TOWARDS A SUSTAINABLE BRIDGE DESIGN

WITH THE SUPPORT OF OPTIMISATION PROCESSES AND DECISION MAKING SYSTEMS

Towards a sustainable bridge design

with the support of optimisation processes and decision making systems

Author:
Alessio Vigorito | 4946219

28 - 08 - 2020

Main Mentor:
Joris Smits | AE+T | Structural Design & Mechanics

Second Mentor:
Michela Turrin | AE+T | Design Informatics

External Mentor:
Stijn Joosten | ARUP Amsterdam

Delegate of the Board of Examiners:
Huib Plomb

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

TU Delft

ABSTRACT

This research aimed to design a new bridge for the city of Rome, Italy, through the support of modern optimisation and decision-making processes that can be implemented to make informed choices regarding aesthetic performance, structural firmness, and environmental impact.

The bridge's design was carried forward considering the city's plans for the new connection and the relationship with the context dominated by a rationalist architecture.

The architectural relationship with the context, the parametric optimization, and the minimization of the material used were the main drivers behind the final design.

ACKNOWLEDGMENTS

Concluding the master program at TU Delft, it is manifest how this two-year journey has had a powerful influence on developing new skills and awareness, leading to personal and professional growth. I am grateful for the set of experiences and knowledge acquired thanks also to a culturally different and lively environment.

The completion of this path would not have been possible without the help of people to whom all my gratitude goes. First of all, I would like to thank Joris Smits for having first fascinated me and introduced me a year before this research into the universe that revolves around the practice of bridge design. This topic's choice would not have been possible without my fascination for the innate passion that my first mentor puts into the study and realization of his projects. I am grateful for the comprehensive guidance I received during the development of this research and the knowledge I acquired over the two years. I am also grateful to have had Michela Turrin as my second mentor, for her introducing me and showing me how to best approach the intricate universe of computational design. I want to thank Stijn Joosten for his support, guidance, and for sharing his expertise with me.

Thanks to all of you for the unconditional and unvaluable help given to me during this thesis.

I would also like to thank the ESTECO company for allowing me to use their software, modeFRONTIER, an essential part of this research.

Finally, I would like to thank those outside the university environment who have supported me in achieving my goals.

I would mainly like to thank my family for the continuous support in countless forms given to me throughout my studies. In particular, thanks to my father, Marco, for showing me how no evil or obstacle cannot be overcome with the right determination.

Particular gratitude goes to my friend Damien for supporting me during the darkest moments of the last year.

A personal memory to Sonia for all the love and support that I will always remember and made me the person I am today.

CONTENT

1 INTRODUCTION

This chapter aims to introduce the purpose and context of this research project. The main field of application, the bridge design, is briefly described underlining its main characteristics. The theme of sustainability applied to bridge design is introduced, followed by the inherent computational optimization possibilities.The focus and restrictions related to the project context that will have to be investigated are presented. The research framework follows describing the problem statement, the objecti-ves and the research questions. Finally, the chapter concludes with the description of the research methodology.

1.1 BRIDGE DESIGN

In the De Architectura, treatise dated 15 BC, the author Marcus Vitruvius Pollio indicates as an effective architecture the one that knows how to combine aesthetics, structure, and functionality (venustas, firmitas, utilitas). In 1450 Leon Battista Alberti, one of the most multifaceted figures of the Renaissance wrote the De Re Aedificatoria. This treatise on architecture incorporates both the ten-book structure and the three fundamental concepts of Vitruvius, quoting numerous Greek philosophers and authors to frame the function of architecture sociologically. In the second part dedicated to utilitas, in the fourth book dedicated to public works, Leon Battista Alberti gives a short but effective description of the function of the bridge. In a re-edition of Vitruvius' work (Pollio, 1832, p.82-83), a paraphrase made in 1609 by Cosimo Bartoli of the definition mentioned can be translated as follows:

> *"the bridge is the main part of the road, but not every place will be suitable for its realization. It will not be desirable to build it at the end of a canton for the convenience of a few, but it must be in the middle of the country for the needs of everyone, certainly, it must be located in a site where it is possible to finish it with a not great expense, and hoping to make it almost eternal."*

A series of indications follow on the considerations to be made in terms of materials, construction methods, and related expenses, concluding by remitting the decisions to be taken in virtue of individual cases to the sagacity of the engineer (Pollio, 1832, p.82-83).

In today's urban context, the need to think about the design of a bridge is becoming even stronger, not as a mere line that connects a point a to a point b, but rather as the attempt to respond to complex problems often in relation to cities in constant evolution. The design of a bridge is perhaps the most direct expression of the intention to find an optimal synthesis, a perfect balance between the values expressed by the Vitruvian triad. Where structure and beauty meet a utility that is no longer possible to separate from a necessary sensitivity regarding the sustainability of the project.

1.2 SUSTAINABILITY

A treatise or article concerning structural engineering often does not provide for a definition of the same at its beginning, while very often when it comes to the topic of sustainability and sustainable development, the first step taken is to give a definition (Bilec, Ries and Matthews, 2007). The language used in conferences and general discussions upon the subject does not help the felt need to define it and the dispute over the best choice and meaning of sustainability. The language used when dealing with this topic very often refers to the word, easier to digest, *green* (Yanarella, Levine and Lancaster, 2009).

The result is a possible uncertainty about what is considered green and what is sustainable. A green design is usually associated with individual processes, technological innovations, and strategies aimed at minimizing the negative impact that a building, for example, can have on the environment, whether it is air, water, or living beings possibly injured by the process. Moreover, the green design focuses mostly on the present time and short-time achievements. Sustainable design on the other hand, not only becomes aware of any long-term repercussions and effects but is defined by a sphere of interests that includes the social and economic aspect as well as the environmental aspect, according to a sustainability tripod. (Munasinghe and Cruz, 1995).

Despite different definitions and ideas about sustainable development, there is consensus that it has to meet the material and social needs of the present generations without depriving the future of the same possibility (McIsaac and Morey, 1998). One of the most quoted definitions is probably the one given in the report Our Common Future redacted in 1987 by the United Nation World Commission on Environment and Development, which was later enriched by engineer Roy f. Weston (1994):

> *"Sustainable Development is a process of change in which the direction of investment, the orientation of technology, the allocation of resources, and the development and functioning of institutions meet present needs and aspirations without endangering the capacity of natural systems to absorb the effects of human activities, and without compromising the ability of future generations to meet their own needs and aspirations "*

1.3 COMPUTATIONAL DESIGN

The architectural design process can be seen as the attempt to achieve a goal that meets specific criteria defined by the designer, through the search for one or more solutions within a space of possible solutions. The advent of computer-aided design (CAD) systems starting from Sketchpad in the early sixties and especially with the spread of AutoCAD in 1982, allowed to automate the production of drawings and simplify this process. Subsequently, between the 90s and 00s, the introduction of 3D modeling software allowed designers to rely on increasingly powerful and accessible tools to develop and represent the entire design process. These means, however, are nothing more than computer aids to the drafting phase. The computer assists in the creation of draft drawings, without adding anything new that was not already in the designer's mind.

The role assigned to the computer can have much more significant impacts on architectural practice when the architect does not try to develop geometry, but the principles that should guide the design process. When the criteria underlying design research are presented in the form of rule-based logic that can be quickly processed by the machine, it is possible to obtain much more complex iterations for a given design objective. In this way, the designer can move from mere computerization to fully exploit the potential of the computer (Terzidis, 2003).

When it is necessary to consider the three pillars of the sustainability of a project, one inevitably comes across the presence of numerous variables and criteria that often conflict with each other. To facilitate the choice between various alternatives available to the designer, multi-objective optimization processes and the use of multi-criteria methods can be considered an attractive solution.

1.4 PROBLEM STATEMENT

In 2000, the municipality of Rome solicited a design competition for a new bridge located in the southwest quadrant of the city expressing the desire to build it for the year 2025.

The new connection designed for both vehicular and pedestrian traffic will have to cross the Tiber river and serve as a new entrance to the city of Rome. The design of the bridge must be able to satisfy the functional requirements keeping in mind the strong relationship it will have with the nearby E.U.R. district, dominated by a monumental and rationalist architecture.

The bridge will have to be durable, functional, and architecturally beautiful while considering the impact that it will have on the environment since the construction industry has to face the need for sensitivity concerning global sustainability.

With the consequent rising demand for sustainable and resilient infrastructures, an approach which considers the optimisation of a structure to the best of its efficiency is nowadays stronger than ever.

1.5 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 aim for an effective use of the materials in order to fullfill one of the numerous criteria involved in the definition of a sustainable design. The result of the research could help a possible strategy leading towards a conscious sustainable design tackling one of its numerous aspects, by exploring the potential of computational design both in regards of the overall configuration and structural typology of the bridge and locally effective use of materials.

The main objective of this study is to design a bridge exploring optimisations processes such as multi-objective optimisation processes and multi-criteria decision-making methods that can be implemented in the design process to return a pool of possible alternatives ranked according to a criterion of minimizing the environmental impact of the project in regards of the use of material. Starting from the chosen structural typology, materials, and design concept, the goal will be to optimize the project to obtain a satisfactory design for architectural quality, safety, while reducing the material usage.

1.6 FOCUS AND RESTRAINTS

The purpose of the research is not to define a method that can lead to a single solution considerable optimal in regards of its sustainability. A unique optimal solution is unlikely to be achieved because, in the first place, the definition of a design as sustainable requires the evaluation of a vast amount of criteria that cannot be considered as a whole within the time available. The efficient use of material is only a first step towards the design of a sustainable bridge, which should also consider deeper implications related to its entire life-cycle. Secondly, the presence of criteria mainly linked to the architectural quality of the design and to the social sustainability factor, makes their objective quantification difficult. The personal sensitivity of the designer will always have the last word over the optimisation process.

Finally, the method will be applied in the development of a design for a specific location in Rome introduced later with its limits and needs. Some structural typologies, materials and shapes will then be preferred over others potentially more performing solutions because of the context and the desired architectural language for the bridge. The final design will then be the result of a strategy that integrates material savings and aesthetic appeal.

1.7 RESEARCH QUESTION

The hypothesis behind this research is that by using computational optimisation methods, the choice between alternatives that have as objective to lean towards a more sustainable design mainly in regards to material savings can be facilitated.

The use of such methods can minimize the environmental impacts of the project while aiming at having economic sustainability without overshadowing its performance and architectural quality. In the context of an optimization of the bridge design process, a main research question is then expressed:

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 research will also address the following sub-questions:

What are the main parameters to consider in order to make a parametric model suitable for this research?

How can be implemented a system to support the decision making from the output of the optimisation process?

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?

1.8 RESEARCH METHODOLOGY

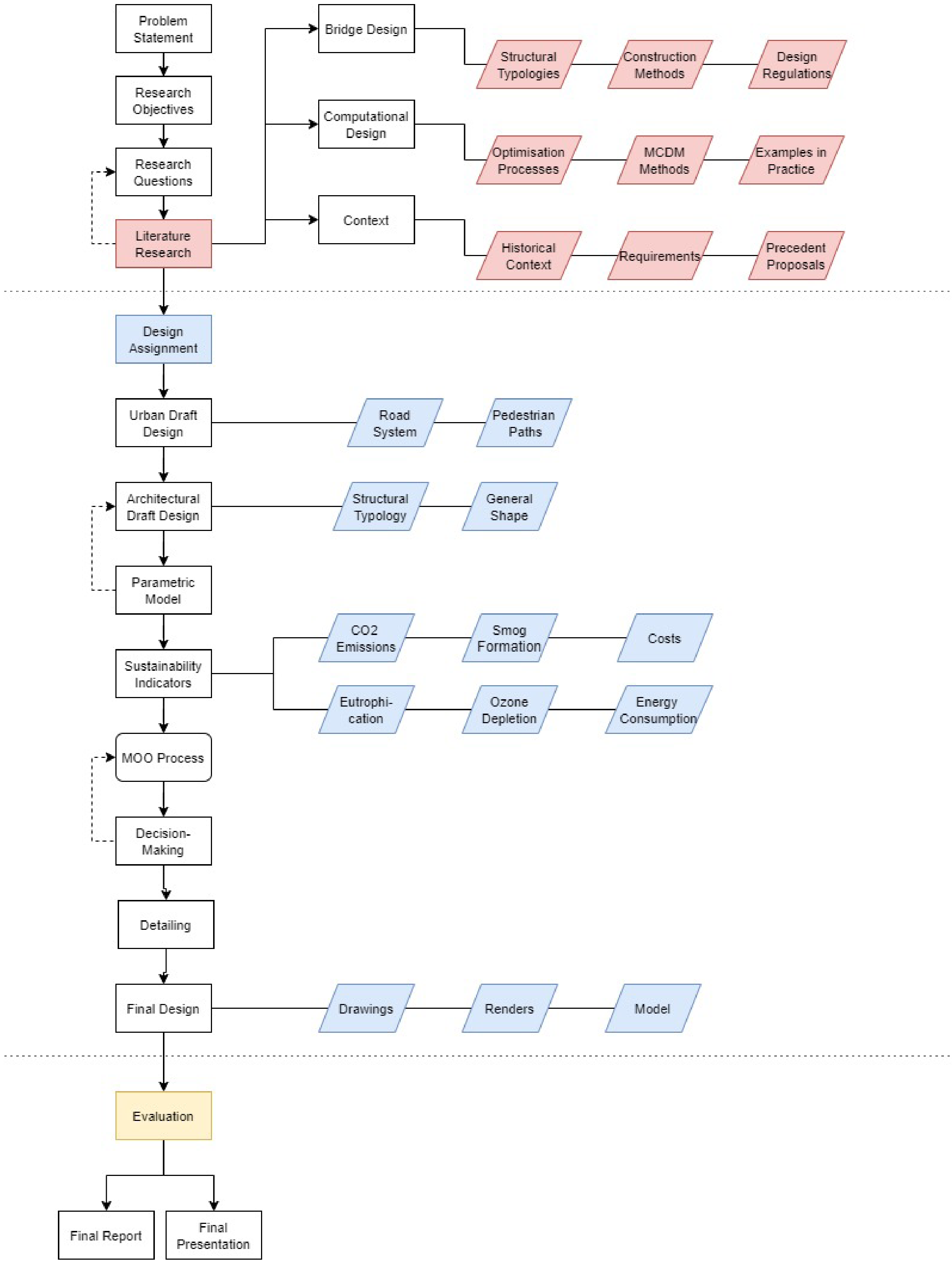
This research has the aim of experimenting with a new method of evaluation and aid for the choice between different alternatives within the design process. The outcome will be the realization of a design as finite as possible, defined from its urban scale to the most important details. The study will go through three main phases introduced below.

Research Phase: it will be vital to understand what are the main factors to consider in the design of a bridge, as well as for the evaluation of what are the main criteria to be implemented in a MOO process and eventually a MCDM method. As far as the practice of bridge design is concerned, the main structural typologies, construction methods and design guidelines will be analyzed. As regards the computational part, the various optimisation methods will be examined, identifying the ones that uses a methodology best suited to the purpose of the research. The available tools to assess the sustainability of a project and the indicators needed for the research will be investigated. Consequently, case studies where optimisation processes have been used in the practice of bridge design will be analyzed.

Design Phase: the first step will be to carry out an analysis of the context, necessity and criticality of the chosen case study as well as a first urban-scale design to define the first restraints useful for the architectural concept design. Once the architectural design will be defined, a parametric model will be constructed in a 3D modeling environment. The variables and criteria to be considered for the optimisation togheter with the best way to assign them a weight will then be assessed. The design will then be refined to obtain a quality and safe architecture where structural optimizations will then be taken into consideration. Finally, attention will be paid to represent graphically the project.

Evaluation Phase: Finally this research will evaluate the results obtained by taking a look both at the enhancement of the project's sustainability and at the role of the optimization methos within the work-flow of the design process. The final design will be critically evaluated to identify its strengths and eventual flaws, suggesting in case possible changes to the design workflow embraced.

Research workflow



2 LITERATURE REVIEW

This chapter takes a look at the consulted literature. First of all, an analysis was carried out on the aspects of bridge design practice that will predominate in defining an optimization process, in particular, the main structural typologies and design regulations. Concerning the computational part, optimization and decision-making methods have been analyzed with specific attention to metaheuristic methods. Some examples were then analyzed in practice and academia, and finally, a methodology for assessing the sustainability of a project with its related indicators was indicated. Finally, an analysis of the location in which the project will take place with particular attention to the historical and cultural context was carried out, highlighting the requirements that the design will have to satisfy and reviewing the previously proposed projects

2.1 STRUCTURAL TYPOLOGIES

Six main structural typologies can be identified in the practice of bridge design. Each typology has its different structural principles, various geometric and material characteristics. To fully understand the potential and features of the various types, an analysis was carried out identifying their fundamental principles.

2.1.1 ARCH BRIDGES

Arch bridges are among the oldest types used by man. From the stone examples still in existence today, technological advances have made it possible to develop and improve the structural capabilities of this typology, so much so that it can be often used in modern practice given its simple elegance and structural firmness.

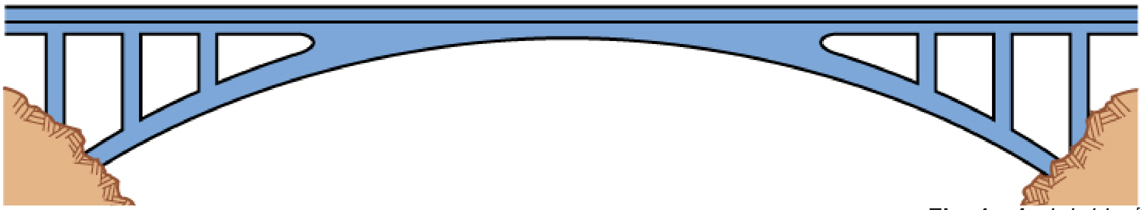


Fig. 1 - *Arch bridge*[1]

Structural principles

The arched structure transports the loads to its foundations mainly by compression, which, therefore, must bear the horizontal thrust exerted by the construction. The loads are transferred to the arch through columns acting in compression or by members in tension. Although the design of the foundations is more complex, the structure can usually cover the same span as a beam bridge but using less material.

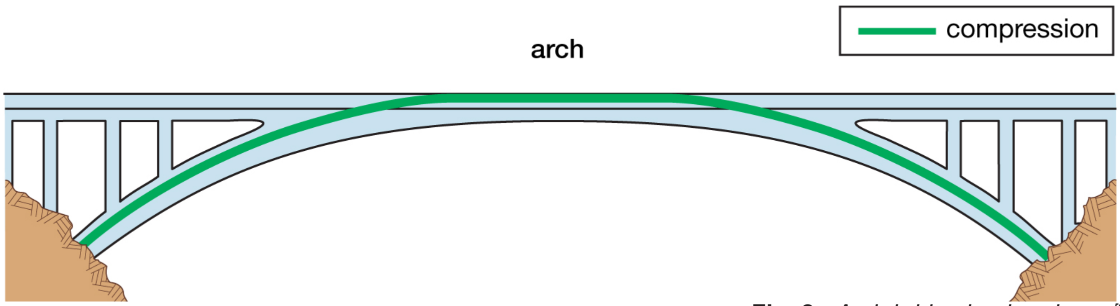


Fig. 2 - *Arch bridge loads scheme*[2]

Materials

The arch bridge can be built with materials such as concrete, stone, wood, composite, and steel. The stone was mainly used in antiquity before the iron and steel age of the mid-1800s. Reinforced concrete is often used in modern examples, while prestressed concrete allows covering greater spans with less use of material. Steel can be used as a reinforcing element or as a primary material due to its strong compressive and tensile strength. Given the fundamental structural principles, the compressive strength of the material is often the most critical discriminant.

Deck arch bridge

In this variant, the arch remains below the deck. The space between the two elements is called spandrel, and the deck loads are transferred via closed-spandrel walls, in the case of stone arches, for example, or by vertical columns, also called spandrel legs. In the case of an open spandrel bridge, the minor use of material can be preferred both for lower costs and for the lower contribution to the dead weight.

Fig. 3 - *New river Gorge bridge*[3]

Through arch bridge

Designed for the first time in 1912 by James Marsh, it has an arch with its base below the deck but surpasses it and then supports it through elements in tension. The central part of the deck is therefore suspended, while the ends behave as in the case of a deck bridge.

Fig. 4 - *Chaotianmen Yangtze river bridge*[4]

Tie arch bridge

In this sub-type, the arch is placed above the deck and the horizontal forces are contained by the latter which is used to tie the two ends of the structure. Given the absence of horizontal forces, the foundations can have smaller dimensions, and also, for the same reason, these bridges can be prefabricated and subsequently brought to the site.

Fig. 5 - *Infinity bridge*[5]

2.1.2 BEAM/GIRDER BRIDGES

Composed of two or more beams with a deck above, which covers a span in its entirety or with the presence of intermediate vertical supports. Its simplicity can easily lead to the definition of this system as the oldest, one as it can be recognized in nature to a log that falling crosses a river. no coincidence that the origin of the word “bridge” in many European languages, comes from Proto-Indo-European roots that indicate a wooden flooring, a crossing or simply wood. (Etymonline.com, 2019) Due to its simplicity and relative architectural poverty, it is usually used for small or medium-sized highway bridges.

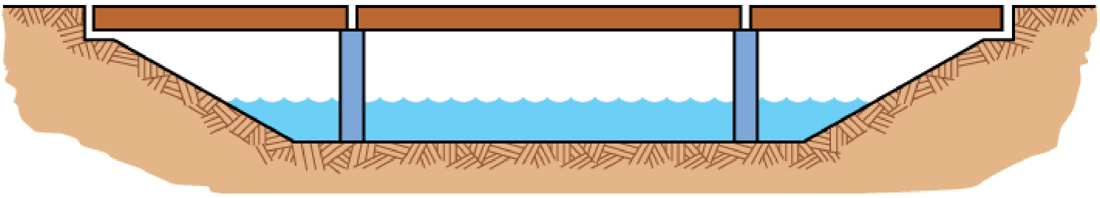


Fig. 6 - *Beam bridge*[1]

Structural principles

The beam carries vertical loads by bending. In the bending process, the upper side resists to compression while the lower one is subject to tension forces. Vertical supports are mainly subject to compression, which they transfer to foundations.

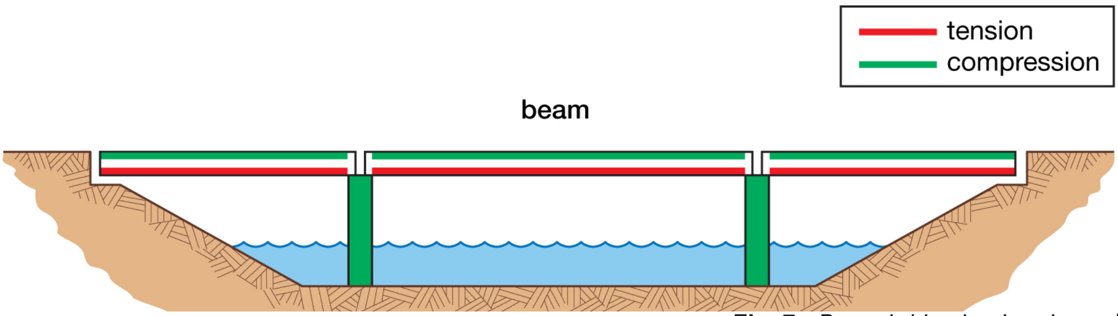


Fig. 7 - *Beam bridge loads scheme* [6]

Materials

A beam bridge can be constructed using various materials such as wood, steel, concrete and composite depending on the sub-type.

Timber stringer

Used from the beginning of the 20th century in case of short spans and low stresses. A wood plank deck is supported by square or rectangular wooden beams. Its strong points are a simple design combined with a readily available and cheap material. An ancient example can be found in the bridge Sublicius, oldest roman bridge built by Anco Marzio around the seventh century BC.

Fig. 8 - *CK Railroad bridge*[7]

Reinforce and prestressed concrete beams

Reinforce concrete beams have been used since the early 20th century. They can have different sections such as T-beams or channel beams. In the case of T-beams steel rods are places at the bottom (called stem) transversly in the slab which contitues the top of the beams, both elements act as a unified structural component. Channel beams can also have diaphragms as a secondary support in which case they are called "waffle slab". They can span same lenghts as flat slabs but with an economical advantage, altough they are less economical than arches and trusses over a certain length.

The first prestressed bridge in Europe was built by Eugene Freyssinet in 1940, since then the technology advanced allowing to cover longer spans than reinforced concrete beams while remaining cheaper. The main structure is identified in the prestressed beams with a slab above them. Diaphragms can be present as well.

Fig. 9 - *Labajin bridge*[8]

Fig. 10 - *Prestressed precast concrete beams*[9]

Prestressed concrete box beams

Evolution of reinforced concrete girders which fell in disuse for high costs of scafolding and framework, although easy to construct. Prestressed concrete box girders have been used since the 1950s and its popularity is mainly due to the speed of construction and a reduced section depth. The box-shaped longitudinal beams are the main support, aided by a slab and transverse strands.


Fig. 11 - *Road Bridge in Richmond*[10]

Rigid frame bridges

Vertical or slanted monolithic are used in case of a single span bridge and act as main support, rigidly connected with the secondary structure, economically advantageous especially for medium spans. V-shaped rigid frame supports are often used in case of multiple spans bridges. The structural principles behind the structure require a certain height for the coloumns to work efficiently. Steel rigid frame bridges are less common than reinforced concrete ones but are often chosen for economic reasons or to differ aestetically. Steel I-beams are usually used to built the inclined rigid frame legs that act as the main support, web stiffners, diaphragms and various decks can be a secondary support system.


Fig. 12 - *Gouritz river bridge*[11]


Fig. 13 - *New Oakland Avenue bridge*[12]

2.1.3 TRUSS BRIDGES

They can be seen as an improvement of beam bridges as the truss act as a single large beam. The truss is composed of relatively small connected elements forming triangular units leading to a high strength obtained with minimal material usage. Truss bridges can vary in height and size of the structure depending on the material used and especially of one of the many sub-types available.

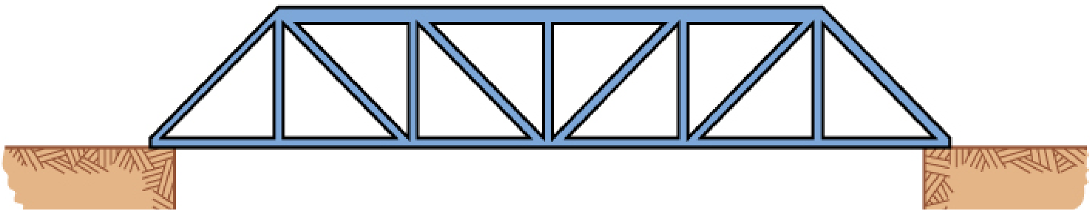


Fig. 14 - *Truss bridge*[1]

Structural principles

Each element of the structure is designed to optimally withstand only compression or tension, leading to a minimum presence of bending moments in the elements. This firmness allows this structure to become elemental in other bridge types such as the bowstring arch, where it acts as a stiffening agent on the deck. The top chords resist to compression while the bottom chords have to withstand tension, the web elements resist in compression or tension depending on their orientation.

