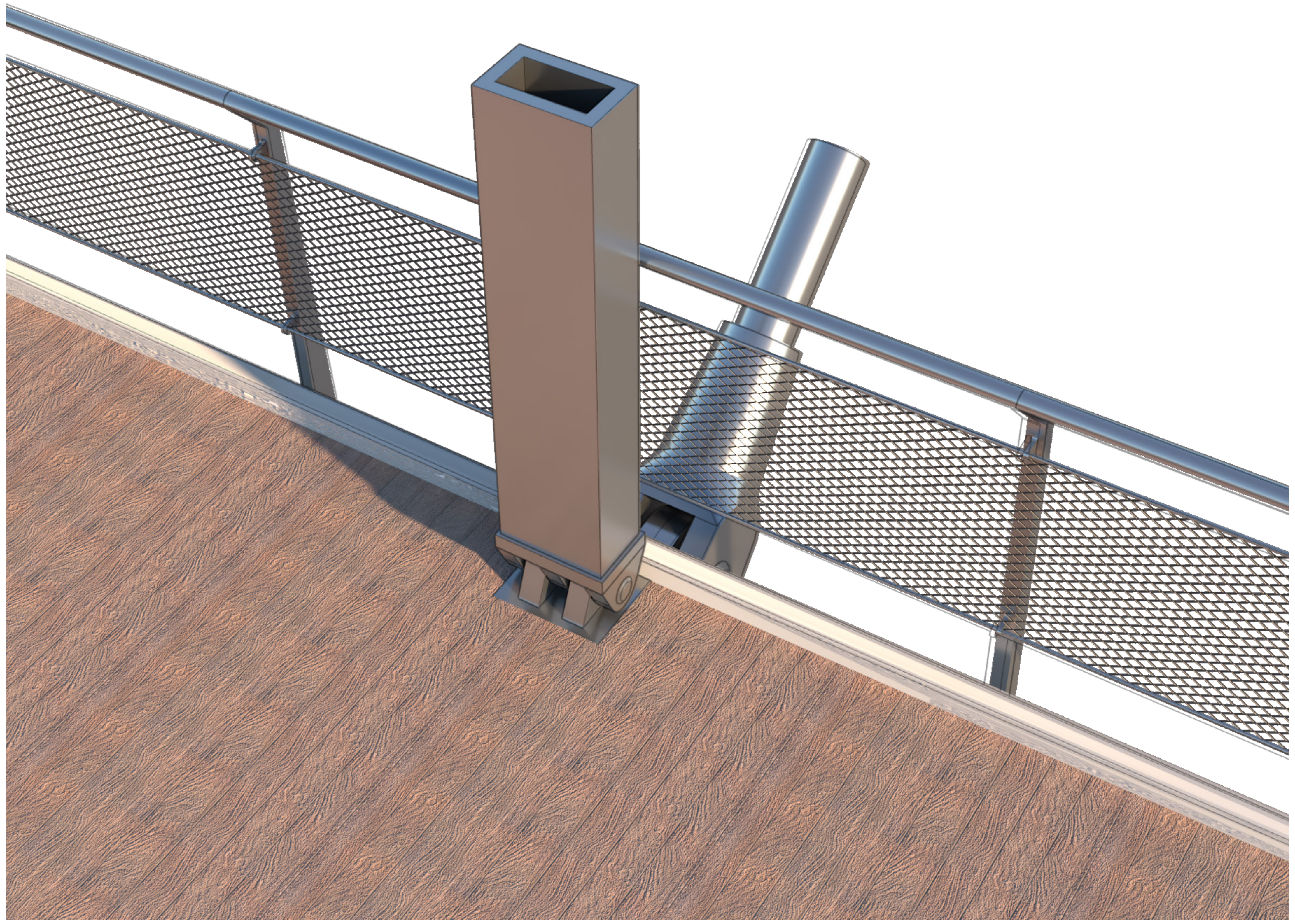


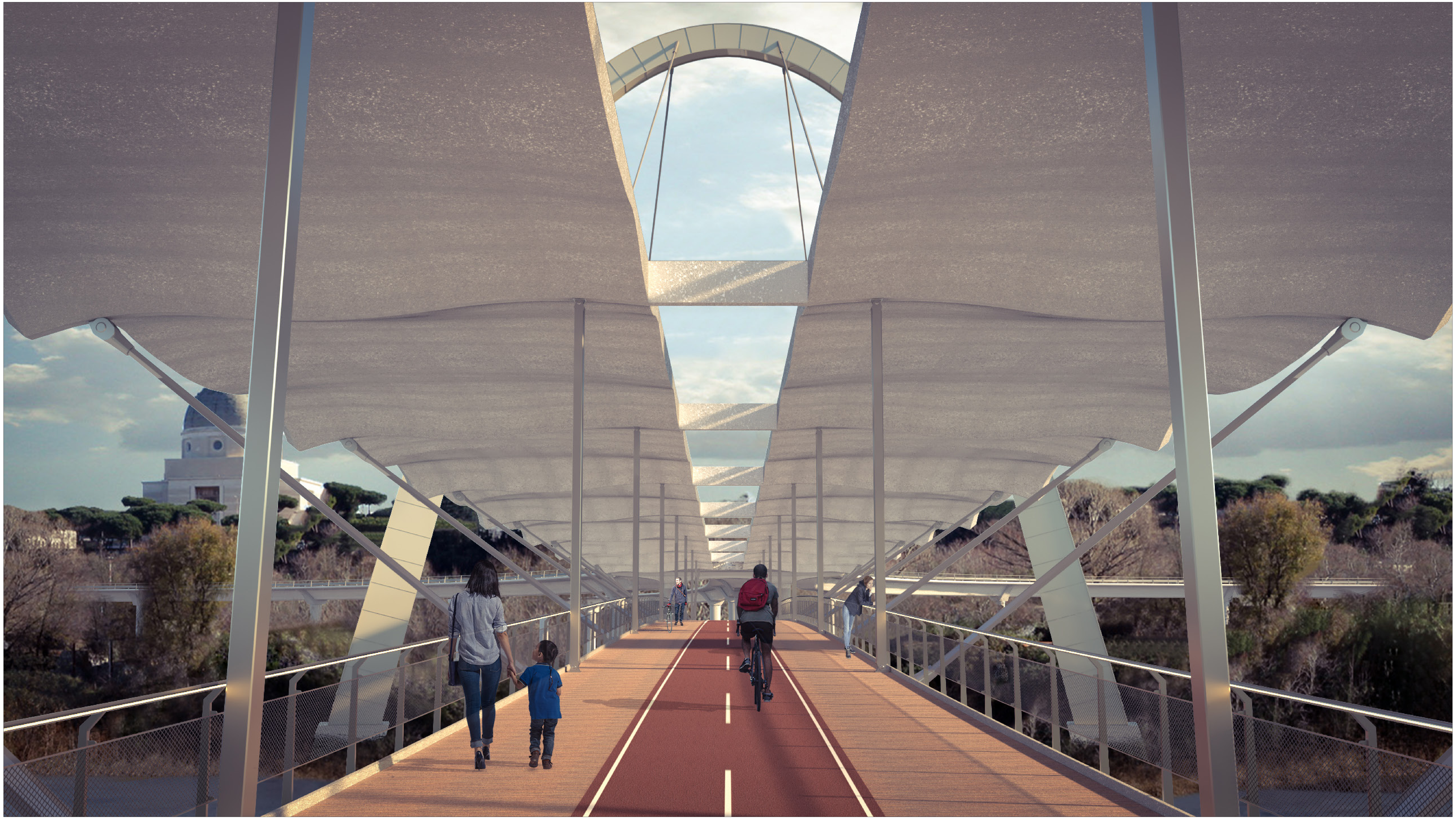
# Footbridge sideview



# Footbridge connections 3D view







# Remarks

# Remarks

- The final design has been shaped for the context in which the project is located. The functional needs are fulfilled, and the main element's dimensions are defined according to the forces acting on the structure. For a more accurate structural verification, a **nonlinear analysis** should be implemented.

- Multi-Criteria Decision-Making methods can partially help the designer have control over the preference of one solution over another, and the entire approach can be considered a powerful tool to help the designer make an **informed decision**.

- The main risk and downturn of the methodology used is the amount of **time needed to develop the optimisation process** due to its steep learning curve associated with the complex model. However, once familiar with the process, the computational designer can quickly set up the model bearing in mind the most necessary criteria to take into account.

- The optimisation process did not guarantee a single optimal solution, but it **guided the design** in the right direction according to the defined objectives.

# Conclusion

Concerning the main research question: "**In what ways does the optimisation method impact the design process workflow and to what degree do these add value in respect to the project's sustainability?**", the results obtained through the optimisation processes can be considered promising regarding the **effective use of the material** and exploration of different configurations in the early phase of the design process.

The result obtained in this research can only be considered as a **first step** towards a project that can be defined sustainable, because of the vast amount of criteria that need to be considered throughout the entire life span of the bridge.

# Thank You