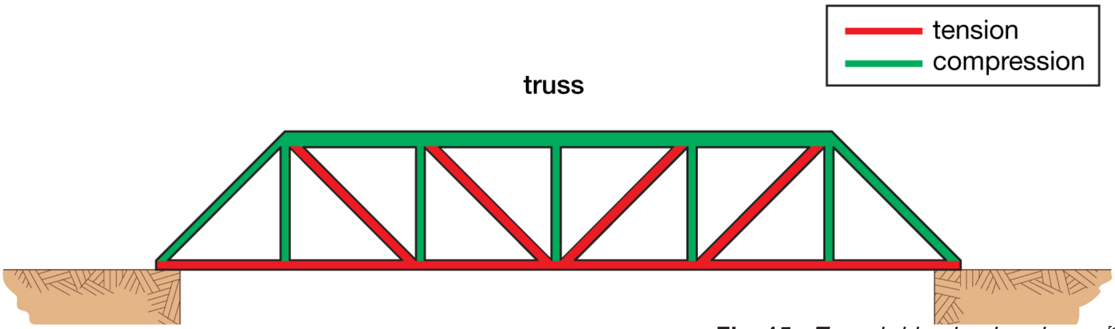


Fig. 15 - *Truss bridge loads scheme* [13]

Materials

Oldest examples of truss bridges present wood as construction material, altough in modern designs steel is the most commonly used for its good strength in both compression and tension.

Sub-types

Truss bridges can count on several sub-types while the structural principles remain the same. Widely used between the 19th century and early 20th century is the Pratt truss, where vertical members resist to compression and diagonals in tension. The Pratt truss was usually chosen over the reverse Howe design due to its more firm stability. This truss will later be replaced by the Warren truss where the top and bottom chords are connected by only diagonal elements working both in compression and tension. From the Pratt design a lot of variants have been explored such as the Baltimore truss with diagonals braced in the middle by sub-diagonals and sub-struts to have a more economic spacing of flooring beams. Modern designs usually combine innovative trusses designs with other structural typologies.

Fig. 16 - *Ikitsuki Bridge*[14]

2.1.4 CANTILEVER BRIDGES

A cantilever bridge uses structures supported only on one side from which they then protrudes, known as cantilevers. A single beam can work as a cantilever but in modern practice there are usually three spans making use of a truss in order to achieve larger spans. Balance is crucial in this typology as the central span is hinged to the two outer spans which balance it with their weight.

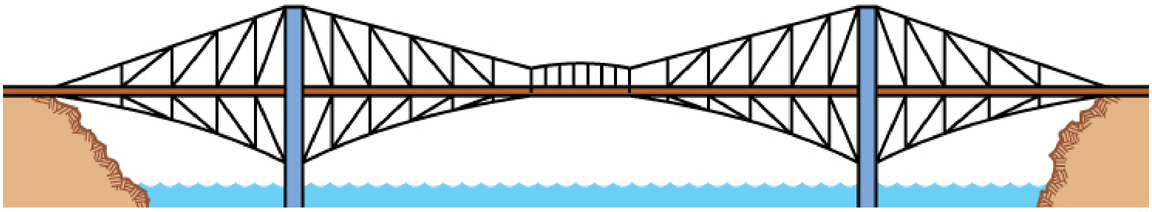


Fig. 17 - *Cantilever bridge*[1]

Structural principles

The outer spans are anchored in one point from which they cantilever out. The central span is supported by the cantilever arms and it acts like a beam or a truss, where compression is present in the upper chords and with tension in the lower chords. The cantilever parts carry their load and present compression in the lower chords and tension in the upper chords. The support towers transfer the forces by compression to the foundations.

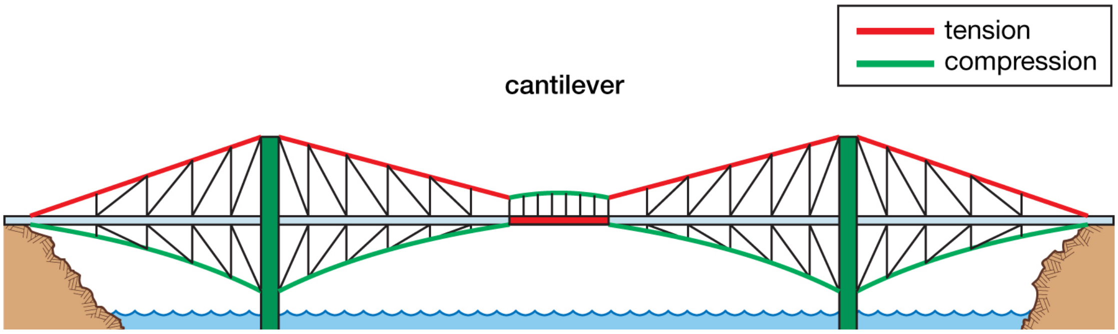


Fig. 18 - *Cantilever bridge loads scheme* [15]

Materials

Old cantilever bridges were built using wood or stone, while in modern practice steel trusses are preferred for their ability to cover longer spans.

Fig. 19 - *Forth Rail Bridge*[16]

2.1.5 SUSPENSION BRIDGES

First modern examples were built starting from 1800s, the system can be seen as an evolution of simple suspension bridges or rope bridge, a primitive system where the deck is suspended and supported by two load-bearing elements working in tension. The modern suspension bridge presents vertical suspenders holding load-bearing cables to which the deck is connected. The system can achieve long spans and it can be economically preferable over others if it is difficult to find piers.

The suspension bridge can achieve the largest possible span of all bridge typologies, although this comes with the needs of really tall towers.

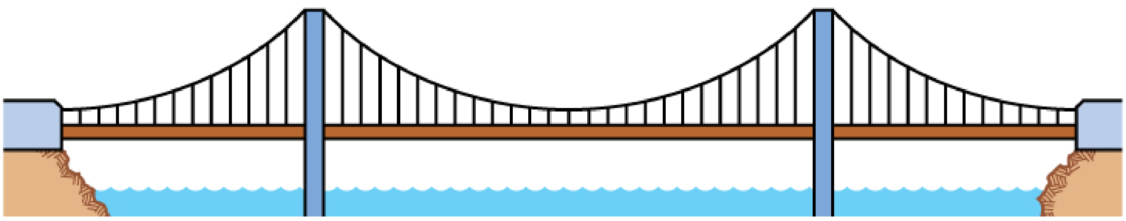


Fig. 20 - *Suspension bridge*[1]

Structural principles

A suspension bridge withstand its vertical loads through cables in tension. These curves cables are hung between the towers and from there, vertical cables in tension are connected to the deck which is suspended in the air. The loads are then transferred to the towers that are loaded in compression and carry the loads to the foundations while the anchorages must resist the inward pull of the cables.

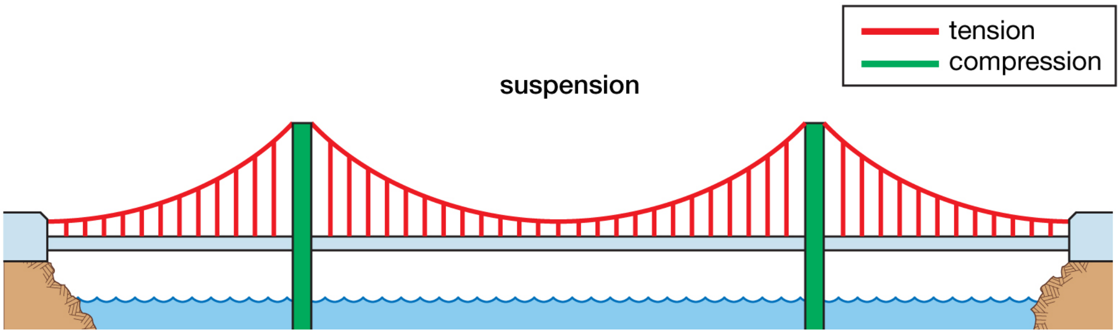


Fig. 21 - *Suspension bridge loads scheme* [17]

Materials

Usually the most commonly used material for suspension bridges is steel. Its great strength in tension makes it the perfect candidate for the cables. Altough for small spans other materials has been used in the past such as vines and ropes. The towers can be made out of steel or concrete, the latter is usually preferred over steel because less expensive and more durable.

Fig. 22 - *Akashi Bridge*[18]

2.1.6 CABLE-STAYED BRIDGE

A cable stayed bridge is a widely used typology which can span important lenghts. The deck is supported by cables connected to one or more pylons. These cables can have different patterns but they need a certain inclination to work efficiently, so in case of long spans it is required to have tall pylons.

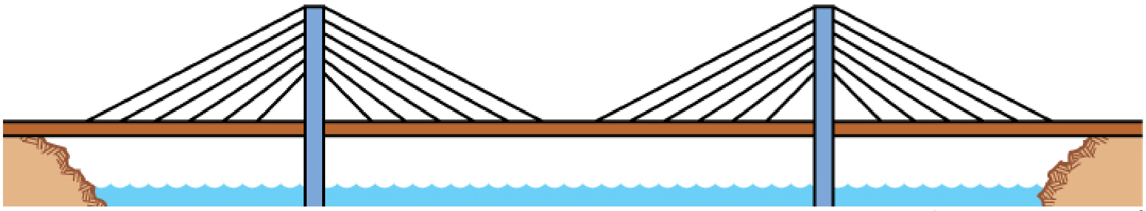


Fig. 23 - *Cable stayed bridge*[1]

Structural principles

The loads are carried by diagonal straigh cables in tension. These cables are connected to the deck and to the towers that are subjected to compression forces which they then transfer to the foundation. Due to the tensile force exercitated by the cables the deck has to withstand compression forces so it has to be stiff enough.

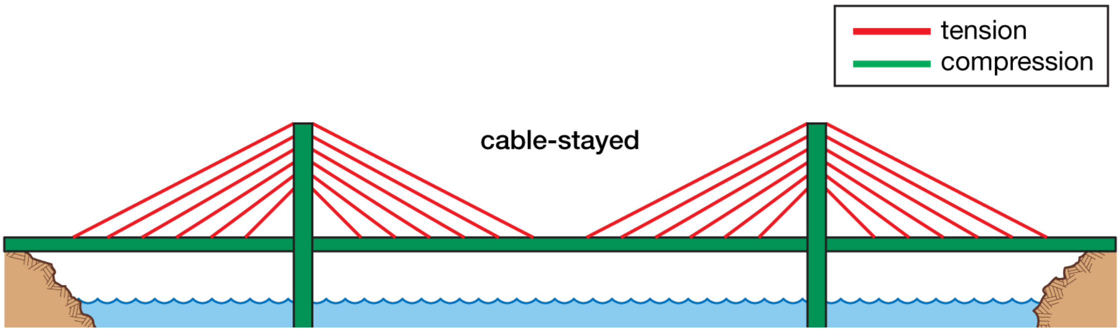


Fig. 24 - *Cable stayed bridge loads scheme* [19]

Materials

As for the suspension bridge type, steel is used for the cables that need to withstand tensile stresses. The pylons can be made out of steel or concrete. The deck requires more attention because of the presence of bending forces and it can be made out of steel, concrete, and composite materials. Costs can be reduced using a higher number of thinner cables.

Cable patterns

Different cable patterns can be used for a cable stayed bridge. The *mono* design uses only one cablefrom its towers to support the deck, it is the less used. The *harp* or *parallel* design uses cables that are placed according to a similar angle in order to have a proportional distance between the height of their anchor point on the pylon and their distance from it at the mounting point on the deck.

The *fan* design is considered structurally superior to the others and present all

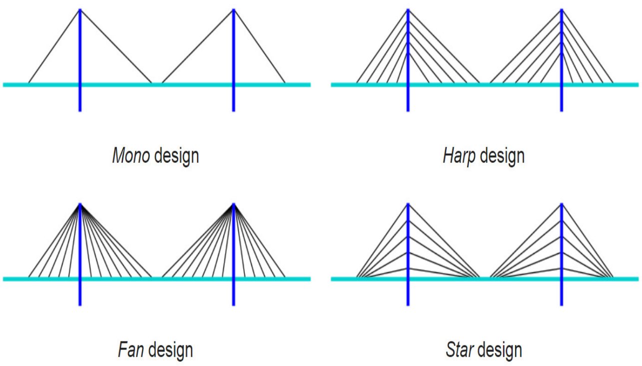


Fig. 25 - *Cables patterns in cable stayed bridges*[20]

cables passing over or connected to the top of the pylons. This arrangement provides a reduced moment applied to the pylons and an easier access for maintenance purposes. The *star* design presents cables spaces apart on the pylon as the harp design but their connection to the deck is provided in one single point or in closely spaced points.

Sub-types

Among the sub-types present there is the side-spar that uses a single tower (spar) supported on one side and that allows the construction of curved bridges. Some sub-types such as the extradosed bridge are a combination of girder and cable-stayed bridges with a more substantial deck that being stronger allows for less cables and in consequence, shorter pylons. An interesting sub-type is the cradle system, where the cables are attached to the deck, go through the tower, and attach again on the other side of the deck allowing for an easier construction.

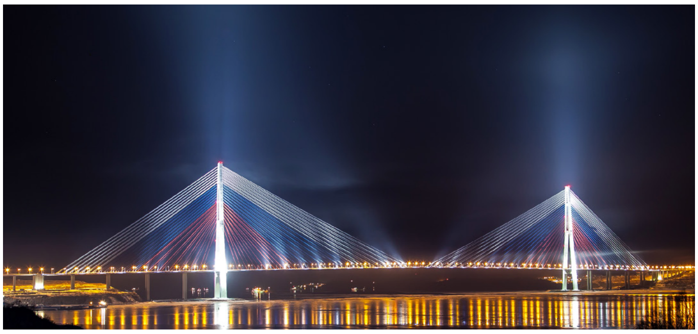


Fig. 26 - *Russky Bridge*[21]

2.2 CONSTRUCTION METHODS

In the following chapter, the most common construction methods are brefly introduced. In order to chose the appropriate construction method for a bridge, several factors usually related to the site peculiarities have to be considered such as the span of the bridge, the obstacles that has to be crossed and the accessibility of the site.

Segmental construction (Cast-in-situ and precast)

The cast-in-situ requires a temporary substructure to be built before the superstructure. It is a viable method for complex geometries and in case of a limited accessibility of the site or if precast elements would be too big and/or heavy to be transported. The large amount of framework makes it cost effective mainly for reinforced concrete slab bridges. Precast elements, on the other hand, ensure a more consistent quality in the fabricated elements and a reduced construction time, if the invidual spans are up to 60m, with the use of a span by span segmental construction through the use of assembly trusses. The main challanges regarding this construction method are within the transportation of the elements on site.

Fig. 27 - *Span by span construction method* [22]

Balanced cantilever construction

Fig. 28 - *Balanced cantilever construction method* [23]

This method is mainly used for spans that range from 50 to 300m, and the elements can either be cast-in-situ or prefabricated. After building the piers segments are attached to the opposite ends of cantilevers in case of precast elements or a form traveler is used in case of the cast-in-situ option.

The cantilever method is used especially for cable-stayed bridges. After erecting the segments are in place, they are supported by their cable-stays during the next erection phase.

Incremental launching method (ILM)

Fig. 29 - *Incremental lauching method* [24]

The incremental launching method is suitable for bridges that have a deck greater than 250m in length. The deck is built during different phases through a series of increments starting from the abutments towards the pier. It is a highly mechanized method where a deck mould can be positioned for the production of cast-in-situ elements. Once completed, the segments are placed on sliding bearings and pushed towards the next span with the help of a steel nose which works as a cantilever support till the next pier. The method is definetly not cost-effective but it can be chosen when the obstacles that have to be crossed are inaccessible or environmentally protected.

Arch method

Fig. 30 - *Arch method* [25]

This method can prove advantageous in case of having to overcome inaccessible obstacles. Modern construction techniques do not necessarily require a centring formwork as in the case of old Roman bridges. The two most used techniques nowadays are the cast-in-situ free cantilever method and the slip formed sections where half arch is erected vertically and afterwards rotated into the desired position.

2.3 DESIGN REGULATIONS

The regulations concerning bridges in Italy are reported within the national regulation code, the NTC 2018 document (Gazzettaufficiale.it, 2020), which refers to and aligns with the directives of Eurocode 1 EN1991-2. As regards the structural analyses of the loads acting on the bridges, these can be divided into two main categories: permanent and live loads and loads dependent on external agents. In the limited time available for this research, only the most critical actions acting on the structure of the bridge will be considered, such as the loads due to the structure's own weight, the mobile vertical loads due to car traffic and pedestrians, and the loads carried by the wind. The actions left out are inherent in temperature, loads acting during construction, horizontal loads due to traffic, snow, and seismic loads. The latter are perhaps the ones that more than the others have an impact on the structural safety of the bridge given the location. The entire Italian peninsula is, in fact, subject to seismic risk (Fig. 31).

Nevertheless, general precautions in this regard can be taken to the extent that the best way to counteract the horizontal forces generated by seismic phenomena is to have a structure that carries the lightest weight possible. The force generated by the seismic acceleration will act on a lighter mass, giving a minor resultant.

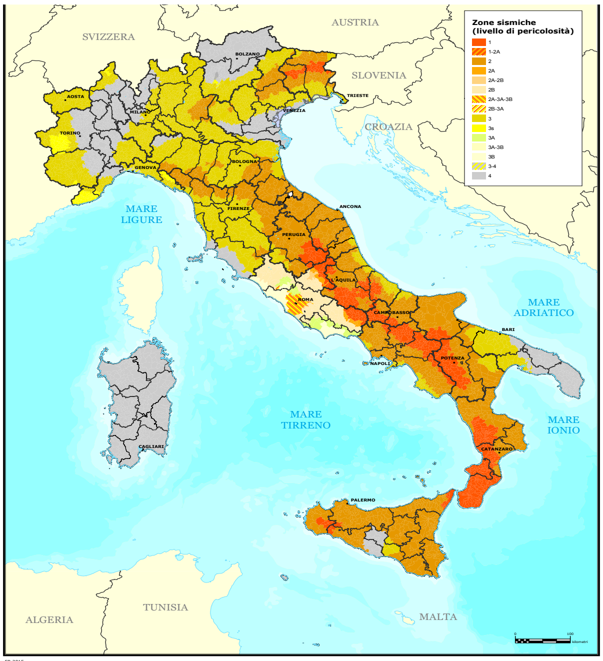


Fig. 31 - *Italian seismic areas* [26]

2.3.1 ROAD TRAFFIC LOADS

The Eurocode EN1991-2 specifies, in chapter 4.2, four different load models:

- Load Model 1 (LM1): Concentrated and uniformly distributed loads, which cover most of the effects of the traffic of lorries and cars. This model should be used for general and local verifications.

- Load Model 2 (LM2): A single axle load applied on specific tyre contact areas which covers the dynamic effects of the normal traffic on short structural members.

- Load Model 3 (LM3): A set of assemblies of axle loads representing special vehicles (e.g. for industrial transport) which can travel on routes permitted for abnormal loads. It is intended for general and local verifications.

- Load Model 4 (LM4): A crowd loading, intended only for general verifications.

For the application of these load models within the design and optimization process, models 1 and 4 will be considered.

Load Model 1

It consists of two partial systems:

- Q_a - Double-axle concentrated loads (tandem system : TS)
- q_k - Uniformly distributed loads (UDL system)

Location	Tandem system *TS*	*UDL* system
	Axle loads Q_{ik} (kN)	q_{ik} (or q_{rk}) (kN/m^2)
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

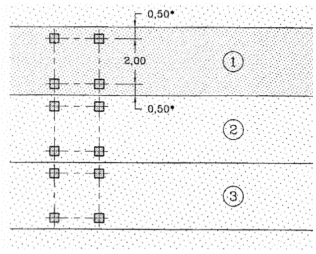


Fig. 32 - *Load Model 1* [27]

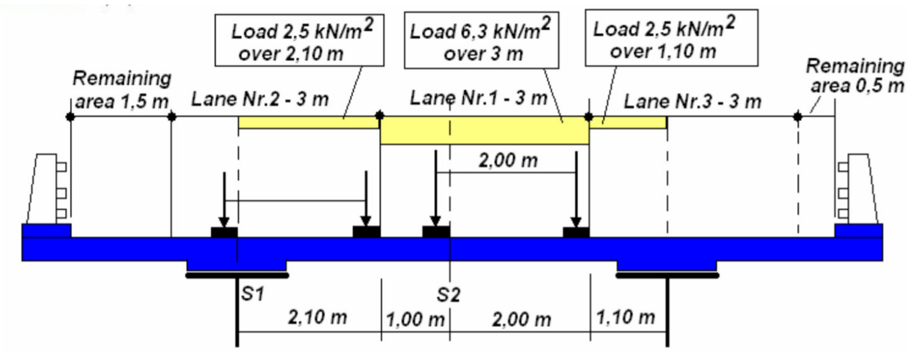


Fig. 33 - *Example of LM1 application* [28]

Load model 4

Crowd loading, if relevant, should be represented by a Load Model consisting of a uniformly distributed load (which includes dynamic amplification) equal to 5 kN/m2. The application of LM4 should be defined for the individual project.

Load Model 4 should be applied on the relevant parts of the length and width of the road bridge deck, the central reservation being included where relevant. This loading system, intended for general verifications, should be associated only with a transient design situation.

Among the notes regarding the field of application its clarified that for large footbridges (for example more than 6 m width) load models defined in this section may not be appropriate and then complementary load models, with associated combination rules, may have to be defined for the individual project. Indeed, various human activities may take place all wide footbridges.

2.3.2 LOADS ON FOOTBRIDGES

In the section 5 of EN 1991-2:2003 three load models for footways, cycle tracks and footbridges are defined:

- q_{fk} - A uniformly distributed load

It is comparable with the Load Model 4 for road bridges, it has a value of 5 KN/m^2. It represents the static loading of dense crowds.

- Q_{fwk} - A concentrated load

It represents occasional maintenance work loads. The value of the load is 10 Kn acting on a square surface of sides 0.10 m.

- Q_{serv} - Service vehicle load

It represents the presence of service vehicle that may be carried on a footbridge if no permanent obstacle prevents a vehicle from being driven onto the bridge deck.

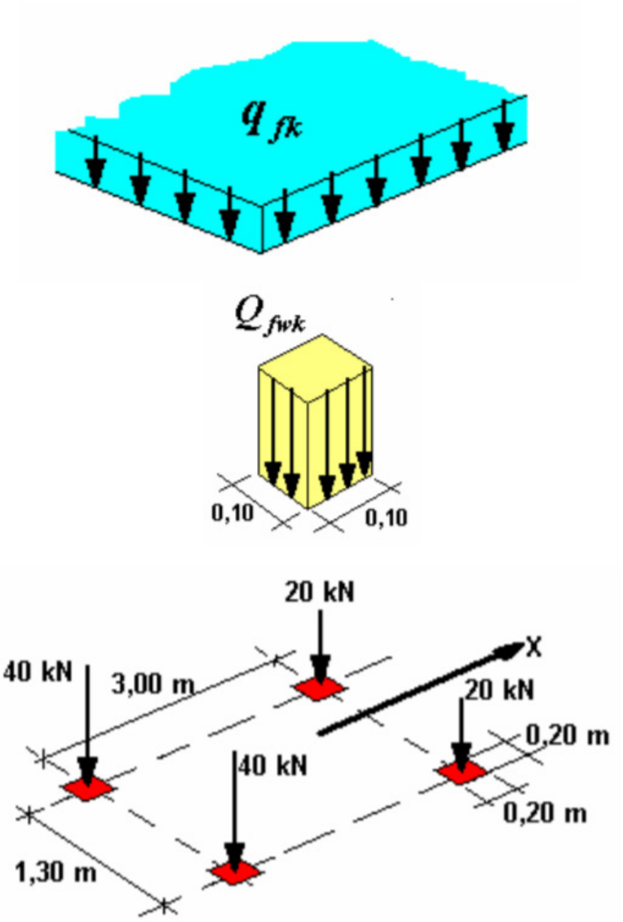


Fig. 34 - *Example of footbridged loads application* [28]

2.3.3 WIND LOADS

The wind load can be assimilated to a system of static loads whose main component is horizontal and directed orthogonally to the axis of the bridge. The calculations necessary for the calculation of the wind load are defined in Eurocode 1: actions on structures under Wind Actions. Since these loads depend on the area in which the project is located, it is essential to refer to the Italian national annex, which can be found in chapter 3.3 of the NTC 2018 document. The following formula, therefore, defines the wind force:

$$F_w = c_s c_d * c_f * q_p(z_e) * A_{ref}$$

- $c_s c_d$ = The structural factor defined in section 6 of the Eurocode EN 1991-1-4:2005 and in chapter 3.3.9 of the nationl annex.

- c_f = The force coefficient for the structure defined in section 8.3 of the Eurocode and in chapter 3.3.8 of the national annex.

- $q_p(z_e)$ = The peak velocity pressure at a reference height Ze defined in chapter 3.3.7 of the national annex while the wind velocities are defined by different wind area in the chapter 3.3.1 (Fig.35).

- A_{ref} = The reference area of the structure definded by the span length of the bridge by the total depth, which has to considere the eventual presence of a solit parapet.

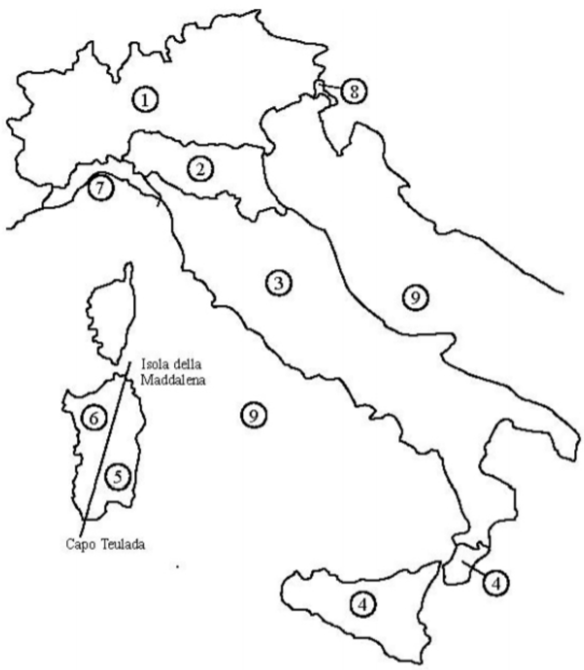


Fig. 35 - *Italian wind areas* [29]

2.4 DESIGN OPTIMISATION

Thanks to the technological advancement of the last decades, with the possibility of relying on more performing computers, the field of architectural design optimization (ADO) has made its way within architectural and engineering practice. At the base of this research field, there is the possibility of using optimization processes in design problems such as cost-effectiveness, daylight, reduced use of the material in related structural problems, lower consumption of resources, and so on. The optimization process for a given problem aims to find the best possible alternative within a space of solutions for a given objective. By objective is meant that indicator defined by the designer, which must be minimized or maximized by the optimization process.

Once a function objective has been defined, the optimization process deals with finding a solution that represents the minimum or maximum of this function. In practice, this can, for example, refer to finding the minimum internal stress of a structure for different design alternatives. However, the computation time required for the search of the global minimum (or maximum) of a given objective function has led the existing methodologies to combine a global search with a local search. The global search purpose is to find an area within which the point of global minimum is present. In contrast, the local search focuses on finding the local minimum of the data function objective, which is the relative minimum point of the function to the closest range.

2.4.1 PARAMETRIC MODEL

For the definition of a design space containing the solutions that will be evaluated by the optimization process, it is first necessary to establish the related variables and constraints, and this can be done by constructing a parametric model.

A parametric model relates various components to each other, describing their interrelation rules by numbers or formal characteristics, allowing the designer to explore different design alternatives starting from quantitative or formal assumptions assigned to the various parameters. Bucci and Mulazzani (2000, p.21) indicate the architect Luigi Moretti as the first formulator of the concept of “Architettura parametrica” in his 1940 writings. Moretti (1971, p.207) speaks of a new interdisciplinary approach to be able to undertake in the field of architectural research, underlining how this parametric approach is based on:

“Defining the relationships between the dimensions dependent upon the various parameters.”

These parameters are nothing more than the rules under which the model comply. Their definition allows the designer not only to have control over the process but also to decide how stricked this control will be, depending on the characteristics assigned and their level of sharpness.

In the field of architecture and, in general, in the parameterization of a model that works with geometries, the most used platform nowadays is Grasshopper, released in 2007 as Explicit History. The advantage given to designers by Grasshopper is the possibility of resorting to a visual-scripting system that facilitates interaction with the software thanks to a user-friendly interface. Grasshopper is used in combination with Rhinoceros, a visualization software developed by the same company, the Mc Neel and associates, in order to graphically return the result of the relationships previously defined by the components within the parametric model.

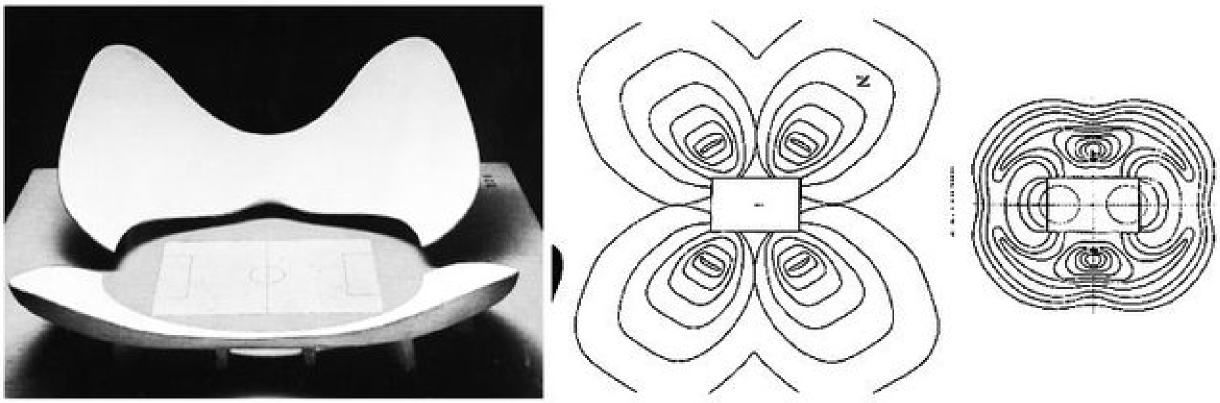


Fig. 36 - *A model of Stadium N by Luigi Moretti* [30]

2.4.2 MULTI-OBJECTIVE OPTIMISATION (MOO)

In architectural practice, optimization problems very often require more than one objective to be met. In many cases, the optimization process must be carried out on a model with a large number of variables, with more than one objective, and with criteria that may conflict with each other. The evaluation of the fitness to the objectives set for the given simulation can be time-consuming since the model has to change the values of the parameters every time a simulation is performed and then decree the quality of the alternative obtained.

To facilitate the computational load to which the machine is subjected, in the case of evaluating numerous possible alternatives, optimization algorithms can be used. Unlike algorithms that deal with finding an optimal solution to a problem with a single objective, multi-objective algorithms may not lead to a unique solution since maximizing performance for one objective can lead to loss of quality for another objective given the possible conflict. The purpose of these algorithms is instead to find the optimal Pareto front, a set of non-dominated solutions chosen because after several iterations it is no longer possible to improve one goal without sacrificing another.

In MOO, therefore, an attempt is made to reach an approximation that ideally must be quite diversified, that is, considering the optimal fulfillment of as many objectives as possible, in order to restore a pool of alternatives from which the designer can then make a choice. This choice can be made a priori, ie assigning weights to the different objectives, or a posteriori, leaving freedom to the designer. This last option is usually the preferred one in the architectural field, as the quantification of the weights to be assigned to the different criteria can be complicated, in particular for qualitative criteria challenging to quantify such as inherent to architectural quality. Nevertheless, in the literature, there are several attempts to develop a decision-making system as support to the designer.

2.4.3 METAHEURISTIC EVOLUTIONARY ALGORITHMS

In the scientific method, a heuristic procedure that does not guarantee the achievement of a solution to a given problem, but it is a methodology that helps to approach this solution through a progressive increase of knowledge in a practical way. In the field of optimization, the metaheuristic algorithm is a high-level procedure designed to construct a heuristic for an optimization problem (Wortmann and Nannicini, 2017). Metaheuristic algorithms do not require to specify the problem in detail, however returning near-optimal solutions thanks to the sole definition of the function objective and the domain of the variables to be taken into consideration. Furthermore, they avoid falling into the local minima and maxima points of a function objective, which could compromise the reading of the results, and discard them in favor of an area that instead contains the point of global minimum and maximum.

The algorithms that fall under the classification of metaheuristic are numerous, and a conspicuous part is introduced in “Glossary of metaheuristic Algorythm” (Rajpurohit et al. 2017). The algorithms that refer to metaheuristic methods fall under different classifications, and some may overlap between more than one of them (Fig 37).

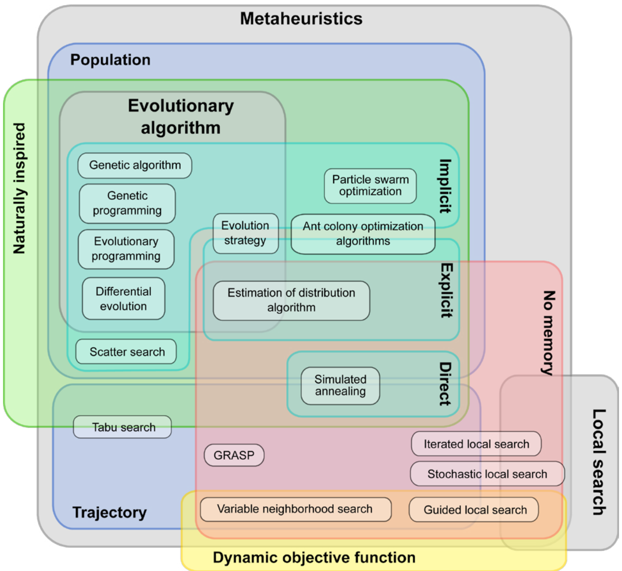


Fig. 37 - *Metaheuristic algorithms classification* [31]

Among the optimization algorithms defined as metaheuristic, particular attention, in the architectural and engineering field, was given to those defined as evolutionary algorithms, which fall into the classification of those with a population-based resolution strategy. The main advantage of population-based methods is the maintenance at each iteration, not of a single optimal solution (as in the case of iterative methods) but a population of satisfactory solutions. This case is preferable in case the designer wants to explore different alternatives and compare the different outputs of the procedure.

Evolutionary algorithms are based on the principle of evolution present in living beings. Starting from a population of randomly generated initial individuals who represent the solutions to the problem, couples of these individuals are chosen to reproduce, forming a new generation where the best individuals (the most optimal solutions) survive by mimicking the natural selection process. The selection of individuals occurs in succession to their reproduction, and to the appliance of genetic operations such as crossover and mutations. The consideration of progressive and random mutations within the population has the aim of avoiding recurrence in local minima and maxima. At every new generation, the population of “parents” and that of “children” are assessed as to how close they are to the objective function (fitness function), and the process can be then repeated. It is important to underline and resume the concept of heuristic method, as it is possible to have potentially infinite iterations without ever arriving at a single optimized solution. It is instead the designer who decides when the approximation of it in a Pareto front is satisfactory and stops the process.

2.4.4 MULTI-CRITERIA DECISION-MAKING METHODS (MCDM)

After carrying out a multi-objective optimization process, the result given to the designer is a set of Pareto-optimal solutions. At that point, the designer must make a choice from the available alternatives, and this usually takes place by relying on his experience and intuition. However, In design optimization scenarios that include a large number of conflicting criteria, the choice must be guided by an understanding of the trade-offs of the different solutions. In the case of the search for sustainable design, it is easy to come across aspects of design alternatives that are usually conflicting with each other such as the cost and environmental impact. To facilitate the choice of the designer and therefore maximize the performance obtained by the optimization process, multi-criteria decision-making models can be applied to the problem. These methods allow the assignment of various weights to different criteria that can be taken into consideration when choosing the best alternative among those available, returning a ranking that therefore makes explicit the choice method used at the end of the process.

Multi-criteria decision-making methods can be classified according to their characteristics, such as scoring methods, distance-based methods, outranking methods, utility/valuate methods, and pairwise comparison methods (Penadés-Plà et al. 2016).

A review of the most used methodologies in the engineering field when facing the topic of the sustainability of a project was conducted by Navarro, Martì, and Yepes (2018). The review shows that the most used method, with the most significant relative impact on the optimization of choice, is the 'Analytical Hierarchy Process (AHP) which is part of the pairwise comparison methods. This method involves the subdivision of the decision problem into smaller and independent problems, as well as subdividing the three major criteria at the basis of sustainability, the economic, environmental, and social ones, into sub-criteria. Once the hierarchy that runs between the different criteria is defined by comparing them pairwise, weights are assigned, helping the decision-maker in the final process of evaluating the alternatives available.

As regards the application of multi-criteria decision-making methods in the practice of bridge design, considering all three or part of the founding pillars of sustainability, a review was conducted by Penadés- Plà, Garcìa-Segurra, Martì and Yepes (2016).

A good overview of the interaction between multi-objective optimization processes and Multi-criteria Decision-making methods is provided in the dissertation "Decision-Making Models for Optimal Engineering Design and their Applications" (Mosavi, 2012).

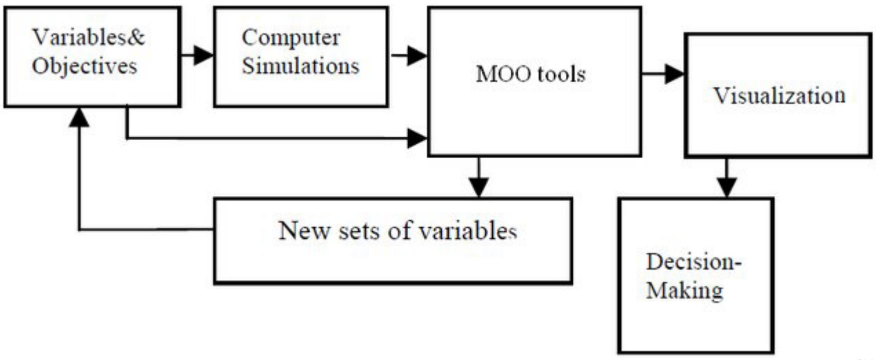


Fig. 38 - *Workflow of the MCDM process including MOO* [32]

2.5 OPTIMISATION IN BRIDGE DESIGN

Sergio Musmeci

In most of the practical cases within bridge design, the optimized performances are often inherent to structural aspects. An example of this approach can be seen in the work of Sergio Musmeci and, in particular, in his masterpiece, Basento's bridge, built between 1967 and 1976. The result of his studies is not, however, tied to real optimization principles, as the tools were not available at the time, but to the concept of form-finding.

The search for an optimized form was carried out through the use of physical models, starting from a first model in soap film, through a second in neoprene, and testing a third in methacrylate. The result is a bridge formed by a continuous concrete shell structure cast in situ with a thickness of 30cm, which supports a deck for 560m with a maximum single span of 59m.

Through the most modern optimization software, a more performing form could be obtained, thanks to the use of non-linear processes that would lead to a multiple optimal solutions (Magrone et al. 2016).

Fig. 39 - *Basento Bridge* [33]

Ney & Partners

The Knokke Footbridge in Deerlyck, Belgium, designed by Ney & Partners, and realized in 2007 is an example of how modern structural optimization software can be used in the practice of bridge design. The 102m bridge, which extends on four supports with two spans of 28m and one of 46m, has an optimized steel shape to which a concrete deck is tied. The obtained design clearly shows the intent of reducing the material used and maximizing stiffness without overshadowing the desire to obtain a high architectural quality.

Fig. 40 - *Knokke Footbridge* [34]

Hitoshi Furuta, Kenji Maeda and Eiichi Watanabe

In the paper "Application of Genetic Algorithm to aesthetic design of bridge structures (Furuta et al. 1995), the authors use a genetic algorithm to produce a pool of alternative solutions regarding the design of a bridge, then attempting to develop a system to support the decision-making phase. The genetic algorithm is used to approximate the optimal solutions for three objective functions related to the aesthetics of the bridge, which is defined, albeit recognizing the limitations of this approach, by psycho-vectors, a concept applied in the field of metric psychology (Sugiyama et al. 1993). The three functions reflect the objectives of formative beauty (structural configuration), balance (functional factors), and slenderness (harmony with the surrounding environment). The process then follows the progress of an evolutionary algorithm (Fig.41).

Interesting is the attempt to set up a methodology to facilitate the decision-maker's choice by assigning different weights to the three components, which can lead to one alternative rather than another depending on whether the DM chooses to give the preference to formative beauty (Fig.42) or the other two criteria (Fig.43).

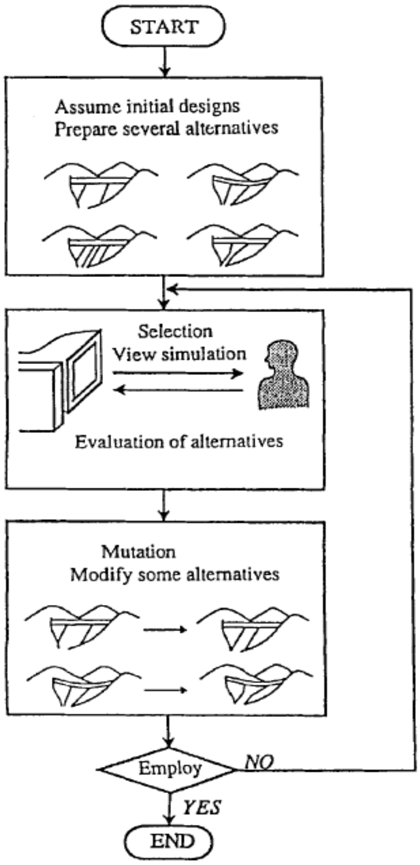


Fig. 41 - *Flowchart of GA calculation* [35]

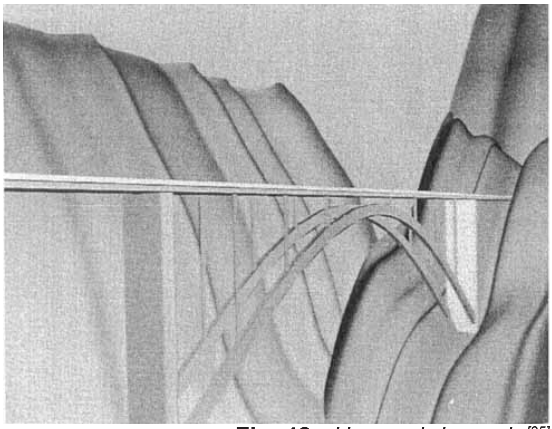


Fig. 42 - *Upper girder arch* [35]

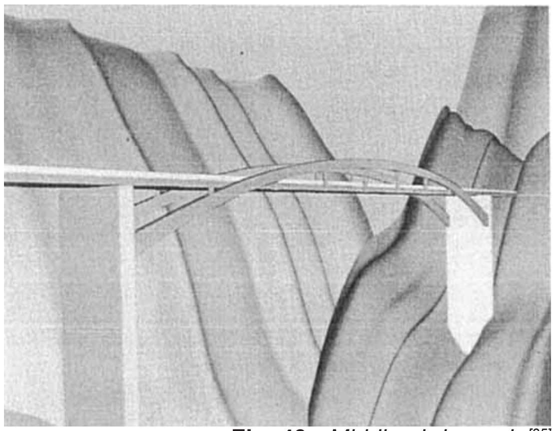


Fig. 43 - *Middle girder arch* [35]

Lute Venkat, Akhil Upadhyay, K.K. Singh

The effectiveness of the use of genetic algorithms to optimize problems inherent in bridge design with numerous variables to be considered simultaneously is highlighted in the paper "Genetic Algorithms-based Optimization of Cable-Stayed Bridges" (Lute et al. 2011). In this research, the aim is to reduce the cost of a cable-stayed type bridge, considering numerous parameters including the choice of materials, cable layout, and practical limitations of the site as regards the height of the towers. The whole process, therefore, starts from the definition of a static scheme for the structural typology and for the construction of a parametric model that considers dimensions and other characteristics of the elements that make up the bridge (Fig.44). To further have control over the iteration and reproduction of the population's members, the authors use penalty parameters that penalize the objective function in case of violation of the constraints assigned, such as limitation of resources and unwanted structural deficiencies.

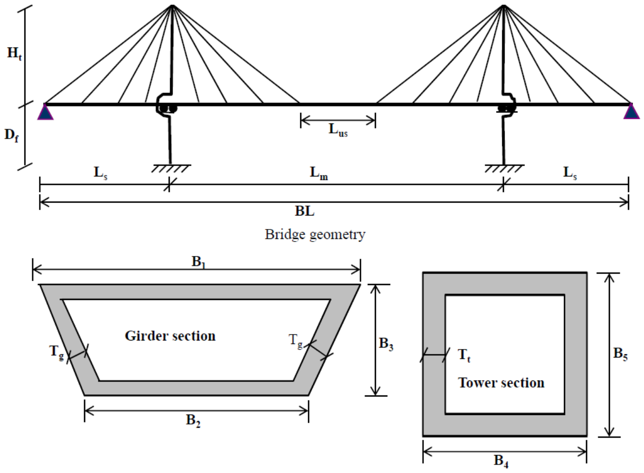


Fig. 44 - *Static scheme and parameters of the idealized bridge* [36]

Momir Nikolic

In the exploratory and research practice, there would be several examples where the design of a bridge passes through optimization processes. Usually, these processes are used in structural optimization, as in the case of the research carried out by Sander Van Baalen (2017). In other research projects, optimization was applied in intermediate stages of the design process, such as in the case of Merijn De Leur (2016) and Mark Ernst (2017).

In Momir Nikolic's thesis, the potential of computational optimization is instead explored from the earliest design stages. In his research, the focus is not only criteria related to structural optimization, but there is also an attempt to define different rules concerning, for example, the quality of the architectural space, meeting the inevitable difficulty of quantifying factors defined by intrinsically qualitative characteristics.

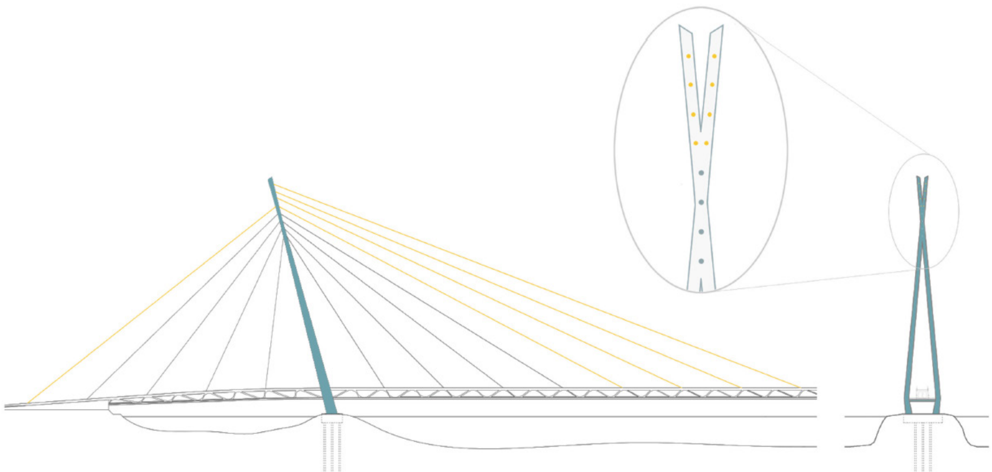


Fig. 45 - *Momir Nikolic's Bridge Design* [37]

2.6 SUSTAINABILITY ASSESSMENT TOOLS

The sustainable development of an architectural and engineering project is a complex process that involves sensitivities regarding its environmental, economic, and social impact. In recent years more and more research institutes, public and private parties, universities have attempted to produce standards, codes, and tools for sustainability assessment, thanks to the growing awareness of the need to direct the construction industry towards strategies and more virtuous behavior regarding sustainability.

A sustainability assessment tool should ideally allow an assessment of the different economic, social and environmental impacts based on a well-defined scale, as quantitatively defined as possible and which can be reused in various projects that have different characteristics.

BREEAM

BREEAM is a tool used worldwide to evaluate and certify the sustainability of a building. Developed by the Building Research Establishment in the UK. The tool uses different sections for the evaluation of characteristics concerning the environmental impact of a project which have a different weight on the final evaluation. The different sections contribute to the definition of the final score by satisfying some requirements to the extent that a minimum amount of credits is achieved. That is, the final score can be penalized for not reaching a minimum score in only one of its sections.

DuboCalc

DuboCalc is a system developed by the dutch Department of Public Works of the Ministry of Infrastructure and the Environment, Rijkswaterstaat (OECD, 2014). The methodology aims to evaluate the CO_2 emissions and the environmental impact using the CO_2 performance ladder and the dubocalc tool, respectively. The CO_2 performance ladder is a certification system that allows you to evaluate the emissions of CO_2 from production to construction, used for example, to define any deductions from the submission price of the bidder in case of public works.

Dubocalc is a tool based on life-cycle analysis that calculates the sustainability of a project by focusing on the materials used. The software calculates the environmental impact of the materials used from their extraction to production up to demolition and recycling. The program is based on a national dataset containing reliable information about the materials, which will then be compared with 11 environmental impact parameters. The score received in these sections protests to a final score called the environmental cost indicator (ECI value).

CEEQUAL

CEEQUAL is a tool developed by the Institution of Civil Engineers to evaluate the environmental performance of infrastructures, landscaping, and public works. As well as BREEAM, this tool assesses the environmental sustainability of a project through different sections. The difference with BREEAM lies in the greater number of sections dedicated to infrastructural projects such as the archeological and cultural heritage section, or others more focused on the public nature of the project to be evaluated. The tool has minor sections dedicated to socio-cultural aspects but is planning to improve this purpose, especially since its acquisition in 2015 from BRE Global Ltd, owner of BREEAM. In its latest 6th version, in fact, CEEQUAL proposes to combine the two systems to obtain a single evaluation scheme that helps to enhance the environmental and social performance of a given project (BRE Global Limited, 2019).

Tortuga

Tortuga is a plug-in for Grasshopper that allows you to evaluate the life cycle analysis and global warming potential of a parametric model. The plug-in has a rather simple operation, allows you to assign a material to geometry in Rhinoceros, and returns the environmental impact of that given material in those given quantities. Tortuga uses existing data on materials stored in two different databases, ÖkobauDat and Quartz Common Product Database.

ÖkobauDat is a database widely used in Germany defined as "German building material database for assessment of global ecological effects" (BMVBS, 2020). The database contains both generic data records and company or association-specific data records from environmental product declarations regarding building materials as well as construction and transport processes.

The Quartz Common Product Database is part of the Quartz Project that started in 2014 to collect data on the environmental impact of different materials. The database uses a consistent and transparent methodology to collect data on composition, environment, and health hazard information on common building products. The project is based on trusted sources such as patents, Environmental Product Declarations, and the Pharos Project and GaBi databases (Quartz, 2020). The data collected by the Quartz Project, focus on six main aspects of the LCA of a material, used as well by the Tortuga plug-in.

The Quartz Project will be used as reference database during the course of this research.

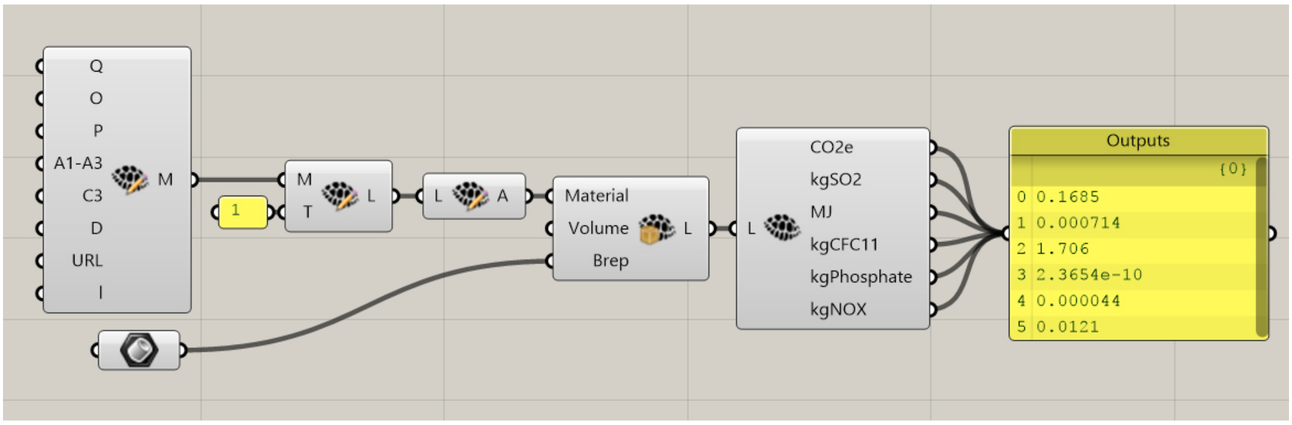


Fig. 46 - *Tortuga work-flow and results*

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP), including biogenic carbon	A measure of greenhouse gas emissions, such as CO2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health, and material welfare.	kg CO2 equivalent	(IPCC, 2013)
Eutrophication Potential (EP)	"Eutrophication" covers all potential impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems, increased biomass production may lead to depressed oxygen levels because of the additional consumption of oxygen in biomass decomposition.	kg N equivalent	(Bare, 2012) (EPA, 2012)
Acidification Potential (AP)	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline, and the deterioration of building materials.	kg SO2 equivalent	(Bare, 2012) (EPA, 2012)
Smog Formation Potential (SFP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems, and may also damage crops.	kg O3 equivalent	(Bare, 2012) (EPA, 2012)
Ozone Depletion Potential (ODP)	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.	kg CFC-11 equivalent	(Bare, 2012) (EPA, 2012)
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g., petroleum, natural gas, etc.) and energy demand from renewable resources (e.g.. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g., power, heat, steam, etc.) are taken into account.	MJ (lower heating value)	(Guinée, et al., 2002)

Table 1 - *Materials Life Cylce Impacts* [38]

SAAS

SAAS (System for Appraising the Sustainability of Structures) is an evaluation method developed by the UCL specifically for the sustainability of bridges (Amiri et al., 2009), altough the methodology can be applied to other infrastructures. This methodology aims to compare the sustainability of different alternatives through a strictly quantitative assessment, including environmental, social, and economic indicators (Fig.47). The assignment of a final score is carried out by reducing the various factors to dimensionless values, allowing normalization of the values to which a weight can be subsequently assigned in choosing the best alternative. A detailed explanation of the methodology as well as a brief review of other available sustainability assessment tools is given by Amiri A. et al. (2010). This system was taken as the first reference within this research as it is not linked to any specific software, and it allows to apply the proposed methodology in different computing environments, ensuring preferable adaptability in the context of design optimization.

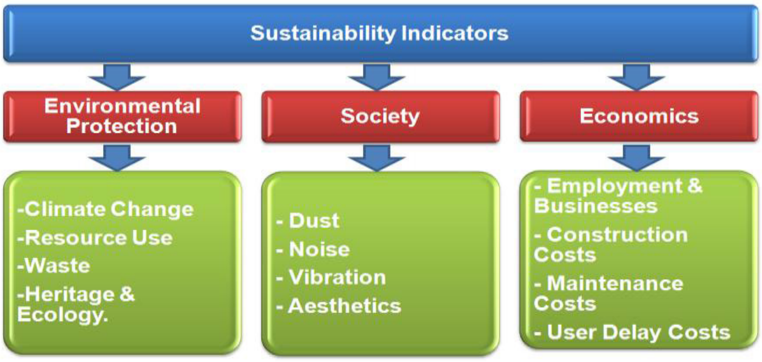


Fig. 47 - *SAAS Sustainability indicators* [39]

2.7 SUSTAINABILITY INDICATORS

Given the limited time available for this research, a choice was made regarding the sustainability indicators that will be used in the design optimisation process. The selection criterion preferred those considered most critical for assessing the sustainability of the design, paying more attention to the environmental aspect in regards to the reduction of used material, but also partially considering the economic one. With the SAAS method in mind, the social aspects of sustainability were deliberately kept out of the computational weightings as they are difficult to quantify objectively but they will nonetheless be considered in the entire design process.

The sustainability indicators introduced below are based on some of those present in the referenced SAAS method.

Life cycle environmental impacts for production and transportation of materials

For each material used in the design, the embodied tons of CO_2, and the other life cycle impacts introduced in Table 1 will be calculated per kg of material used in the project the life cycle environmental impacts generated by production processes and transportation are estimated according to the Cradle-to-gate data available in the QuartzProject databse.

Cost of contruction

The economic impact assessment will be carry out calculating the cost of construction. An estimation of the costs for the materials quantities and work required will be obtained by the price book specific for the region where the site is located (Regione Lazio, 2012). If there will be lack of information in the regional price list, other sources such as the SPON's Price Book (Langdon, 2009) will be surveyed by applying the necessary conversions and normalizations based on the Italian version.

2.8 CONTEXT

The chosen location is in the south-west quadrant of the city of Rome, between the EUR and Magliana districts (Fig. 48). The nearby Magliana bridge, which crosses the Tiber river, represents a road junction affected by significant traffic flows. It constitutes the end of the Rome-Fiumicino highway that connects the city with its main airport. The new bridge will have the task of mitigating the flow of traffic currently present on the nearby bridge of the Magliana and the future ones directed towards the new stadium as well as linking two very culturally different districts.

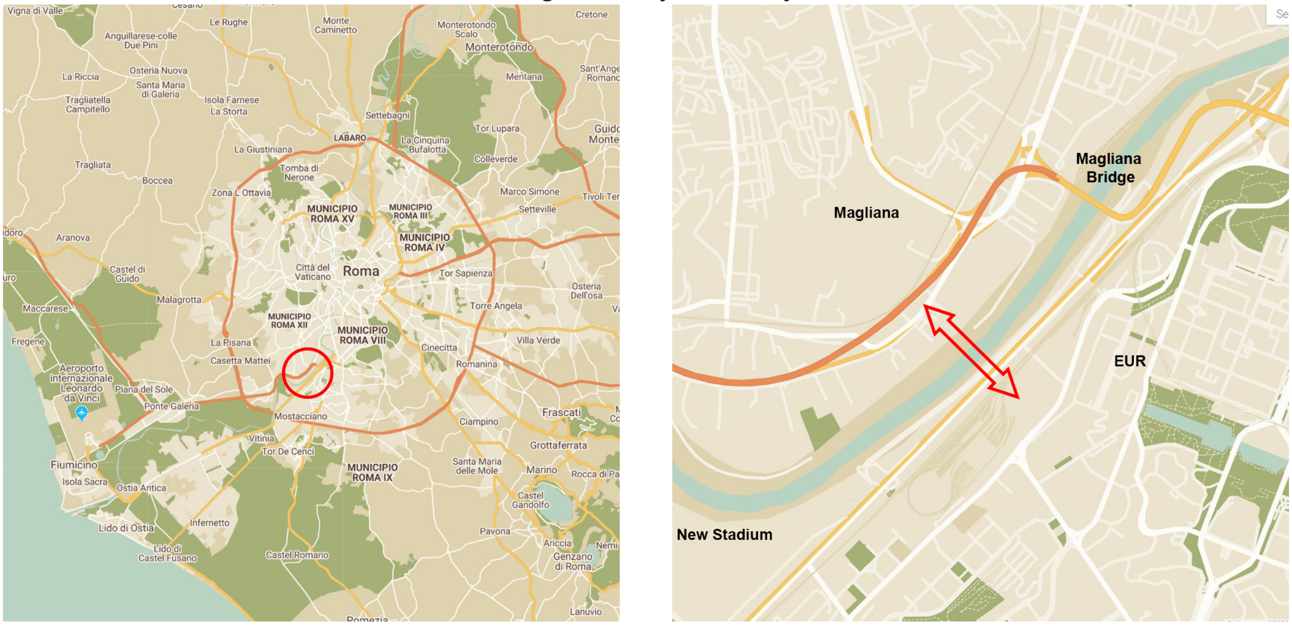


Fig. 48 - *Site location*

2.8.1 MAGLIANA

The Magliana district is delimited by the Tiber and adjacent neighborhoods: Eur, Marconi, and Gianicolense. The name derives from the agricultural property of the Roman family Manili or Manlia, while unverified sources hypothesize that the name may derive from the bamboo cane mallets placed by the Romans on the paths of this wetland to make it practicable. In Roman times the district was crossed by the important Via Portuense, which led to Portus (Fiumicino). It was a track used by the towing animals to trace the Tiber against the current to the boats that carried goods to Rome.

Fig. 49 - *Magliana district* [40]

The area has always been mainly used for agriculture until the urbanistic improvements with the 1960 Olympics, the construction of the Metro line B, and the Fiumicino airport. The urbanization that followed, however, took place for purely speculative purposes not respecting any urban plan, so much so that the neighborhood was the subject of intense construction of houses with poor architectural quality, lack of infrastructure, and below the level of the Tiber. Starting from the 90s, the municipality of Rome made a commitment to redevelop the area.

2.8.2 EUR

The EUR district is delimited by the Tiber river and the adjacent neighborhoods: Ostiense, Laurentino, Magliana and Ardeatino. The name derives from the acronym Universal Exposition of Rome as it was designed for the 1942 Universal Exhibition, which never took place since the outbreak of the Second World War. It will then be renamed district Europe in 1951.

The design of the neighborhood was commissioned by Benito Mussolini to celebrate the twenty years since Fascism took power and with the circumstance of the upcoming universal exhibition. The urbanistic plan behind it was that the neighborhood would become the new pole for the south-west expansion of the city towards the sea. Mussolini chose the architect Marcello Piacentini as head of the project, flanked by renowned architects of the time. The final design was presented in 1939 after the war had started, and the works stopped three years later. The project was then redefined and completed in the following years on the occasion of the 1960 Olympics with modern buildings and sports facilities.

Following to the fascist ideology, the model of the project is inspired by classical Roman urban planning, bringing elements of Italian rationalism proposed at the time as state architecture (Biraghi, 2008), however, mainly giving space to the simplified neoclassicism proposed by Piacentini. The urban layout includes a road system with orthogonal axes and majestic and monumental architectural buildings, massive and square, built with white marble and travertine to remember the glory of imperial Rome. The neighborhood is a residential area but also houses public and private offices as well as educational institutions. The architecture symbol of this ideology is the palace of Italian civilization (Palazzo della Civiltà Italiana).

Fig. 50 - *EUR district* [41]

2.8.3 PALAZZO DELLA CIVILTÀ ITALIANA

It is a monumental building designed in 1937 for the EUR district and inaugurated incomplete in 1940; the works will be completed after the war. The building has a square plan and looks like a parallelepiped with four equal faces, with a reinforced concrete structure and travertine cover. It has 54 arches per facade, 9 in line, and 6 in a column, and for its appearance, it has been named the "square coliseum". In the arches on the ground floor there are 28 statues representing the virtues of the Italian people, while on the façades, there is the inscription:

> *"a population of poets of hero of artists, of saints of thinkers of scientists, of navigators of transmigrators".*

Architecturally, the building reflects the fascist ideology with its monumental nature and the material choice of travertine to refer to imperial Rome but also to emphasize the self-sufficiency and ability of the state in creating such a massive architecture using stone being the use of iron made difficult from sanctions to Italy after the Ethiopian war (Rossi and Gatti, 1991).

Fig. 51 - *Palazzo della Civiltà Italiana* [42]

2.9 BRIDGES OF ROME

Ponte della Magliana

The Magliana bridge connects the Portuense and Ostiense districts. It was designed in 1930 by Romolo Raffaeli as an entrance to the Universal Exhibition area (EUR district). The works were interrupted by the outbreak of the war, and it was completed in 1948. From 1959 the bridge became part of the road system which leads to the highway that connects Rome with the Fiumicino airport. In 2001, foreseeing the construction of the new Congress bridge, its closure was hypothesized due to structural problems. Later this option was set aside in favor of a renovation and new function within the more comprehensive urban plan linked to the construction of the new bridge and the new stadium. The bridge consists of seven arches in reinforced concrete and is covered with travertine, with a span of 223m and a width of 19m.

Fig. 53 - *Ponte della Magliana* [43]

Ponte Fabricio

The Fabricio bridge is the only bridge in Rome together with the Cestio bridge that does not connect the two opposite sides of the Tiber river, as it connects the Tiber island with the left bank of the river. It is the oldest bridge in Rome in its original composition, consisting of two arches with a span of 24.5m for a total length of 62m by 5.5m in width. The middle pylon has an opening to relieve water pressure during river floods. Originally there were two other openings at the two ends but today buried. The structure is made of tuff stone with a travertine exterior. The brick part was made in the seventeenth century.

Fig. 52 - *Ponte Fabricio* [44]

Ponte Cestio

Built by Lucio Sestio between 46 and 44 BC but rebuilt in 370 with reuse materials also coming from the nearby Marcello theater, it connects the right bank of the Tiber with the Tiber Island. The bridge has three arches for a total length of 80m, while the original Roman bridge had a single arch that measured 48 and a half meters.

Fig. 54 - *Ponte Cestio* [45]

Ponte Sisto

Arched stone bridge connecting Piazza Trilussa to the left bank of the river, built by Pope Sixtus IV between 1473 and 1479 on the ruins of the oldest Roman bridge in Agrippa. The bridge has four arches for a total length of 108 meters and a width of 11m. In the central pylon there is a round hole (oculus) to reduce the water pressure in the event of a river flood.

Fig. 55 - *Ponte Sisto* [46]

Ponte dei fiorentini

Suspension bridge of Rome in steel and wood built between 1861 and 1863 by a French company commissioned by the papal state. Also known as the “coin bridge” for the toll that had to be paid to cross it. Dismantled in 1941 and replaced by the Prince Amedeo bridge.

Fig. 56 - *Ponte dei fiorentini* [47]

Ponte dell’industria

Bridge connecting the Ostiense and Portuense districts built between 1862 and 1863 by a Belgian company according to the principles of prefabrication. The bridge was in fact, was produced in England and subsequently transported to Rome for construction. Cantilever bridge built in metal with three lights covering a total length of 131m with a width of 7.25m

Fig. 57 - *Ponte dell’industria* [48]

Ponte del Risorgimento

The bridge was designed by the engineer Giovanni Antonio Porcheddu and built between 1909 and 1911 connects the Flaminio and Vittoria districts. It is the first bridge in Rome in reinforced concrete, and at the time, it was the largest span in the world built with this technology. The bridge covers a span of almost 160m with a width of 21m.

Fig. 58 - *Ponte del Risorgimento* [49]

Ponte Duca d'Aosta

Fig. 59 - *Ponte Duca d'Aosta* [50]

Arch bridge with a reinforced concrete structure and travertine cladding built between 1936 and 1939. The bridge consists of three arches where the widest one crosses the river with a span of 100m, and the two placed at the ends act as vents for the floodwaters with a total length of 222 meters and a width of 30m. The bridge was conceived as an entrance to the Flaminio district within the urban planning of the Italic forum, a sports complex desired by Mussolini. The bridge can be considered as one of the examples in which the fascist state influenced modern Roman architecture.

Ponte della musica - Armando Trovajoli

Fig. 60 - *Ponte della Musica* [51]

The bridge was foreseen by the urban plan of Rome as early as 1929 but built only in 2011 by the designer Buro Happold and the kit Powell-Williams Architects winners of a 2000 competition. Arch bridge made of reinforced concrete and steel initially designed as exclusively for pedestrian use subsequently modified for the transit of public transport and cyclists. The bridge develops a span of 190m with a width of 22m.

Ponte Ostiense - Settimia Spizzichino

Fig. 61 - *Ponte Ostiense* [52]

Built between 2009 and 2012 according to the project of the engineer Francesco del Tosto for the overcoming of the Rome-Ostia railway line. The reticular arch structure rests on three supports and supports the deck with steel cables. The study of the lattice structure was carried out through the use of structural optimization software and has a span of 160m with a width of 25m

2.10 PROJECT REQUIREMENTS

The need to build the new infrastructure is supported by the fact that the nearby Magliana bridge has visible traffic congestion phenomena in the morning and evening rush hours. The Magliana bridge is now the end of the Rome-Fiumicino highway and also fulfills the function of connection between the left bank of the river with the traffic flows coming from the highway, Magliana and Via Newton and the right bank from which come the flows of the EUR, Via C. Colombo and Via Ostiense. The critical points of the existing infrastructure are shown in Fig 62: the access ramp on the viaduct of the Magliana (1), the curve of a reduced radius at the Magliana bridge (2), and the mixture of the incoming flows on the side of the Magliana district (3). The current road system also does not allow the direct Magliana-EUR connection (4) and the connection with the new stadium project (5).

The project will have to solve these needs through the construction of a bridge that spans 170 meters separating the two banks of the river. It will have to provide four one-way lanes that connect the left bank with the right bank following the indications given by the urban planning department (Fig.65-66) following the analyzes regarding the traffic flows made by the Politecnico of Turin (Fig.63-64) with also the provision of pedestrian walkways and bike lanes. The design must reflect the expectations of the municipality of Rome, which wants the new structure to be a new gateway to the city for the flows coming from the Fiumicino airport, a new landmark for the city.

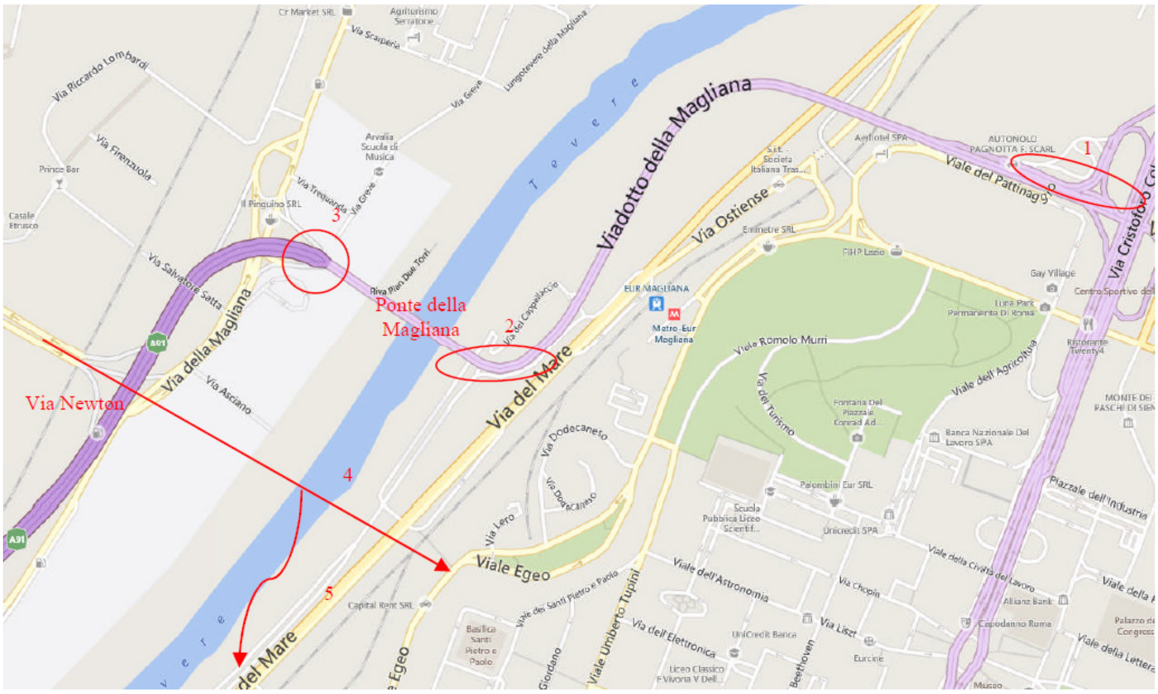


Fig. 62 - *Current situation*

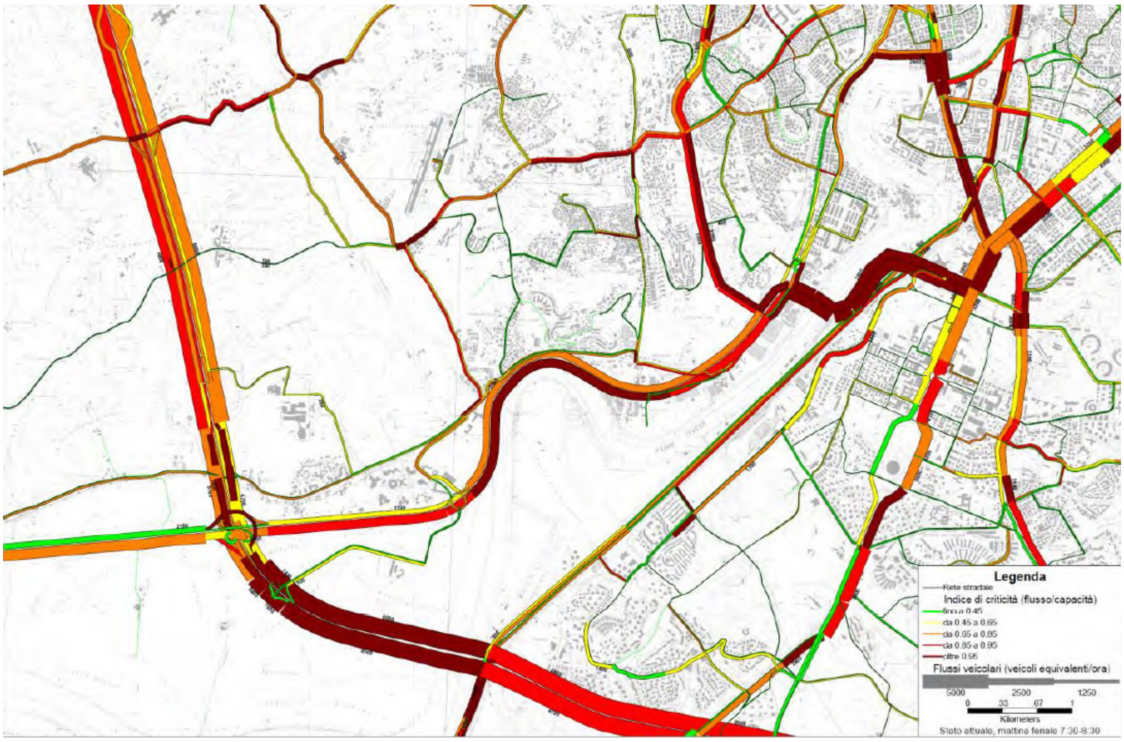


Fig. 63 - *Morning rush hours traffic flows without the new bridge* [53]

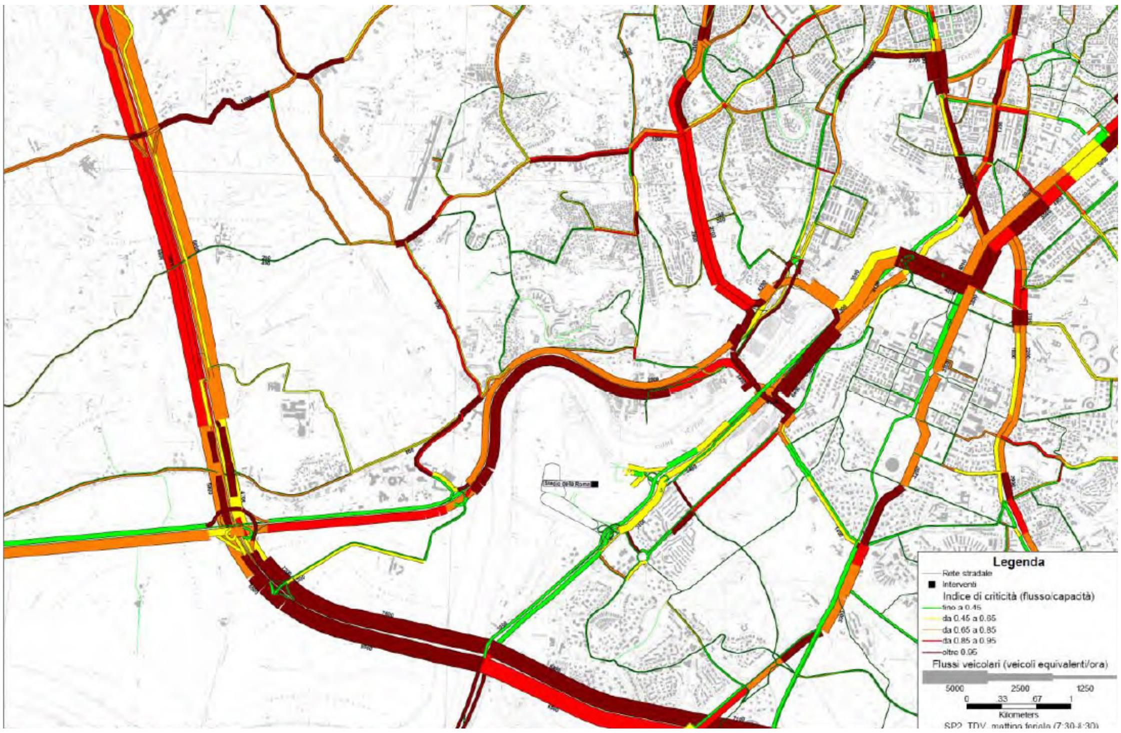


Fig. 64 - *Morning rush hours traffic flows with the new bridge* [53]

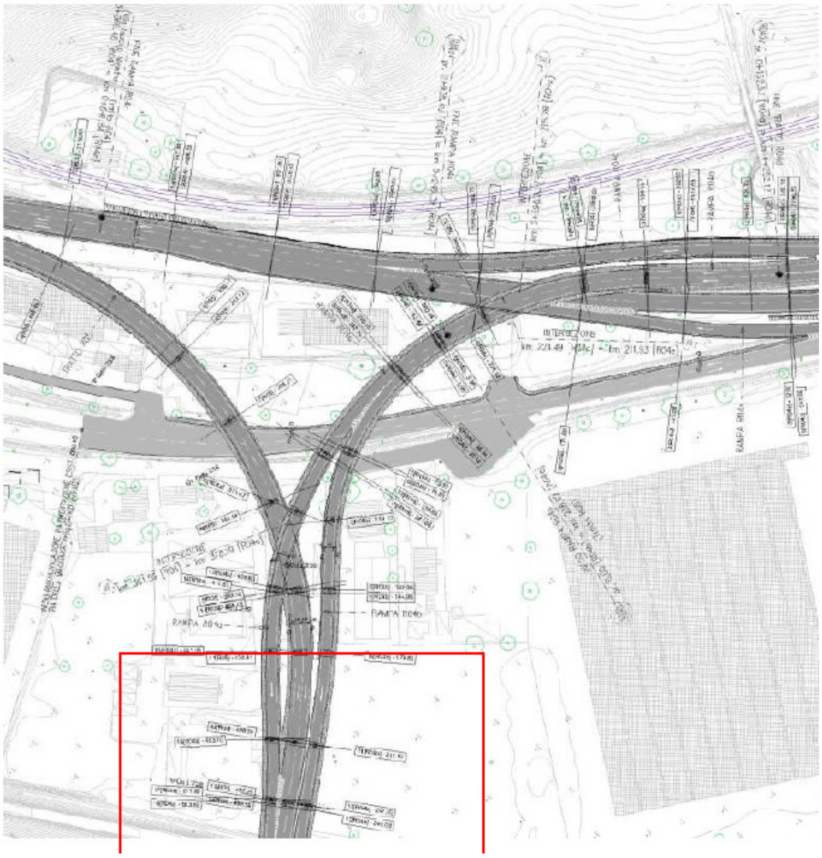


Fig. 65 - *New road system on the left bank towards Magliana* [54]

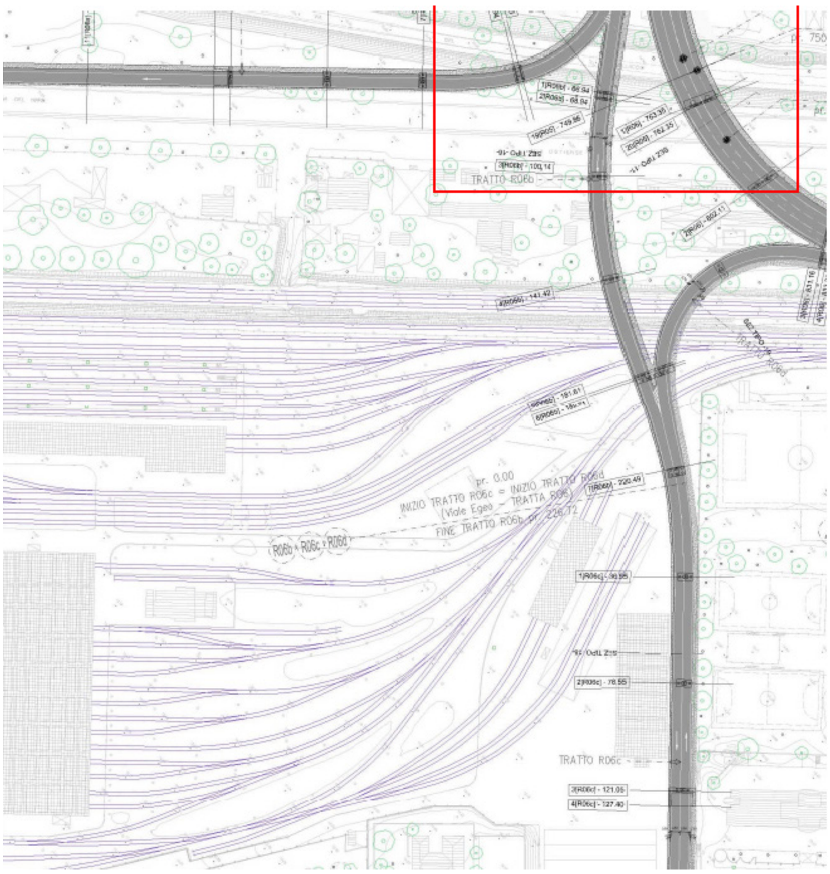


Fig. 66 - *New road system on the right bank towards EUR* [54]

2.11 PROJECT PROPOSALS

In 2000 the municipality of Rome launched a competition for the design of the Music bridge (Fig.60), Science bridge (Fig.61) and the Congress bridge to connect the districts Magliana and EUR.

Finalist projects include (Capuano, 2005):

- The solution without anchors and vertical structures of 5 + 1.
- The double arch that supports the double deck of Ove Arup.
- The two-level bridge of Calzona and Aymonino.
- The system of two overlapping viaducts of d’Ardia.
- The burial of the road and the double curvature of the pedestrian bridge by Desideri.
- The bridge that recalls the shapes of the Basento bridge by Musmeci proposed by Sclaich.
- The arch with tie rods that supports the driveway and pedestrian bridge of Siviero.

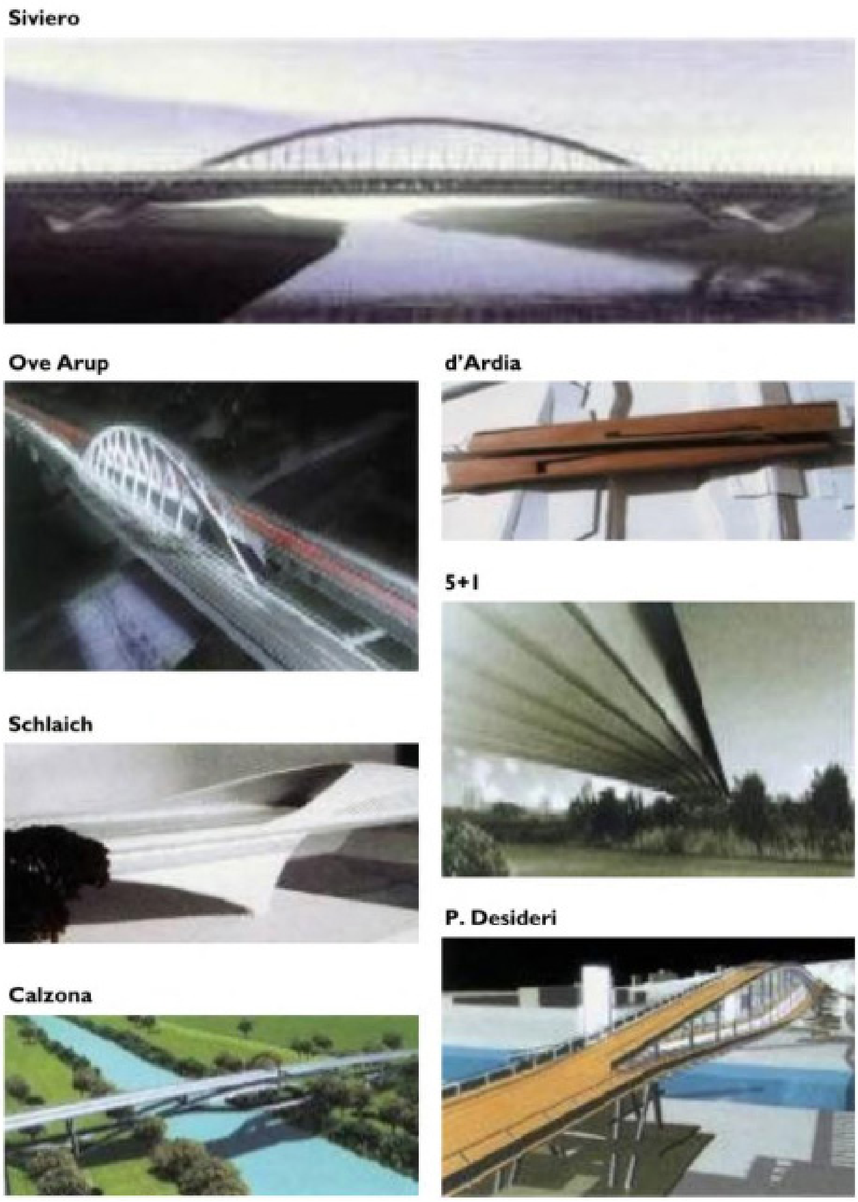


Fig. 67 - *Finalist projects* [55]

The winner of the competition will be Enzo Siviero with the initial proposal indicated in Fig. 68. Subsequently, for the changes made to the urban plan by the municipality of Rome, the winning studio will be asked to change the project. The final proposal (Fig. 69) is a 180 m spanning bow-string bridge with a 16 m high arch above the deck. The deck is made up of two levels, one dedicated to cars and one lower dedicated to cyclists and pedestrians.

Fig. 68 - *Siviero's first winning proposal* [56]

Fig. 69 - *Final proposal* [57]

3 DESIGN PHASE

This chapter includes the design process that followed the evaluation of the information collected during the research phase. First impressions in terms of architectural concept and urban alignment are given. The definition of a parametric model in a three-dimensional space follows, in order to permit the optimization process. Numerous preliminary analyses were carried out in order to be able to define and choose the best possible approach keeping in mind the limitations of this research. After the decision-making phase, a configuration was chosen and used as a starting point to develop a final design.

3.1 URBAN DESIGN

Following the analysis of the context and the requirements of the project, a draft design phase followed. The results focus on traffic management on the bridge and the desired relationship that the bridge will have with the city and the context.

3.1.1 ALIGNMENT AND PROGRAM

Rome's municipality already has a plan for the future development of the road network in the area; the decision taken for the alignment of the bridge was to follow the existing proposal. However, changes have been made to the way traffic is handled in correspondence of the two landings.

The municipality's program and the winning project of the competition do not provide for a separation of the flows from the north and south (Fig.65). When approaching the bridge, drivers will find themselves having to cross one or more lanes if they want to head south from the north and vice versa. The situation would seem too chaotic, and if traffic congestion is in one direction, potential inconvenience could occur for the entire road system.

The solution adopted was to divide the roadways to organize the course of the traffic flows upstream. The division on the main deck is provided by an opening to also allow for better illumination of the footbridge below (Fig.70).

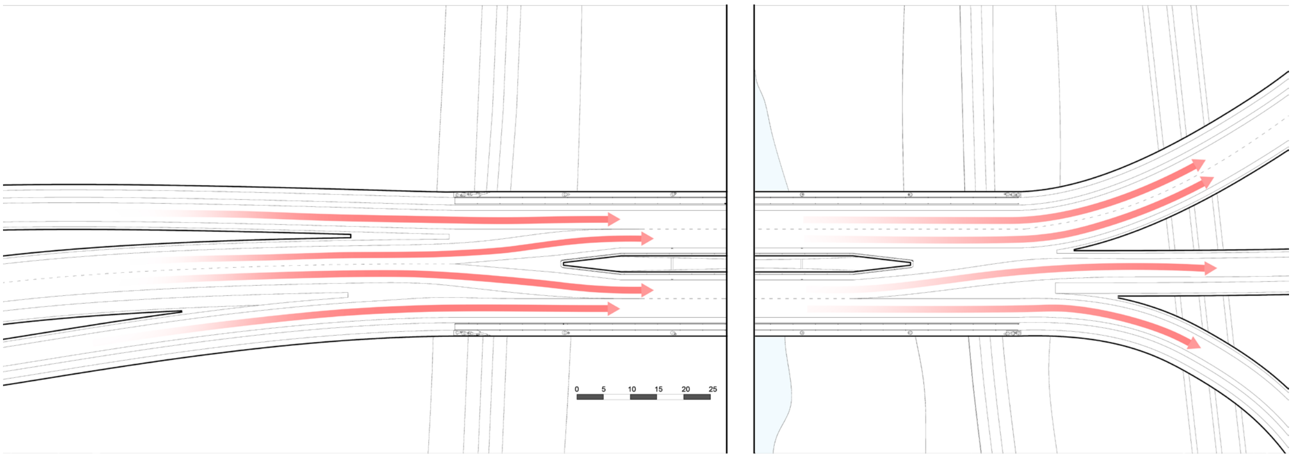


Fig. 70 - *Management of the traffic on the bridge*

According to the plans of the municipality of Rome, the bridge program concentrates exclusively on vehicular traffic. However, future projects on the redevelopment of the banks of the Tiber river include cycle paths that run along with it. Therefore, a connection between the two shores has been provided through a footbridge placed under the main deck with a two-way bike lane.

The choice of having a single connection instead of two passages on the sides of the bridge was dictated by the objective of minimizing the use of secondary structures. At the same time, this solution takes into consideration the eventual proximity to traffic exhaust fumes as well as the gentler slope that leads from one side of the river to the other.

Regarding the nautical route, the course of the Tiber river is navigable by small boats and canoes. Not providing for bridge supports placed within the river, it was considered sufficient to ensure a clearance of height that was equal to or greater than that of the nearby Magliana Bridge (Fig.71) which is of 13m.

Fig. 71 - *Magliana Bridge* [58]

3.1.2 ARCHITECTURAL LANGUAGE

The structural system of the bridge is what will impact its architectural language more than anything else. Since the bridge had to cross a span of about 200m, the two typologies that were initially considered from a structural point of view were the arched one and the cable-stayed one.

Looking at the bridges already present in the city of Rome, for consistency of language, the arched bridge typology would seem preferable. Even the two most recently built bridges along the Tiber the Music Bridge and the other one refer to this typology, albeit with two different approaches.

However, the primary function of the new bridge is to be the new main entrance to the city for the traffic coming from the Fiumicino airport. Rome's municipality has always expressed the desire to build a bridge easily recognizable from different parts of the city that could be considered a modern landmark. It should also formally refer to the idea of a gateway to the city. Its position puts it in relation to both the rationalist modernity of the EUR district and the contemporary architecture of the AS Roma stadium's future project to which the bridge leads.

The choice fell on the cable-stayed type with two arched pylons. The concept wants to recall the most widespread and characteristic architectural element of the city, and for wanting to create a structure that can recall to actual portals of access to the city such as the roman triumphal arches or the access arch to the nearby EUR district envisaged by the architect Libera and never built (Fig. 72)

Fig. 72 - *Libera's monumental arch* [59]

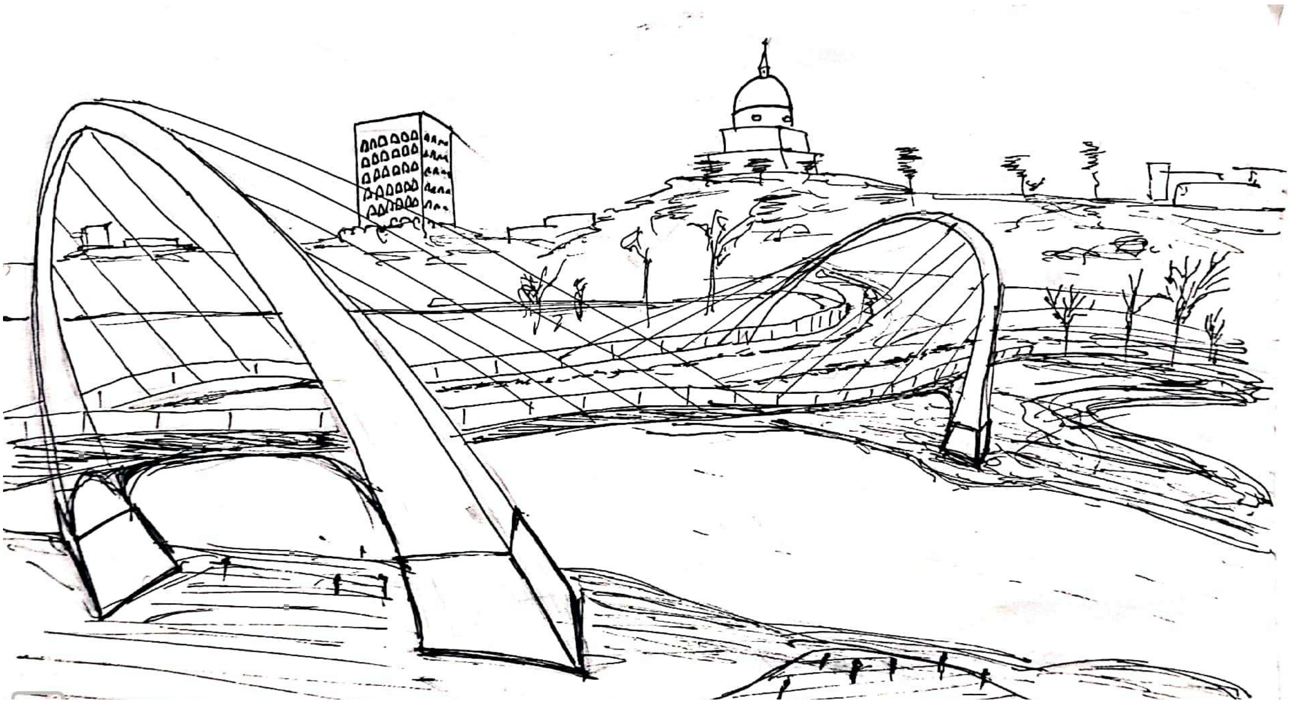


Fig. 73 - *Draft design and first impression*

3.2 DESIGN WORKFLOW

From the study of the context and functional demands of the project up to its conceptualization, the followed procedure can be considered conventional. Once in the design development stage, the optimization process was inserted, following the objectives described in chapter 3.3.

The first step taken to accommodate the optimization process within the research was to define its design framework. To be able to identify and limit the set of possible solutions that will be analysed after the optimization, it is necessary to make a priori choices. These choices were made to introduce limitations essential to define the space within which the optimization process can take place and respect the desired architectural language following the urban draft design phase. This phase aims to direct the general geometry and configuration of some elements of the bridge towards the best solutions concerning the defined objectives.

The whole process is possible thanks to the development of a parametric model that describes its room for manoeuvre. The parametric model was initially set up to have vast ranges of variables so as not to exclude potential optimal solutions outside the intuitively optimal space (for example, having pylons inclined towards the centerline of the bridge). A reduction of the parameters' range followed the preliminary optimizations.

Once the general geometric configuration was defined, the design was developed to reach its final shape. Starting from a configuration chosen among the many available based on a preference supported by the use of MCDM, the final dimensioning of some elements was completed while carrying out a last structural verification applying the prescribed load cases.

3.2.1 DESIGN FRAMEWORK

To be able to set a parametric model and to limit the size of the virtual space of possible solutions, some constraints have been defined a priori.
The structural tipology cons

The main limitations are:

- Structural system: following the considerations expressed in the previous chapter, the parametric model was built around the cable-stayed type;
- Shape of the pylons: In order to recall an arch shaped pylon, catenary curves where used as a primary logical way to withstand the pylons self-weight. Altough since they will be inclined and object to the tension forces of the stay cables a specific optimisation has been carried out later on, see chapter 3.7.1;
- Width of the decks: The need for four car lanes on top of the bridge and a footbridge below with enough space for pedestrians and cyclists, the width of the decks was set a priori. The main deck will have a width of 27m comprehending the opening of 3m in the middle, while the footbridge is 6m wide in its narrower part so to leave enough space for a bikelane in the middle.
- Pylons position: The banks of the river limited the possible position of the pylons in regards to one dimension while the distance between the two foundations of a pylon in the other direction was set to not be less than the width of the bridge and no more than 100m (later on the latter maximum distance of 100m will be reduced according to the initial results of the analysis to restrict the design space to only the most performant configurations);
- Bridge span: 220m, in order to have the supports for the approaching roads at both ends beyond the bike lanes path.
- Minimum height clearance: Set to 13m accordingly to the clearance of the nearby Magliana Bridge to not compromise the naval navigation on the river.

Pylons and deck material

To assess the impact on the objectives of different material solutions, two different options for pylons and decks are considered, for a total of four possible combinations.
The pylons have a square cross-section of variable dimensions throughout the entire arch lenght and it can be made of reinforced concrete or steel plates.
The decks main structure can be a reinforced concrete slab with variable thickness or supported by primary and secondary steel I-beams shaped according to the forces acting on it.

Deck substructure

To support the footbridge, it was decided to use slented steel rods, which start from the anchor point of the bridge's main stay cables. After preliminary structural analyzes, rigid vertical elements to connect the two decks were added for two reasons. The first is that they help stabilize the footbridge against horizontal thrusts exerted mainly by the wind. The second is that they can partially contribute to supporting loads of the overlying deck by acting in conjunction with the support cables similarly to a tied arch tipology (Fig.74), significantly reducing the material needed for the deck structure (Fig.75)

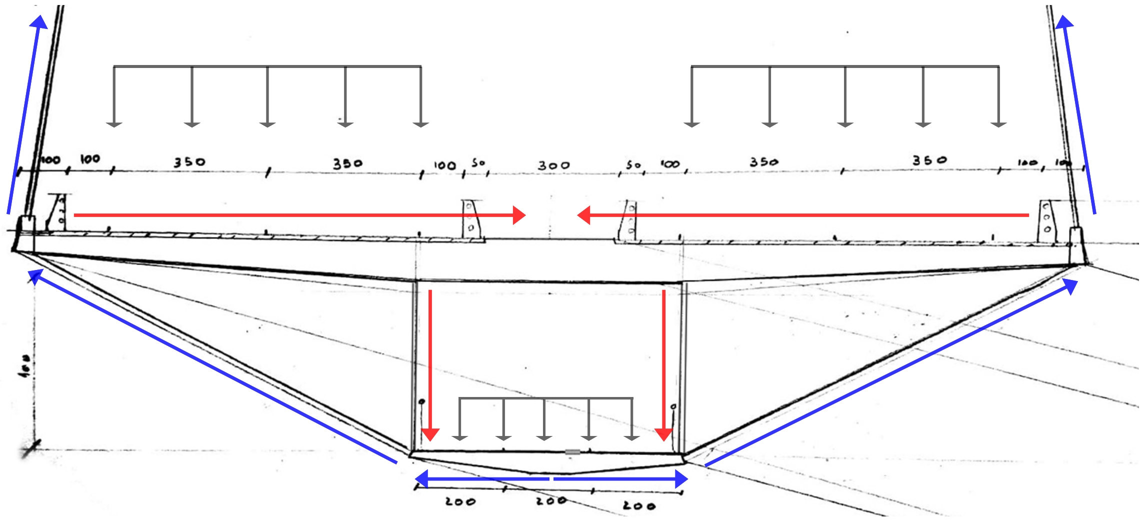


Fig. 74 - *Decks configuration and main forces acting on its structure*

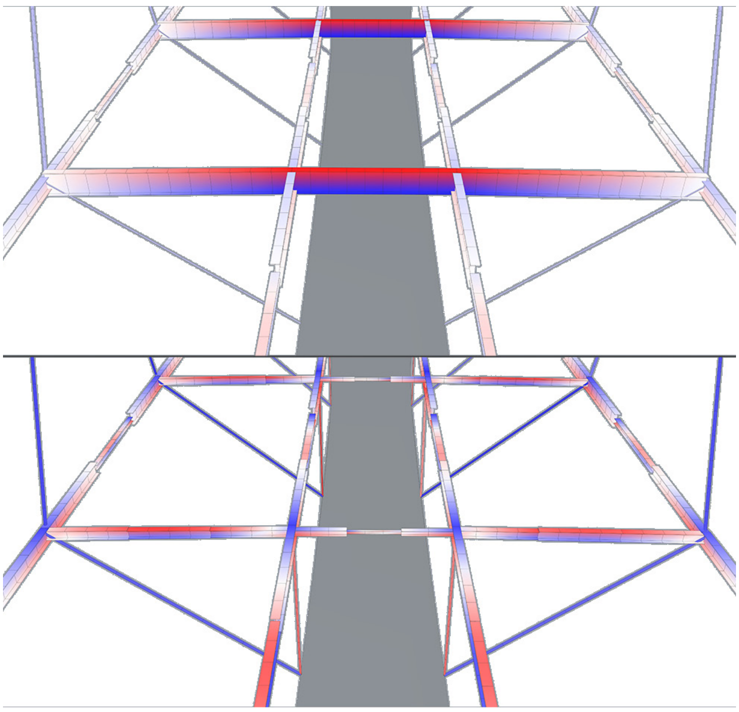


Fig. 75 - *Material reduction due to addition of extra vertical elements*

3.3 MAIN DESIGN OBJECTIVES

The precise definition of the design objectives is of crucial importance for achieving a satisfactory optimization. Referring to the intentions expressed in the formulation of the research questions, two main objectives are set: the minimization of the project's environmental and economic impact. These two objectives have been joined by a third concerning the achievement of structurally sound design.

Environmental impact

The environmental impact of the design is closely related to the effective use of the material and the minimum sizing of the elements that make up the structure. This aspect was naturally considered and is explained in chapter 3.4.1.

Regarding the sources used to determine the environmental impact of the different materials used, the quartzproject database was used, which includes the energy and emissions deriving from the manufacturing processes in the indicators of each component for a so-called analysis " from cradle to gate." This differentiation between the elements is vital to get as close as possible to an accurate analysis as considering the environmental impact of steel, for example, is different for stay cables or metal profiles as for the same material used, the former requires high energy consumption processes. The database allowed the differentiation of the individual components and not only of the family of materials to which they belong.

For each component, all the indicators described in Table 1 are available; however, since they are proportional to each other, only the co2 emission was considered as the target to be reduced. However, the total of the individual indicators for the final configuration has been calculated nonetheless.

Four main materials have been identified and considered within the optimization:

- Concrete: used for pylons and the main deck structure. The database considers all aggregates and processes but not any admixtures.
- Rebar steel: used in the reinforced concrete sections of pylons and decks, the database refers to ASTM a615 steel.
- Structural steel cables: describes the impact of the stay cables, it is the element with the highest environmental impact.
- Structural steel: used for the steel beams of the decks, profiles of the pylons, and the vertical elements supporting the footbridge. The database refers to astm a992 steel.

System Boundary
35% fly ash mix. Includes all cradle-to-gate data, including raw materials extraction, transportation of ingredients to the concrete mixing plant, and plant operations. Transportation taken from averages, based on NRMCA report/survey (Athena 2014). Admixtures are not included. Dataset does not include any steel reinforcing or formwork. Fly ash is modeled from coal electricity production using economic allocation.

Foreground Data Source
NRMCA; GaBi; primary research

Background Data Source
GaBi; USLCI

Post-consumer Recycled Content
0%

Reference Region
United States

Reference Year
2015

Declared Unit
1 kg

Cradle-to-gate LCA Results (per declared unit)

Acidification Potential	Eutrophication Potential	Global Warming Potential	Ozone Depletion Potential	Smog Formation Potential	Primary Energy Demand
8.67E-4	4.11E-5	1.94E-1	5.09E-10	1.29E-2	1.38E+0
kg SO_2 eq	kg N eq	kg CO_2 eq	kg CFC-11 eq	kg O_3 eq	MJ

Fig. 76 - *Environmental profile of concrete* [60]

System Boundary	Foreground Data Source	Reference Region
Cradle-to-gate. Combination of electric arc furnace (EAF) / blast furnace averaged route. Includes all upstream manufacturing and transportation to the gate of the structual steel fabricator.	worldsteel	United States
	Background Data Source	**Reference Year**
	n/a	2015
	Post-consumer Recycled Content	**Declared Unit**
	70%	1 kg

Cradle-to-gate LCA Results (per declared unit)

Acidification Potential	Eutrophication Potential	Global Warming Potential	Ozone Depletion Potential	Smog Formation Potential	Primary Energy Demand
3.53E-3	1.63E-4	1.26E+0	1.21E-8	4.43E-2	1.64E+1
kg SO_2 eq	kg N eq	kg CO_2 eq	kg CFC-11 eq	kg O_3 eq	MJ

Fig. 77 - *Environmental profile of rebar steel* [61]

System Boundary	Foreground Data Source	Reference Region
Cradle-to-gate. Electric arc furnace (EAF) route. Includes all upstream manufacturing and transportation.	worldsteel	North America
	Background Data Source	**Reference Year**
	n/a	2007
	Post-consumer Recycled Content	**Declared Unit**
	100%	1 kg

Cradle-to-gate LCA Results (per declared unit)

Acidification Potential	Eutrophication Potential	Global Warming Potential	Ozone Depletion Potential	Smog Formation Potential	Primary Energy Demand
4.42E-3	1.12E-4	9.38E-1	6.05E-8	4.39E-2	1.17E+1
kg SO_2 eq	kg N eq	kg CO_2 eq	kg CFC-11 eq	kg O_3 eq	MJ

Fig. 78 - *Environmental profile of structural steel* [62]

System Boundary	Foreground Data Source	Reference Region
System boundary includes upstream material production, energy generation, and inbound transport. Production includes hot dip galvanization of steel, spray application of zinc-rich blocking compound, and wire twisting. Packaging is excluded.	GaBi;worldsteel	United States
	Background Data Source	**Reference Year**
	GaBi	2015
	Post-consumer Recycled Content	**Declared Unit**
	24%	1 kg

Cradle-to-gate LCA Results (per declared unit)

Acidification Potential	Eutrophication Potential	Global Warming Potential	Ozone Depletion Potential	Smog Formation Potential	Primary Energy Demand
8.17E-3	3.71E-4	2.65E+0	1.07E-8	1.09E-1	3.34E+1
kg SO_2 eq	kg N eq	kg CO_2 eq	kg CFC-11 eq	kg O_3 eq	MJ

Fig. 79 - *Environmental profile of structural cables* [63]

Measures to reduce the environmental impact of the project beyond the amount of material used were taken into consideration. The emissions caused by vehicular traffic, which crosses the bridge, for example, in the long-life span for which the bridge is designed, has been considered. The two main measures adopted were: the better flow management mentioned in the urban design chapter, in order to reduce potential traffic jams while minimizing the slope of the bridge. As even if minimal in the single event, the energy and CO2 emissions produced by traffic must be considered multiplied by the volume of flows and the life cycle of the bridge.

Since the research aimed to have a general picture of the impact of different structural configurations and different material options, the environmental impact of secondary elements such as the footbridge parapets or the main deck road rails was not considered as present in any case.

Economic impact

It is important to underline how, in general, the project's economic impact can be related to the actual use of the materials. Optimal sizing of the elements translates into a lower amount of material and the relative cost of the project. This consideration does not take into consideration any manufacturing, labor, and maintenance processes.

Within the limited time of this research, it was not possible to analyze and quantify the numerous variables involved in the project's economic aspects. However, an attempt was made to quantify the economic impact of different solutions by looking at the cost of the material on the market and primary maintenance interventions to combine the objective with reducing the environmental impact.

The lower precision of the quantification of this factor was then taken into consideration later when selecting the best alternative.

As for the cost of materials, the database in the CES EduPack software (Granta Design, n.d.) was used in order to obtain a value in €/kg directly correlated to the amount of materials used. The database used by the software provides for a range of more or less broad values; the individual values used have been extrapolated by averaging between the minimum and maximum values indicated.

As regards the cost of maintenance, the estimate proposed by the SASS method was used (Amiri et al., 2009, p.29-32). The economic impact assessment proposed by the methodology includes an estimation for the cost of maintenance on different materials. The methodology assumes that a percentage of the surface of each element is subject to maintenance several times during the life span of the bridge and proposes a cost per square meter for each work needed. In this research, repairs and patching of the concrete elements and painting of steel elements were used.

Buckling Load Factor

The entire structure's capacity to resist instability has been considered one of the objectives to be maximized in the optimization process. Even before failing due to stresse higher than the material strength, elements such as slender beams and thin shells may fail due to buckling.

Second-order theory calculations have been carried out in Karamba to take into account the axial forces that impact stiffness of the structural elements and not only the forces that cause stress in the cross-sections. Second-order effects were considered to choose the largest compressive force giving a lower limit for the structure stiffness.

After the analysis of the model in Karamba, a Buckling Load Factor can be retrieved. The BLF indicates the factor of safety against buckling. In an ideal model, this value needs to be above 1 (Fig.80), but a higher value is always preferable in order to have a more consistent safety factor.

The maximization of the BLF was considered an objective optimization, and not only as a constraint due to the strategy adopted when defining the loads considered for the optimization. The loads acting on the structure in the first phase of the analysis do not consider the worst-case scenario prescribed by the Eurocode, hence the aim to have a structure previously considered more stable than strictly necessary (more on the loads used for the optimization on chapter 3.4.1).

BLF Value	Buckling Status	Remarks
>1	Buckling not predicted	The applied loads are less than the estimated critical loads.
= 1	Buckling predicted	The applied loads are exactly equal to the critical loads. Buckling is expected.
< 1	Buckling predicted	The applied loads exceed the estimated critical loads. Buckling will occur.
-1 < BLF < 0	Bucklin possible	Buckling is predicted if you reverse the load directions.
-1	Buckling possible	Buckling is expected if you reverse the load directions.
< -1	Buckling not predicted	The applied loads are less than the estimated critical loads, even if you reverse their directions.

Fig. 80 - *Buckling Load Factor* [64]

Evaluation

To evaluate the results that are going to be obtained concerning the defined objectives, it is necessary to determine the correct dimensions of the individual structural elements. In order to do so, a first optimization process present within the parametric model and carried out by the Karamba plug-in through the definition of structural elements, loads, and supports has been carried out.

Following the dimensioning of the individual elements, the quantities of material used can be calculated and multiplied by the various sustainability indicators taken into consideration.

3.4 PARAMETRIC MODEL

The parametric model in this research acts as a medium for the exploration of structural configurations that can be evaluated both from an architectural point of view and concerning the goals defined for the optimization process. The development of the parametric model was carried out, taking into account that the goal was not to generate a finalized design, but rather to obtain a general geometric configuration of the bridge and its main elements.

The overall objective is to evaluate the solutions proposed by the optimization process according to the results obtained in relation to the defined objectives and the desired architectural performance.

Not all the parameters that define the geometry of the bridge have been used in the optimization process. The choice was made due to the need to define limits to the space of solutions within the algorithm will have to search, but also from decisions made a priori for architectural matters and structural insights. In the first phase of the development of the parametric model, only the variables that define the general geometry of the bridge were taken into consideration.

Factors such as cross-sections of the individual elements were defined and optimized in the phase including the structural analysis explained in the following chapter.

The primary geometric parameters defined as constraints are:

- Position of the landings of the main deck and footbridge: The landing of the main deck were set in regards to the position of the supports for the approaching roads at 15m height from the ground level. The landings of the footbridge respect the course of the bikelanes along the river at a height of 11m from the water level in order to remain safe in case of eventual floods of the river;
- Width of both decks and the opening in the main deck: As previously explained the width of the bridge was designed in order to accomodate the traffic and pedestrians bearing in mind safety and comfort.
- The general shape of the pylons (arches): To fullfill the aesthetic appearance addressed in the architectural draft design phase;
- Equidistance of the cable anchors on the main deck: In order to better distribute the load and to have equal spans for prefabricated elements;
- Alignment of the footbridge supporting elements: The elements underlying the main deck and the connecting beams between the roadways were aligned according to the same plane.
- Presence of back cables for each stay cable to the main deck: In order to balance the forces acting on the pylon.

While as regards the initial variables used within the optimization process, they are:

- Position of the Foundations of the two pylons: The river banks and the bikelanes running along set the limit in one direction with a range of 58m for the first pylon approaching the bridge and 29 for the second one;
- Height of the pylons: The two pylons were initially able to reach a height of 150m;
- Width of the Pylons: The width of the pylons was directly connected to the Karamba model in order to address the needs for each cross-section (explained further in the next chapter);
- Inclination of the pylons: The two pylons were originally left able to range between an inclination of 45° towards the bridge landings and 20° towards the midspan;
- Number of cables: The number of cables was initially set in order to have between 8 and 20 anchorages on the deck.
- Distance between the cable anchors on the pylons: The distance between the cables on the pylon was set having in mind the only limit of not permit any anchorage on the pylon that was below the plane on which the main deck lies.

While setting of the parametric model, it has been ensured that every change in configuration would keep the contact between elements in the parts where forces need to be transmitted, crucial for a correct structural analysis.

During the first optimization phases, the range of values of the variables considered was left very wide, not to exclude possible optimal solutions. Some of them have been deliberately left able to range between intuitively counterproductive configurations, for example, having the pylons inclined towards the centerline of the bridge.

Subsequently, the ranges have been decreased while increasing the number of possible solutions within them to obtain a more targeted search following the first results obtained.

The use of a parametric model within a 3D modeling space has made it possible to continuously evaluate the best-performing configurations from an aesthetic point of view and linked to the project's architectural intentions.

The following image (Fig.81) shows the parametric model built in Grasshopper with its different sections.

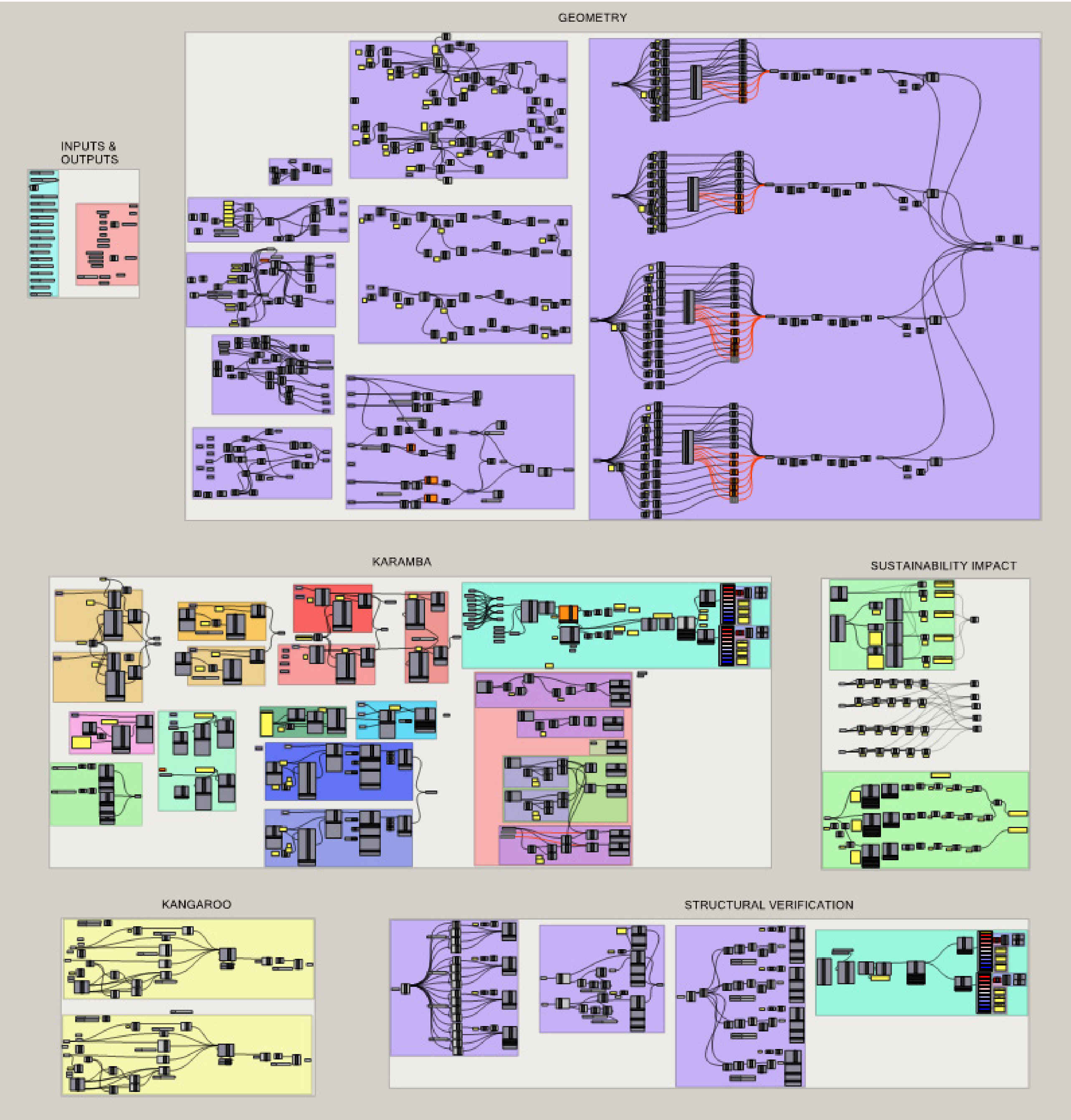


Fig. 81 - *Parametric Model*

3.4.1 KARAMBA MODEL ASSEMBLY

The first step was to define the elements, supports, and loads acting on the structure. As for the dimensions of the elements, a range of sections was given. Among the cross-sections defined, the component subsequently favored those with the smaller size that could satisfy the forces acting on the single element, taking into account the strength of the material.

The thickness ranges in the case of reinforced concrete elements are deliberately wide so as not to exclude a priori solutions and to be able to evaluate them also from an aesthetic point of view subsequently.

Elements

The structural elements within Karamba are classified into shells and beams. The pylons and decks in the possibility that they were in reinforced concrete are the only ones defined as shell elements.

If the pylons consist of steel profiles, they were defined with a section increasing in dimension towards the foundations for aestethic puroposes while a variable thickness was taken into account for the optimisation and effective use of material. An alternative approach (equally structurally valid) would have been to have a constant section and variable internal thicknesses.

Similar reasoning was used for the rigid support elements between the main deck and the footbridge. They have a constant section and variable internal thicknesses in order to have a recurring aesthetic result on the footbridge.

As for the range of sections that can be used for the possibility of having steel beams supporting the deck, the library in Karamba for I-Beams was used.

Finally, for the sizing of the cables, reference was made to the dimensions gathered from the cable manufacturer Tensa (Tensacciai, n.d.).

Supports

The static scheme utilized for the bridge consists of clamped supports for the pylons, while the two decks' landings have been considered simply supported. In case the elements connected to the supports were defined as Karamba beams, the supports were assigned to their endpoints. In the case of shell elements such as pylons and concrete decks, supports have been assigned to the vertices of the mesh located on the outer edges corresponding to the support's position.

Loads

In order to obtain an optimized configuration and shape of the arches for a uniform and symmetrical load configuration, temporary loads were used in this first phase. The loads considered were the effect of gravity on the structure (self-weight), two uniformly distributed loads of 5 KN/m^2 for the footbridge, and 9KN/m^2 for the main deck.

This configuration does not reflect the load model proposed in Eurocode and in the Italian legislation, for which the structure for an unfavorable asymmetrical load configuration must be verified. The choice to apply these loads was made consciously with respect to the strategy of dimensioning the elements' cross-sections applied subsequently.

Cross-Section optimization

The elements' cross-sections were optimised according to the stress caused by the loads acting on the structure and considering the buckling factor. The elements were divided according to whether they were in concrete or steel.

Given the nature of the loads applied in this first phase, it was envisaged that it would not have been ideal to assign sections that fully exploited the strength of the material. The structure would not have been able to withstand the unfavorable load conditions indicated by the legislation regarding the nominal stress of the elements and the risk of buckling. The strategy used conceived assigning sections that would consider limited use of the actual strength of the material in order to over-dimension the structure for the loads set in this first phase and later test their capacity to withstand the unfavorable conditions.

Following several analyses, it was decided to assign the sections defining the material use limit as 50% for the concrete elements and 70% for the steel elements. Both components of Karamba used for this operation were fundamental for the definition of the constraints to be considered during the optimization process. If the geometric configuration of the bridge requires sections larger than those present in the set ranges, the information from the components has been translated into numerical values of 0 and 1, which can be easily used within modeFRONTIER to verify which configurations were feasible and which were not. In the following figure the behaviour and outputs in case of concrete failure are shown.

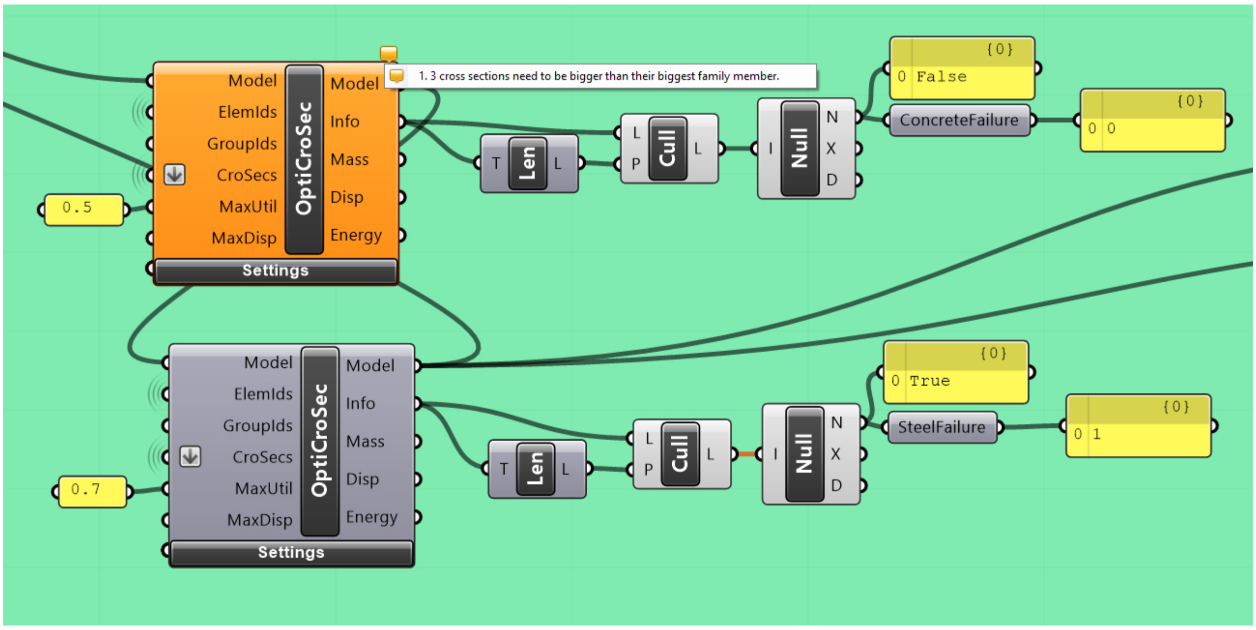


Fig. 82 - *Cross-sections optimisation*

3.4.2 AMOUNT OF MATERIALS USED

Once the cross-sections were calculated for a specific geometric configuration, the model was disassembled, and the elements that compose it divided according to the type of material used.

Ultimately, the amount of materials used in terms of mass (kg) has been multiplied by the sustainability indicators used to calculate the environmental (CO2/kg) and economic (€/kg) impact.

As regards to the economic impact relating to maintenance operations, the surface of the elements derived from the mesh obtained from Karamba (m^2) was calculated and multiplied by the costs estimated by the SASS method (€/m^2).

3.5 OPTIMISATION PROCESS

The optimisation process was carried out through the use of the modeFRONTIER software, developed by ESTECO, connected to the parametric model in Grasshopper, so that it can directly change the variables defined in the inputs and return the results for the required outputs. Some of the outputs have been used to better understand the behavior of the structure and how some elements can influence the final objectives to a greater extent than other elements used.

Two of these outputs were used to measure the difference in height and width between the two pylons for purposes related to the desired architectural language of the project. The hypothesis of defining them as constraints and eliminating a priori those solutions that did not respect the desire to have the first pylon bigger than the second, expressed during the draft design phase, was rejected. The aim was to allow the algorithm to evaluate those options even if they were not aesthetically preferable so as not to exclude potential optimal solutions that did not respect the initial design concept. However, they were subsequently taken into consideration in the decision-making process.

As for the remaining constraints they were defined and used by the algorithm chosen to exclude solutions that had a buckling load factor less than 1 and a total displacement of the structure higher than 0.5m. All the solutions also had to satisfy the requirement of having elements with sections capable of supporting the stresses depending on the selected range.

The main objectives were therefore defined such as the minimization of the environmental and economic impacts and the maximization of the buckling load factor for the overall structure. Among the different outputs defined to facilitate the subsequent decision-making process, there is the total mass of the structure, so that a preference for lighter solutions can subsequently be defined. The general precaution being the seismic risk present in the country, the force generated by the seismic acceleration will act on a lighter mass, giving a minor resultant.

After defining the inputs and outputs to be examined, it is necessary to choose an algorithm to be used for the optimization. Initial tests were conducted by exploring the capabilities of different genetic algorithms, particularly in MOGA II and NSGA II. Subsequently, the use of the pilOPT algorithm developed by ESTECO was preferred. The pilOPT algorithm has a hybrid behavior that uses multiple numerical investigation strategies while maintaining the logic of a genetic algorithm, making the best out of time and computational resources (ESTECO, n.d.).

The algorithm was used starting from a DOE sequence defined by the Latin Hypercube method in order to have a first generation of solutions distributed over the entire design space. This action allows for a quick evaluation of very different configurations, giving the algorithm an essential starting point to avoid the risk of omitting potential optimal solutions.

The optimization process was carried out individually for each of the four possible combinations concerning the material used for the main structural elements. This choice was made so as not to allow the algorithm to concentrate the research on a specific combination that would have eventually appear preferable, consequently excluding the others. Once the results of the four optimizations were obtained, they were compared in their entirety in order to make a more informed choice.

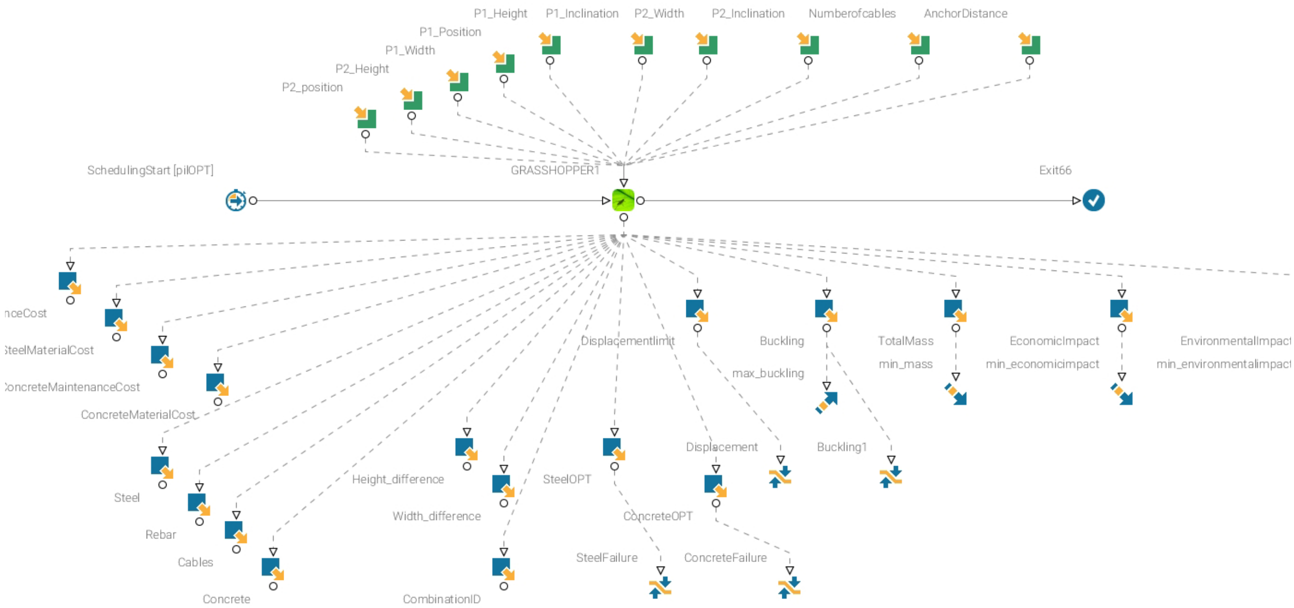


Fig. 83 - *Workflow of the optimisation process*

3.5.1 RESULTS

The number of possible solutions is vast. Given the number of variables considered and the range assigned to them, it was necessary to decide when to stop the optimization process. This choice was made considering satisfactory to double the number of solutions to be evaluated in relation to the number of iterations after which the design solutions already had optimal results.

This strategy led to analyze, for example, 400 solutions for a combination even though it presented optimal results already around the 200 iterations.

The different combinations were identified by an ID as follows:

- ID 1 - Reinforced concrete pylons and steel deck
- ID 2 - Steel pylons and reinforced concrete deck
- ID 3 - Steel pylons and decks
- ID 4 - Reinforced concrete pylons and decks

The Figure 84 shows all the feasible solutions for all combinations in relation to the set objectives (the size of the point identifies the economic impact).

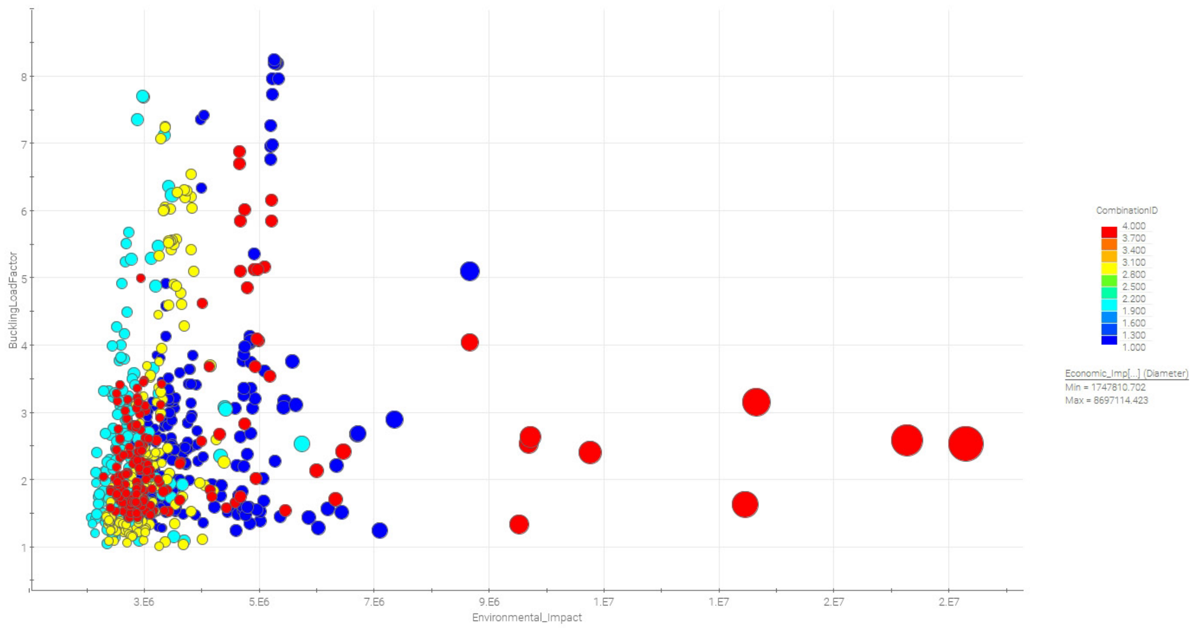


Fig. 84 - *Optimisation results*

It is evident that the economic and environmental impact are the two most closely related to each other; this is even more evident when the influence of the outputs on each other is calculated (Fig. 85)

This behaviour reflects the expectations expressed and as previously stated, the environmental impact will have a higher weight on the choice of the final solution because of its more precise determination.

It is interesting to note that the desire expressed in the draft design phase to prefer that the first arch encountered when approaching the bridge was higher and wider than the second excludes solutions with a high buckling load factor (Fig.86).

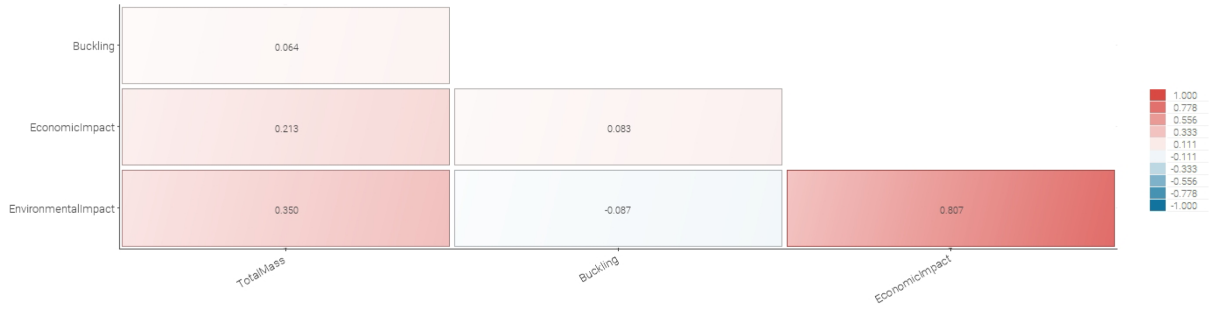


Fig. 85 - *Correlation between outputs*

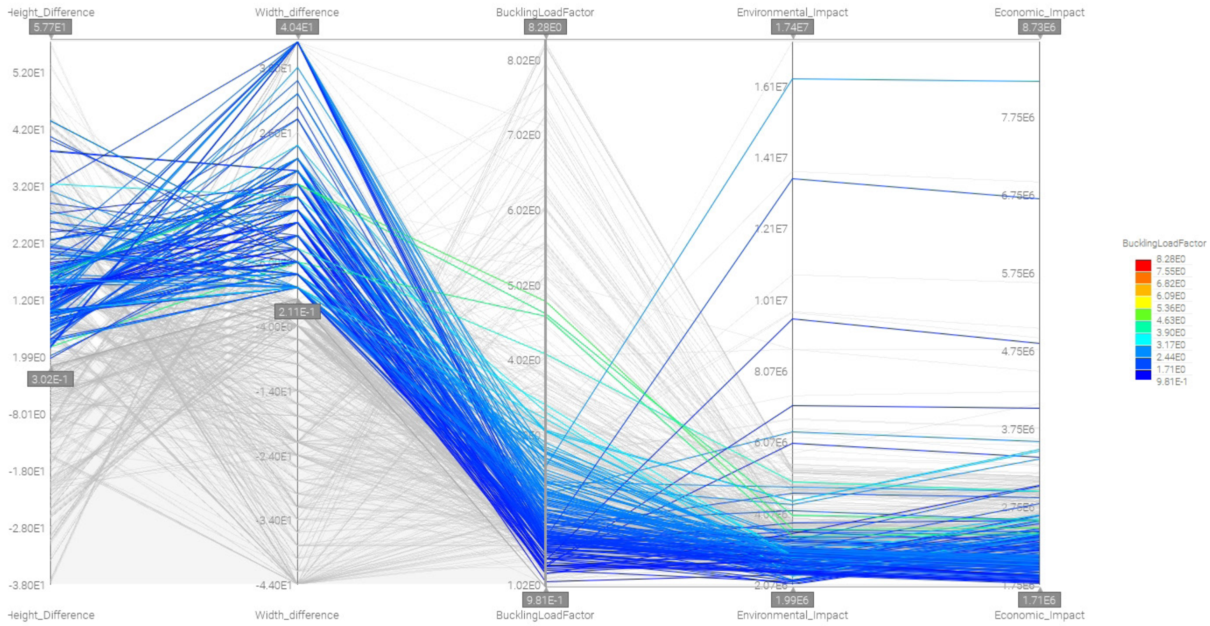


Fig. 86 - *Solutions available in relation to the desire expressed in the draft design phase*

3.6 MULTI-CRITERIA DECISION-MAKING PROCESS

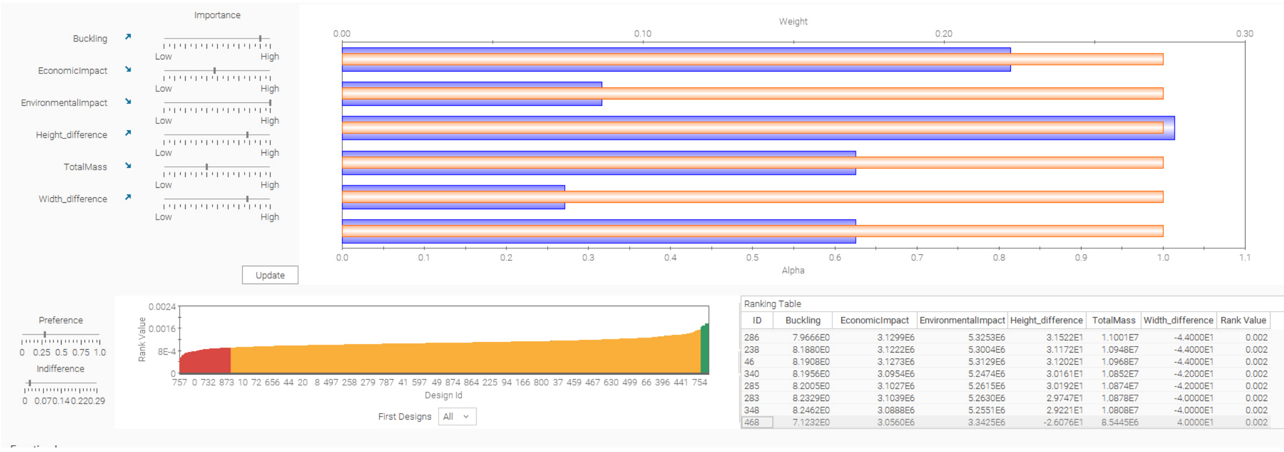
The modeFRONTIER software allows the classification of the results obtained according to the preferences expressed by the designer through multi-criteria decision-making methods.

Among the methods available within the software, AHP was used for its simple but effective approach in classifying the solutions obtained. The method allows the division of the problem of choice into sub-problems and then compares the solutions based on the score obtained for each of them. Different weights are assigned according to the designer's preference.

The values considered for the classification of the solutions, in order of weight assigned, were:

- Minimal environmental impact
- Maximum buckling load factor
- Minimal economic impact
- Maximize the height of the first arch compared to the second
- Maximize the width of the first arch compared to the second
- Minimize the total mass of the structure

In the following figure, the values considered for the classification of the solutions with the relative weight assigned are displayed. The solutions in the table are ranked from the bottom to the top.



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

Fig. 87 - *MCDM results*

Following the ranking obtained, it is noticeable how some of the first solutions are not part of the Pareto front. This outcome is due to the inclusion of factors not initially assigned as objectives, such as the difference in height and width between the two arches.

The conclusions drawn from the ranking obtained are as follows:

- In the first 50 classified designs, no combination with a deck with a steel structure is present.
- The combination with reinforced concrete pillars and reinforced concrete deck occupies the first positions, mainly due to the higher buckling load factor values obtained during the optimization process.
- There are no solutions in the first positions, which consider having the first arch simultaneously higher and wider than the second.

The design chosen as the basis for further design development is number 468, part of the combination that includes steel pylons and reinforced concrete decks. The choice is ranked first altough it does not respect the conditions initially expressed as favored about the greater size of the first arch in both height and width. However the choice has been made because of its performances in regards to the objectives and the possibility to have the first arch wider than the second (Fig.89).

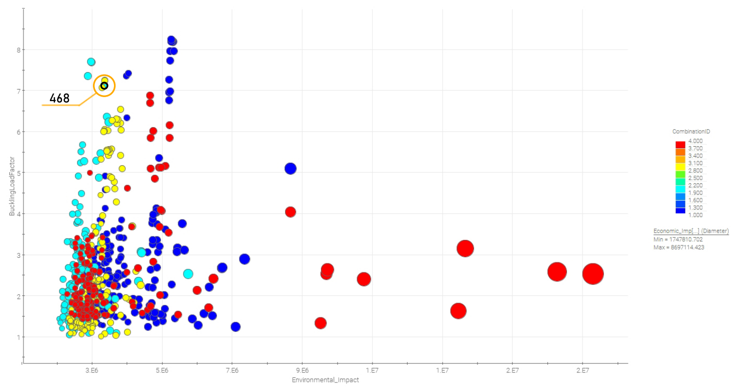


Fig. 88 - *Position of the chosen design in relation to the results obtained*

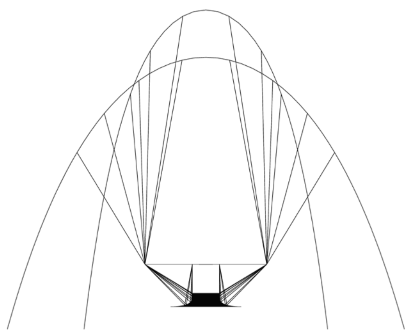


Fig. 89 - *Chosen design*

3.7 FINAL DESIGN DEVELOPMENT

Once the final configuration from which to elaborate the final design was identified, the last step was to refine the design and its graphic representation. Firstly a further optimization process for the shape of the arches was carried out. Moreover, the capacity of the structure to withstand the load models taken into consideration was verified. Finally, the dimensions of some elements have been modified accordingly.

3.7.1 FORM FINDING

The shape of the arches was optimized according to a form-finding process. The Kangaroo plugin for Grasshopper was used for this purpose. The procedure carried out involved the application of the cables' resultant forces to their anchor points on the pylons. The shape obtained was then manually perfected to obtain a smooth curve that favored the uniform transfer of forces to the supports. The final forms obtained were then reinserted within the structural analysis process to obtain the new optimal dimensions of the elements and verify the actual improvements. The results obtained show a general improvement in structural behavior both as regards nominal stresses and concerning the buckling load factor. The environmental impact is reduced by 7% mainly due to a more efficient use of the material in the pylons with a CO_2 emission reduced by 267 tonnes.

Due to the difference in height, width, and disposition of the cables, the final shape of the second arch wasn't considered acceptable on a aestethic point of view leading to a less harmonic relationship between the two pylons.

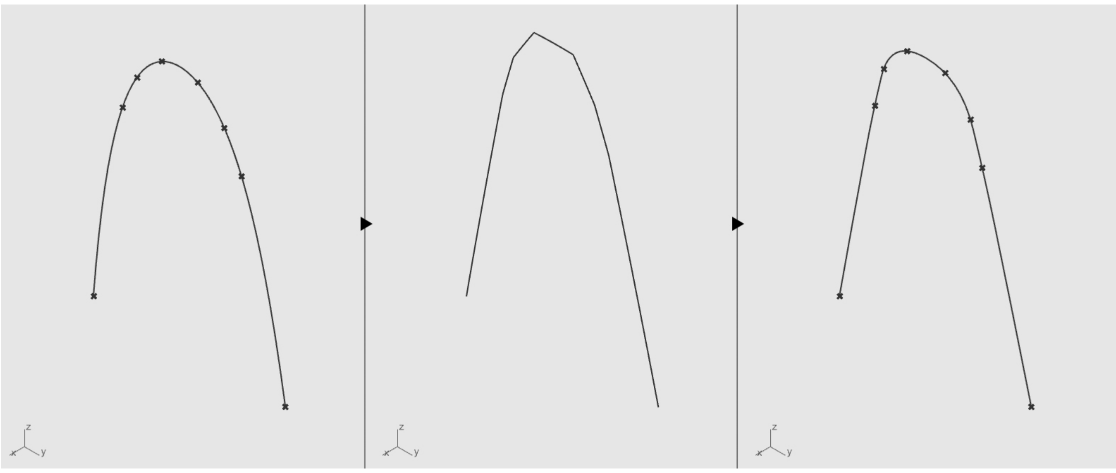


Fig. 90 - *Second pylon's form-finding evolution*

Due to this reason some adjustments were made to the second pylon: the height was reduced and the cables were spaced in such a way to obtain shape that could work in conjuction with the first arch obtaining a more coherent architectural language. In the following images it's shown the appearance of the pylons before the adjustments (Fig.91) and after (Fig.92).

Fig. 91 - *Second pylon's shape after form-finding*

Fig. 92 - *Secon pylon's shape after the adjustments*

3.7.2 STRUCTURAL VERIFICATION

Once the final shape of the entire bridge was defined, the load models required by the regulations were applied for the last structural verification (chapter 2.3). To the uniformly distributed loads, wind load was calculated according to the Italian legislation for the project area which gives a value of 0.87 KN/m^2.

The point loads prescribed by the Eurocode were placed in correspondence with the part of the deck already most stressed following a first analysis.

In the structure analyzed after the first optimization phase, the displacement observed was 24cm, while during the structural verification it reaches 43cm. Due to the asymmetrical nature of the load case considered for the structural verification, it can be seen in the following figures how it produces a torsion in the deck and the pylons compared to the deformation resulting from the first optimization. For better visualization, the deformations have been multiplied by 50.

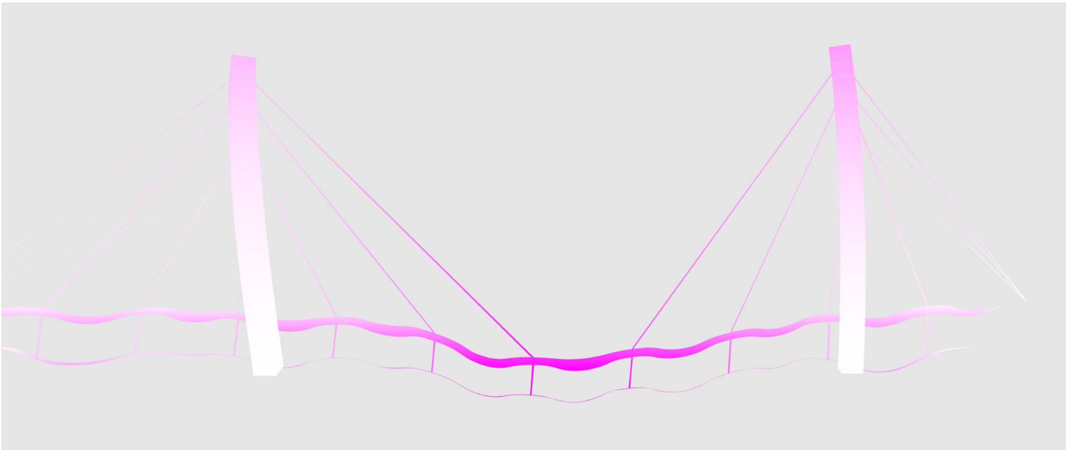


Fig. 93 - *Deformation after first optimisation*

Fig. 94 - *Deformation after structural verification*

Due to the cross-section assigned before hand to the pylons for aestethic purposes, with smaller dimensions towards the top of the arches, assigning a constant thickness would lead to an extreme utilization of the material in those smaller areas (Fig.95). The thickness was then optimise in order to have more material where needed in an effective way, leading to a more distributed utilization. (Fig.96).

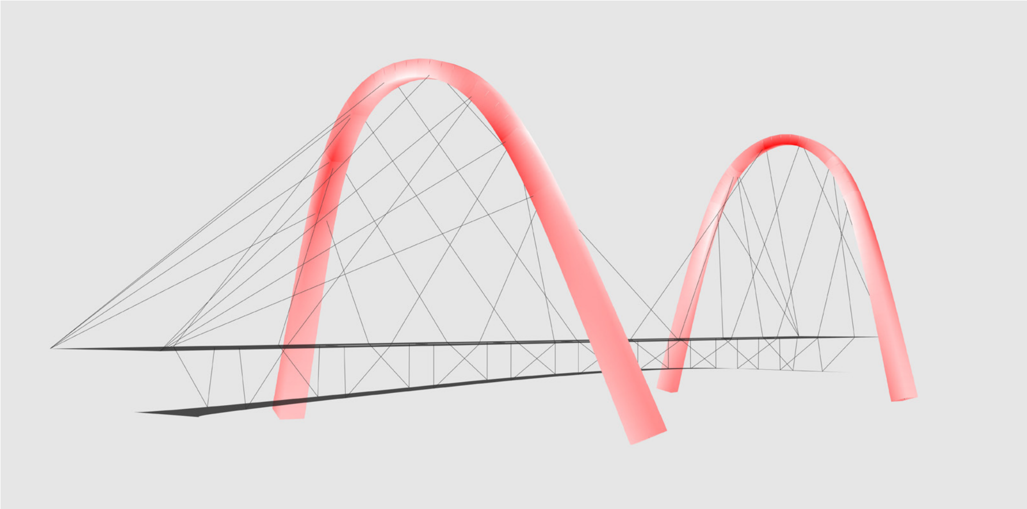


Fig. 95 - *Material utilization with constant cross-section thickness*

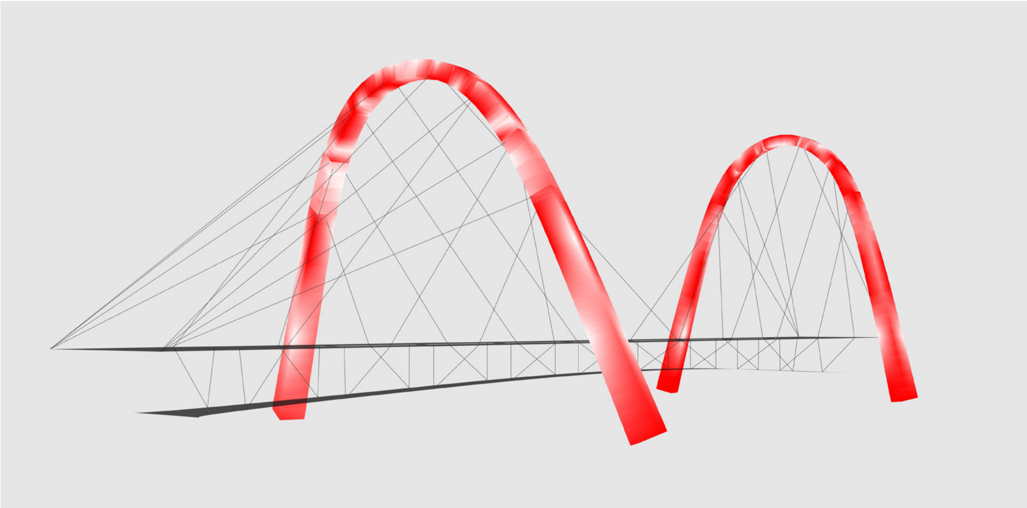


Fig. 96 - *Material utilization with optimised cross-section thickness*

The main problem encountered following the structural verification was the progression of the stresses acting on the structure almost to the strength limits of the material. In particular, in the pylons there were peaks reaching 90% of the material's strength.

This behavior was expected because of the strategy used for the first optimization phase. A final dimensioning process of the individual elements was carried out by assigning a lower percentage of use of the material within the first optimization phase. The thicknesses of the cross-sections was gradually increased where necessary to stay below the 70% utilization of the material in regards of its yield strength.

The final configuration present a displacement of 41cm and a Buckling Load Factor of 6.9, while all the concrete and steel elements are dimensioned to stay below the 70% of their utilization.

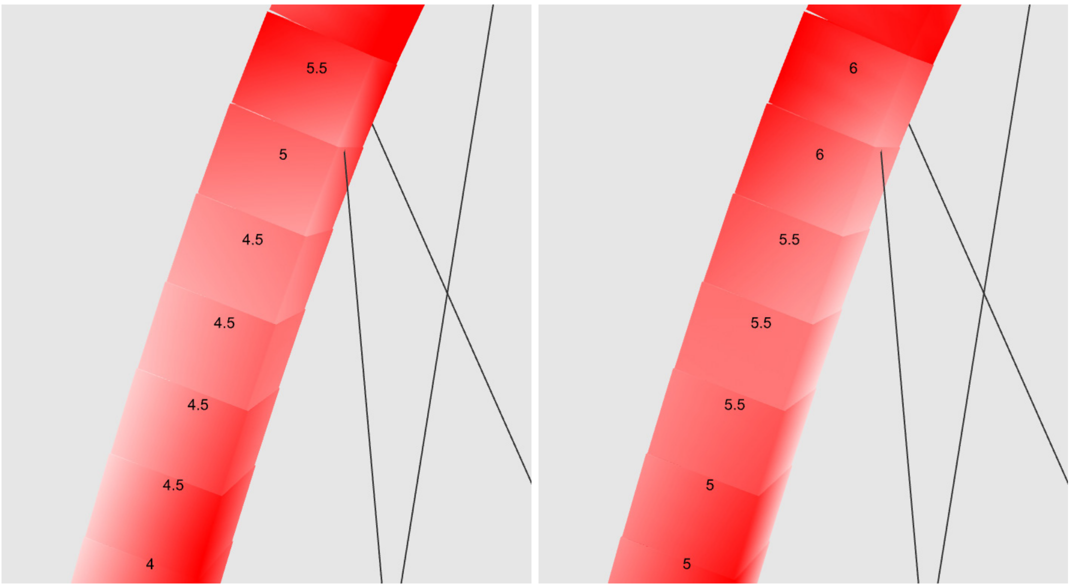


Fig. 97 - *Increment of cross-sections thickness to reach 70% material utilization*

3.7.3 DETAILING AND GRAPHIC REPRESENTATION

The last step taken was to represent the project graphically. During this phase the meshes calculated and given as output from Karamba were translated in surfaces and solids in Rhinoceros. As in the case of the form-finding carried out with Kangaroo, some surfaces and elements were slightly softened according to the desired architectural appearance, never going below the thicknesses considered necessary following the structural analysis. The minimum dimensions necessary for the part most subject to stress have been applied to the rest of the sections of the decks for greater safety. The decision was taken considering that during the structural verification, only the load-case prescribed by the code was analyzed and not any extraordinary situations. More recommendations and considerations in this regard are present in the chapter 3.9.1. During the finalization of the design, the structure's most sensitive connections were also detailed to allow the flow of the stresses through the elements, especially the main cables and the secondary cables below the main deck.

In the following figure an overview of the bridge is given to introduce the final design appearance and make more clear the following description of its parts and details.

Fig. 98 - *View of the bridge approaching from South (airport)*

Pylons

The foundamental role of the pylons is to transfer the tensile forces from the main cables to the foundations. The shape of the pylons, inclination and dimensions were retrieved according to the optimisation process and dimensioned taking into consideration both the structural performance required and the desired architectural language. The square cross-section made out of steel wants to recall the rationalist architecture of the nearby E.U.R. district while at the same time differentiate from its history linked to the fascist era by the use of a modern material such as steel. The colour chosen for the painting is a warm white to partially recall the effect the sunlight has on the nearby buildings made out of stone and travertine.

The main compressive forces are carried by the pylons themselves, while the supports at the edges of the bridge and the incoming roads counter the tensile forces exercited by the back cables.

The pylon is anchored to the concrete pile foundations using anchor bolts throughout the entirety of the pylon's perimeter. The concrete pile foundation present a flat surface on top for both easier realization and inspection, while the sides are sloped for aesthetic purposes but also to allow a better flow of forces and avoid accumulation of water. In the following figure it's also shown how stairs for maintenance and inspection are present in the pylon and how the different sections are connected to eachother by an edge weld on the inside and a butt weld on the outside.

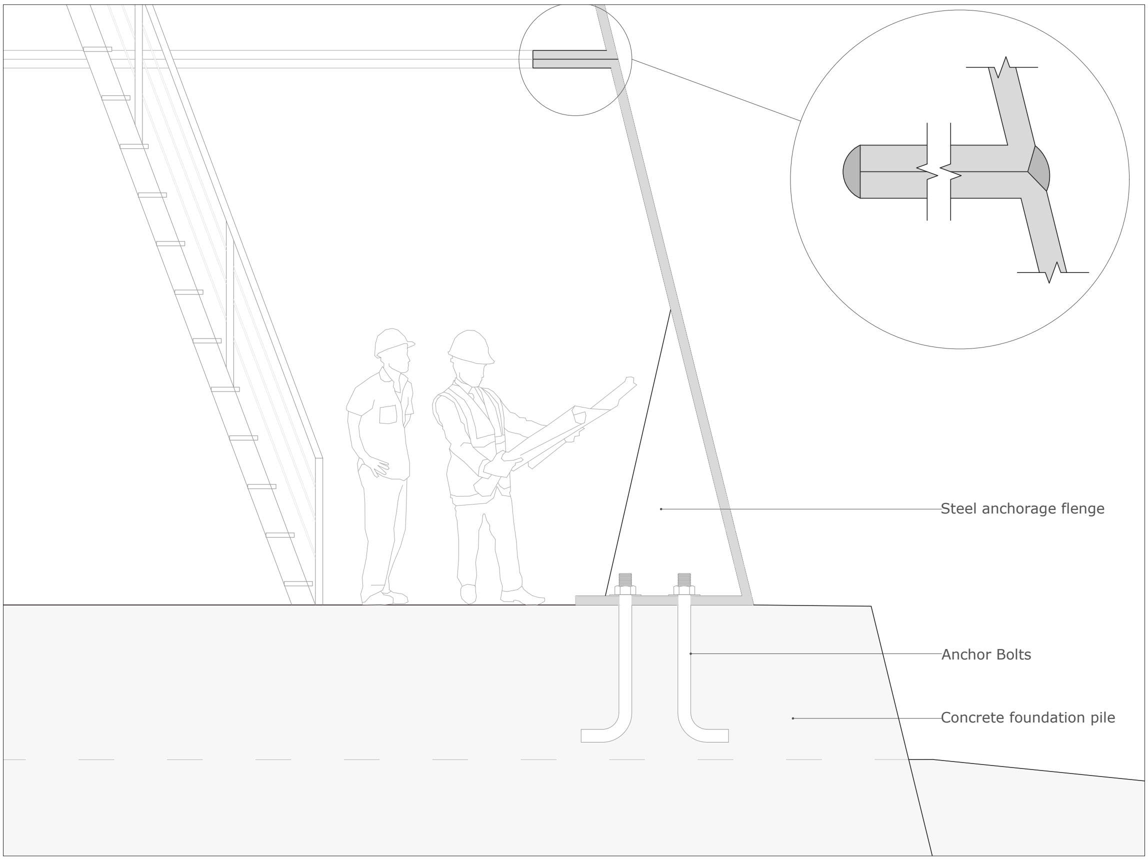


Fig. 99 - *Anchorage of the pylon to the concrete pile foundation*

For what concern the anchors of the cables on the pylon, the intention was to place all the connections inside the pylon to have a more clean and smooth surface on the outside. The cables end in a VSL system attached to steel elements that transfer the forces to two steel plates positioned at their end. The plates allow for a better distribution of the forces and help stiffening the entire cross-section. The space between them and the holes cut in the middle allow the access for maintenance and inspection.

In the following figure is also shown how the corner joint of the steel plates forming the cross-sections are realized. The corners of the pylon are welded to eachother taking into account the need of one plate to overstep the other, both for easier realization and to avoid accumulation of water.

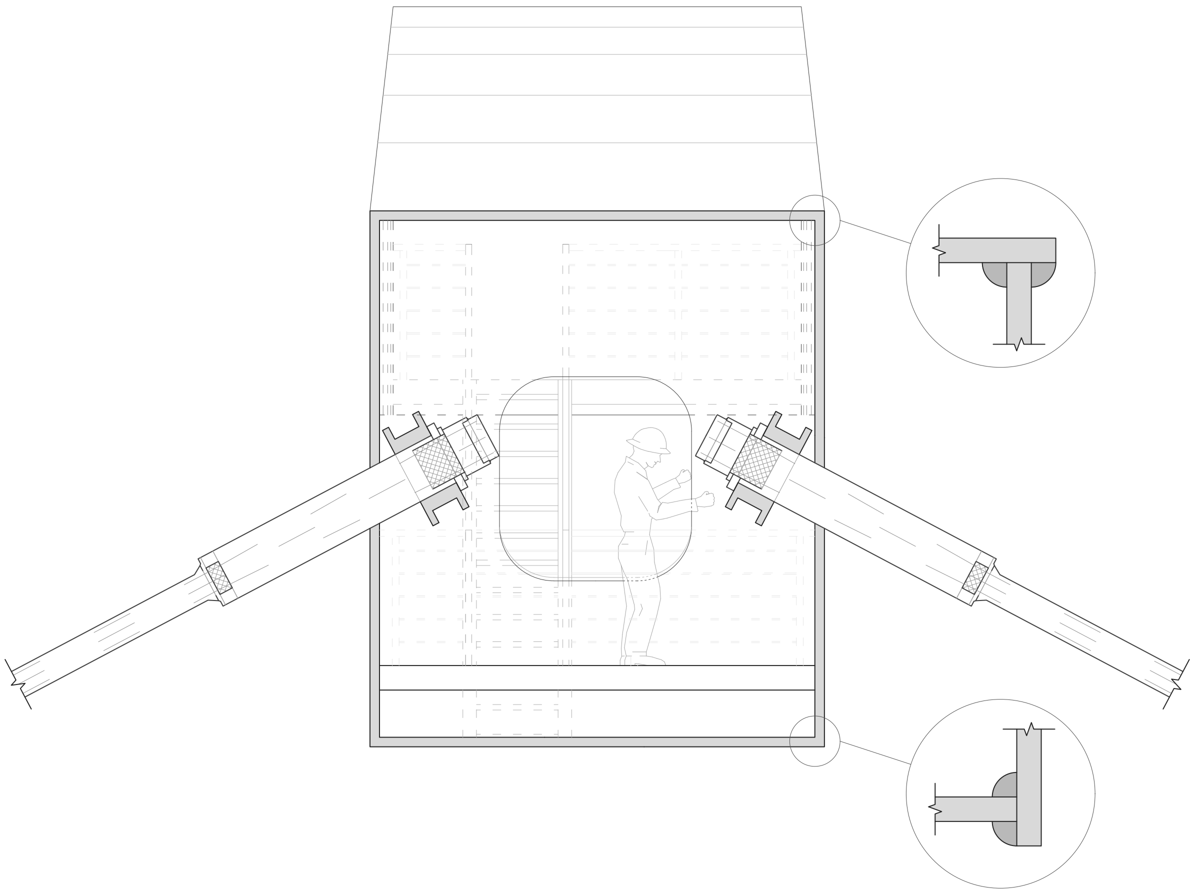


Fig. 100 - *Cables anchor on pylon*

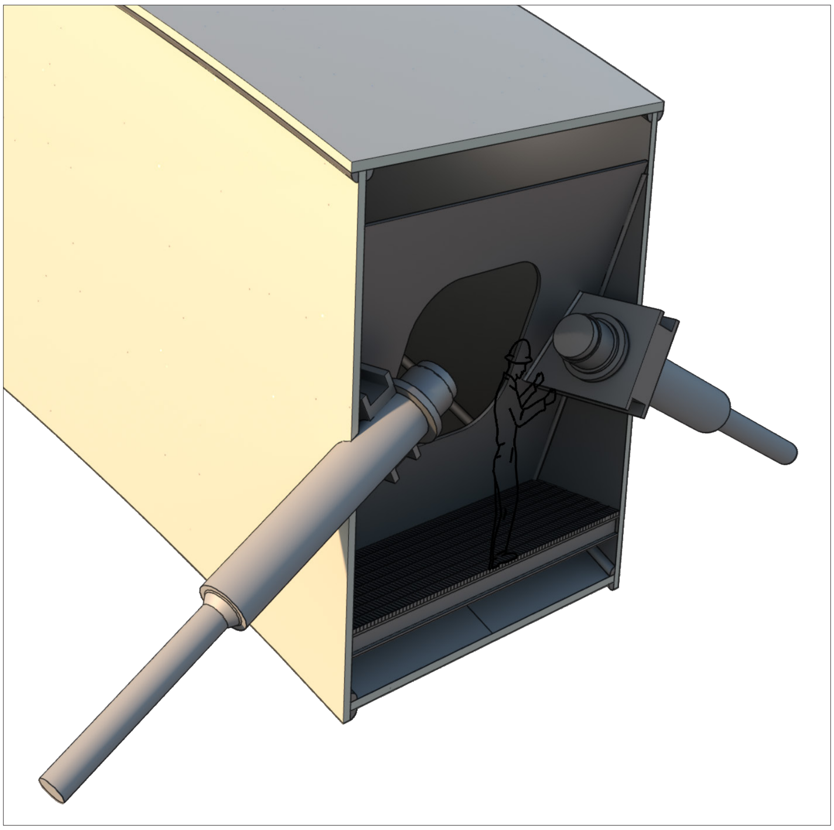


Fig. 101 - *3D view of the cables anchor on the pylon*

Decks

The two concrete decks are shaped according to the results of the optimisation carried out during this research aiming for an effective use of the material. Considering the structural system used, the shape and thickness of the decks reflects the amount of stress in the cross-section for each specific part. A greater thickness is needed along the edges and in particular where the cables are anchored, where the peak stresses can be found. The upper decks has to withstand mainly compression and the footbridge deck below mainly tension due to its role of transfering the forces from the vertical supports to the slented steel rods. The presence of tension in the footbridge deck lead to a more consistent thickness because of the concrete mechanical proprieties and its weakness in resist tension. In the Figure 102 it's shown a simplification of the bending moment and the main compressive and tensile forces acting on the vertical supports, cables and steel rods while in Figure 103 a transversal section of the bridge shows what are their dimensions in correspondance of the main supports and the relation with the car and pedestrian traffic flows.

The nature of the decks surface was also smoothened and designed having in mind the added value it would have bring on the footbridge, creating a wavy surface almost recalling the river below (Fig.104).

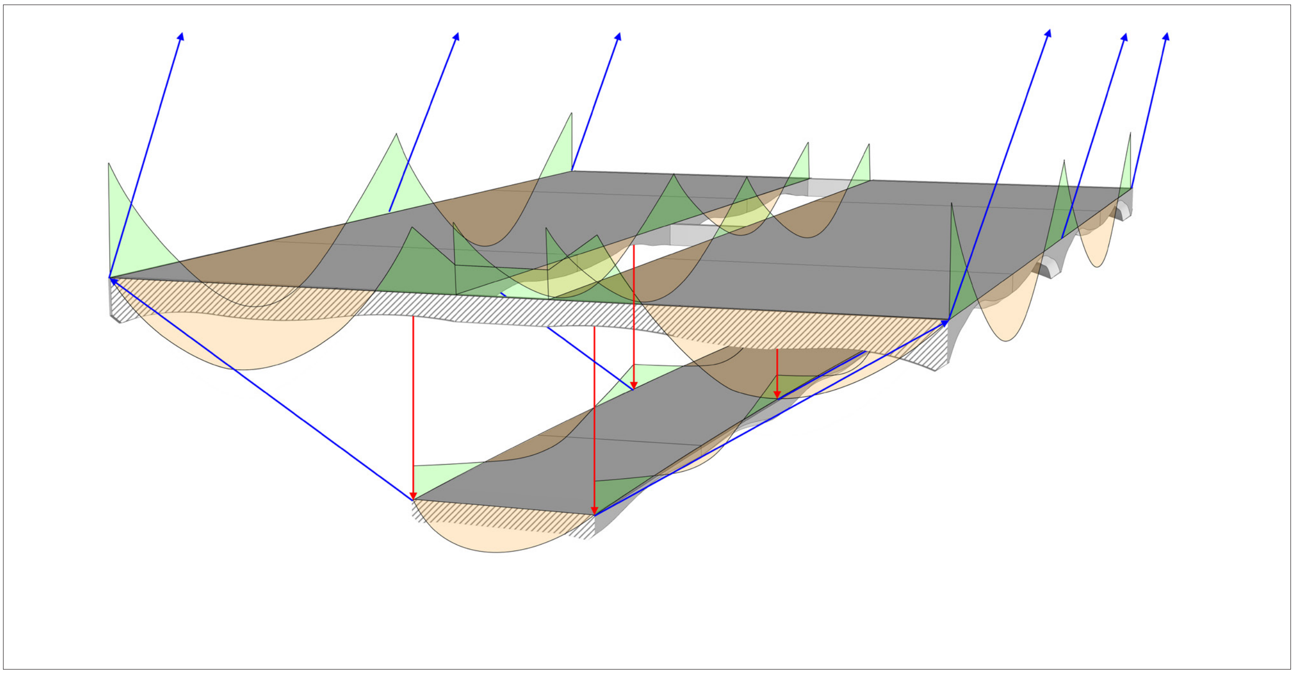


Fig. 102 - *Simplification of bending moment and main forces acting on the decks*

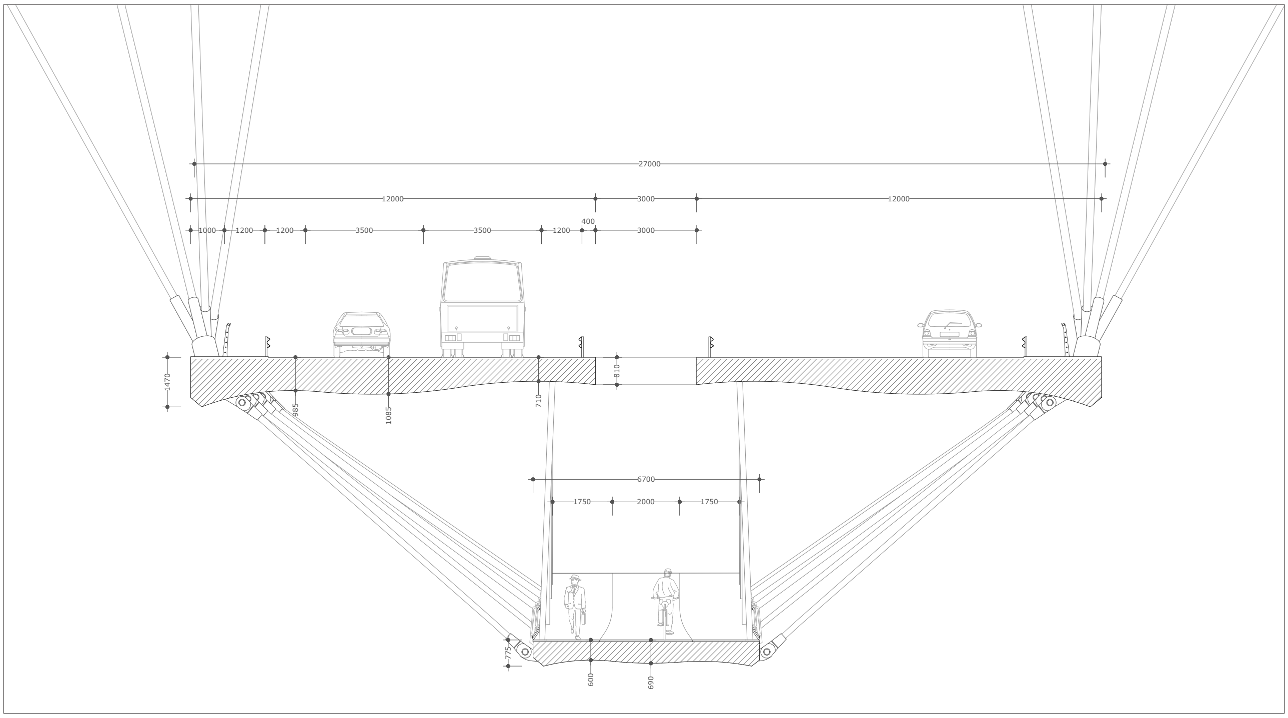


Fig. 103 - *Transversal section on bridge*

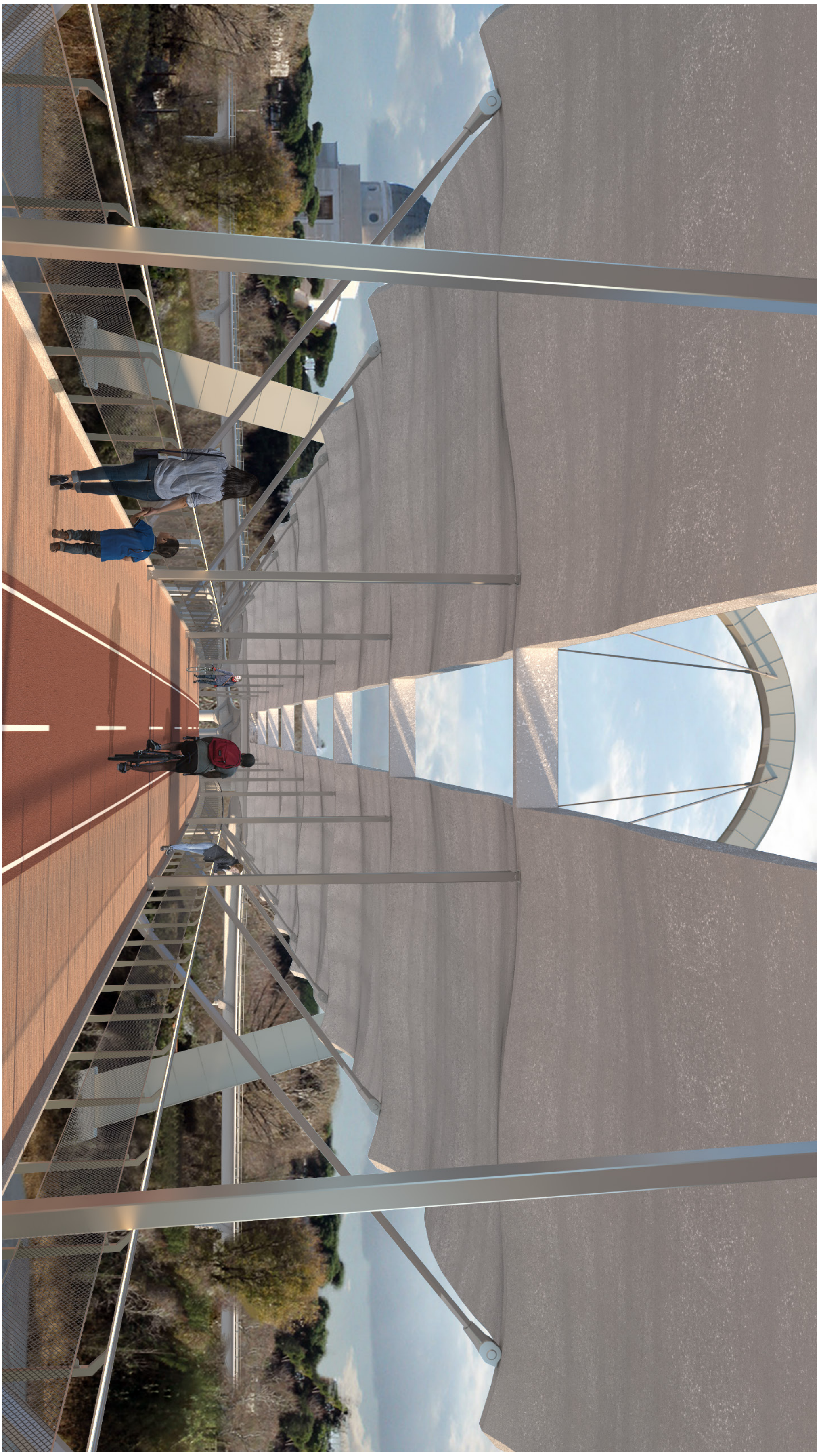


Fig. 104 - *View from the footbridge*

Building Sequence

A building sequence is hereby proposed to make for a feasible design. First the foot of the pylons with their foundations and the supports for the roads approaching the bridge will be placed casting in situ the concrete. The decks of the roads will then be placed towards the bridge, a temporary substructure can be used being above land. The next step would be the construction of the pylon starting from its foundation. The main span will then be built, placing each upper deck segment and temporary hold in place through the use of cranes till the below footbridge segment is connected with it since they structurally work in conjuction, before proceding with the next segment.

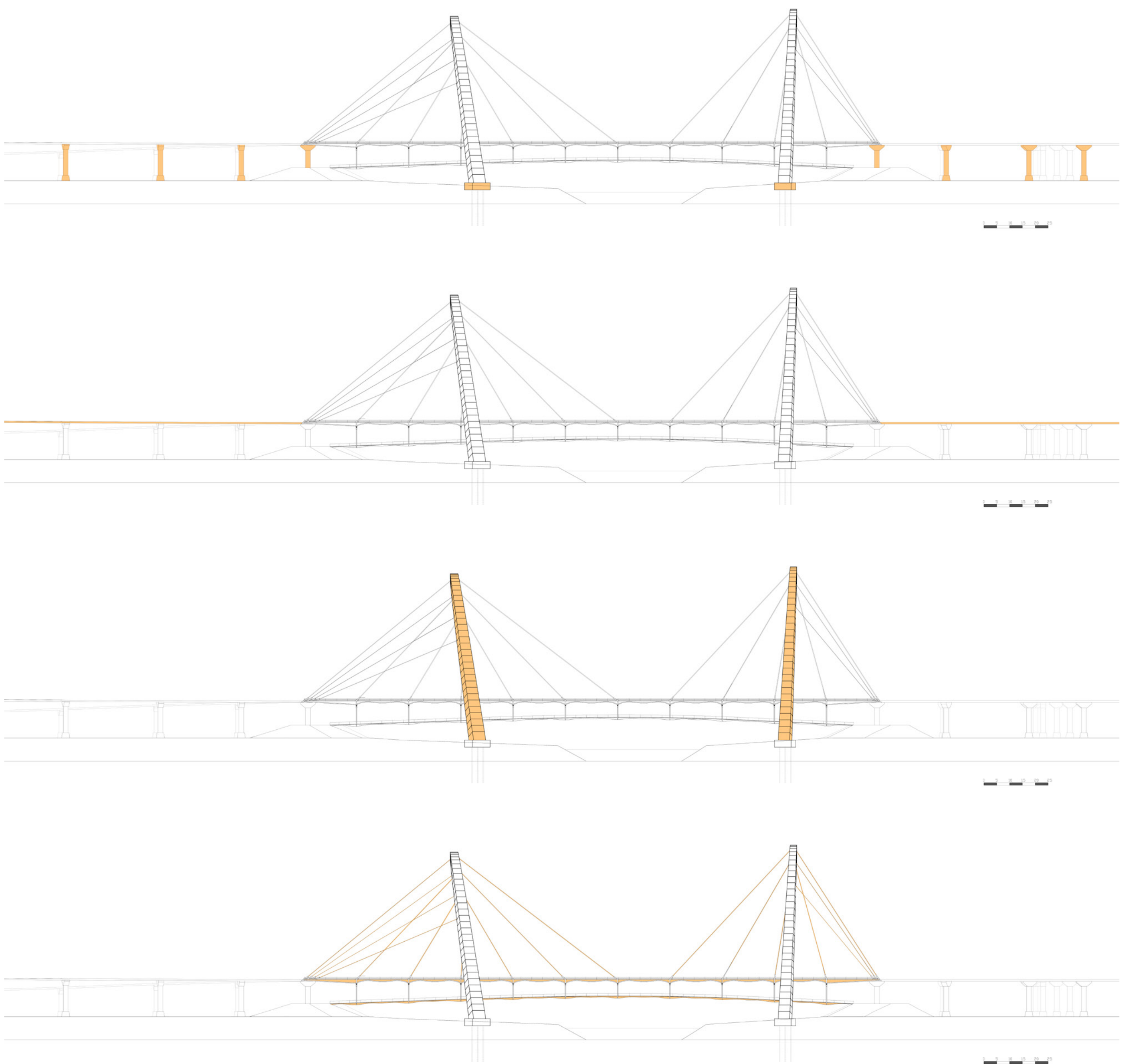


Fig. 105 - *Proposed building sequence*

Main deck segments

The main deck segments will be lifted and held into place. While in place, the prefabricated decks will be connected to the previous adjacent ones casting in place the grout connection (Fig.106).

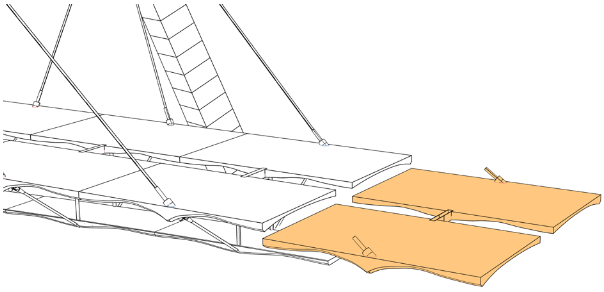


Fig. 106 - *The main deck segments are lifted in place*

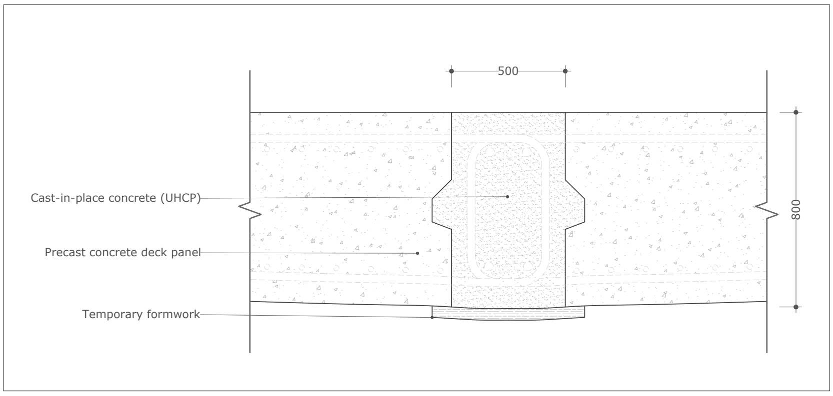


Fig. 107 - *Connection between adjacent deck segments*

Connection beam

While holding in place the deck segments with a temporary structure, the beam connecting the two decks of the main bridge will then be cast in situ.

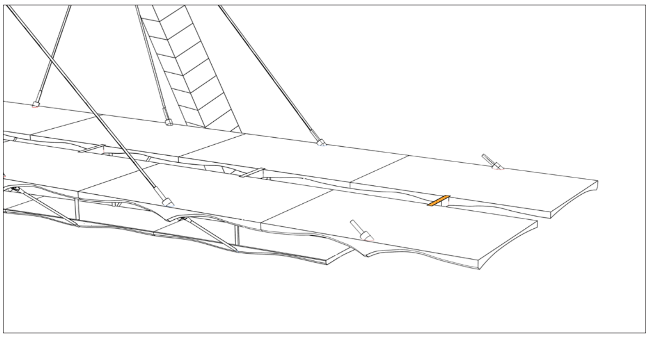


Fig. 108 - *Grout connection between deck segments*

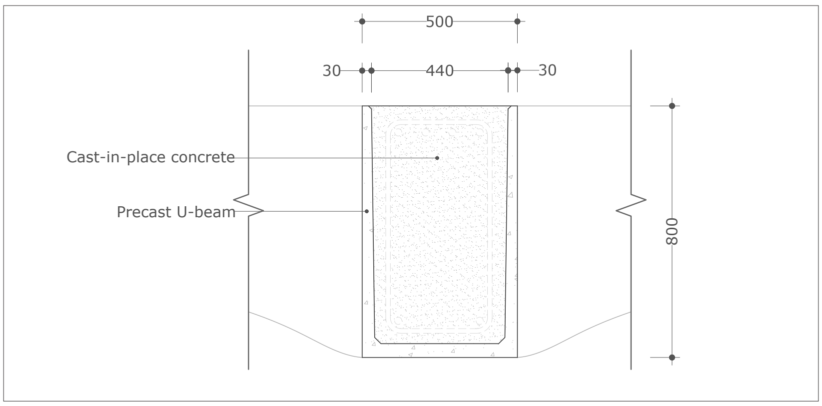


Fig. 109 - *Transversal section of the connection beam*

Cables anchorage

The deck segments will be then connected to the pylon by the main supporting cables. The anchorage system is embedded and precast in the prefabricated deck segment.

To allow for a proper flow of the forces between the main cables and the steel rods that will be connected to the footbridge, a precast steel plate is present. The steel plate is perforated to allow for extra rebar elements to go through and account for the tensile forces from one cable to the other. In the next detail is shown the anchorage system of the main cables and the steel rods.

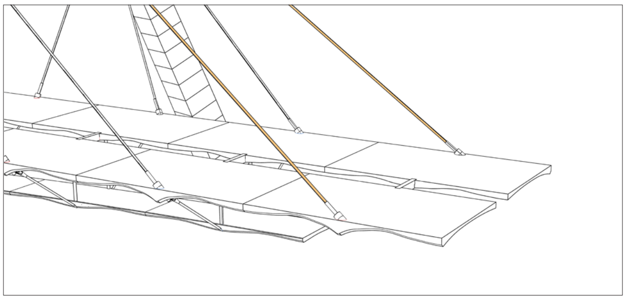


Fig. 110 - *The cables are anchored to the main deck*

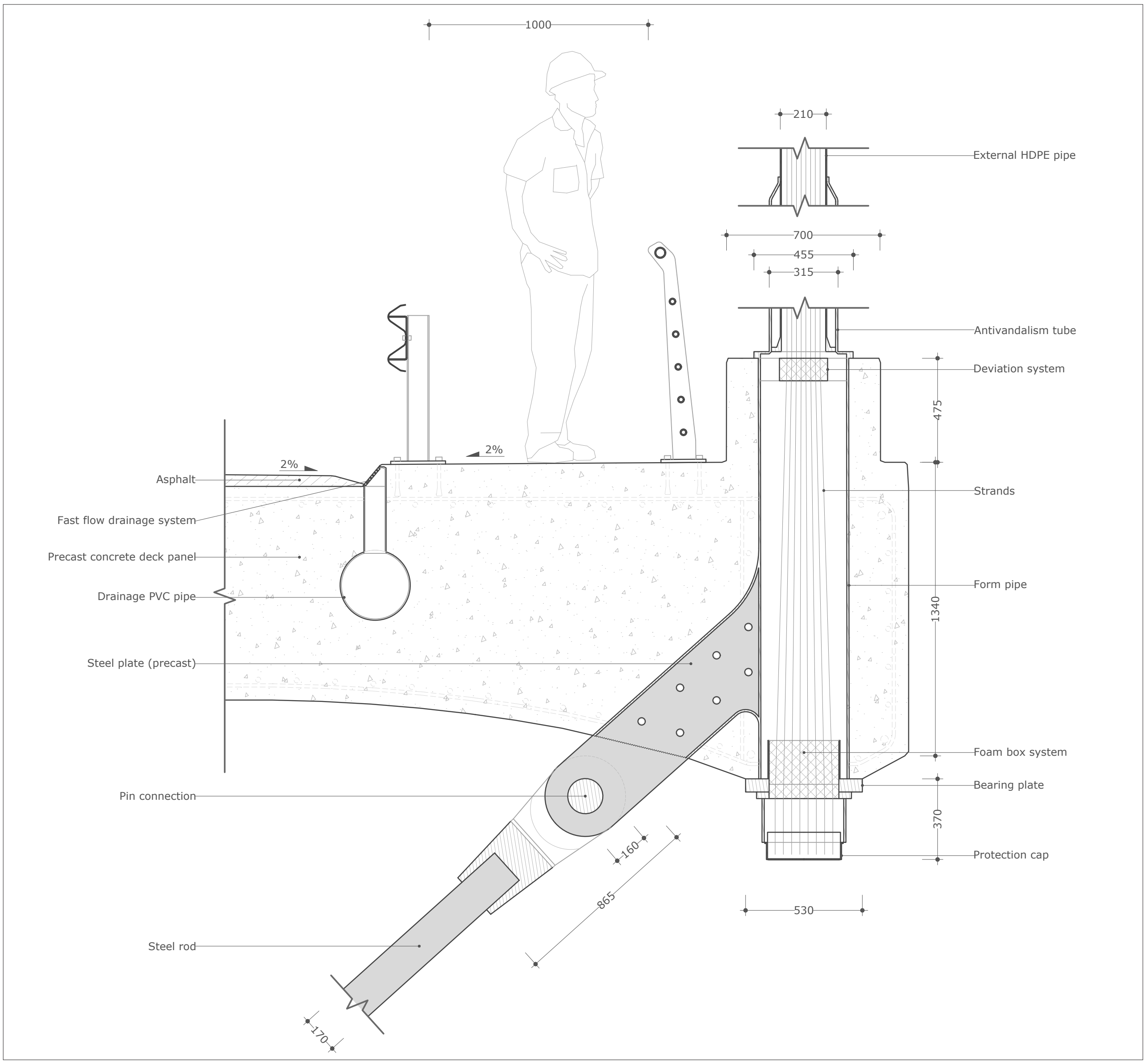


Fig. 111 - *Detail of main cables anchorage*

Footbridge

The last step needed in order to be able and continue the building sequence with the next span, the footbridge deck segment will be lifted and held in place to connect it with the adjacent one. The vertical supports and steel rods are then connected using the anchorage precast within the concrete deck. The two connection have a hinge behaviour thanks to the pin connection on the vertical supports and the fork connection of the steel rods. Due to the relatevely high tensile stresses acting on the concrete deck, a perforated steel plate is embedded in the concrete and runs through the width of the deck not only allowing for the forces to flow from the vertical supports to the steel rods and to compensate for the tension forces in the deck.

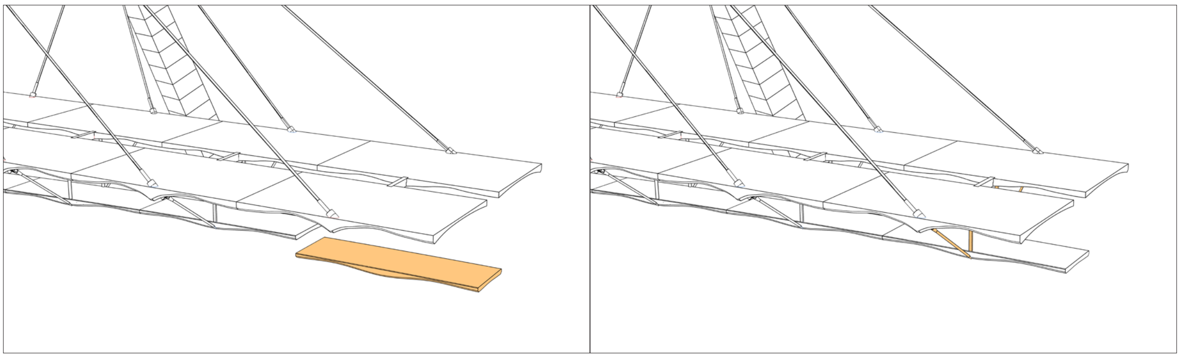


Fig. 112 - *Footbridge deck segment and secondary supports sequence*

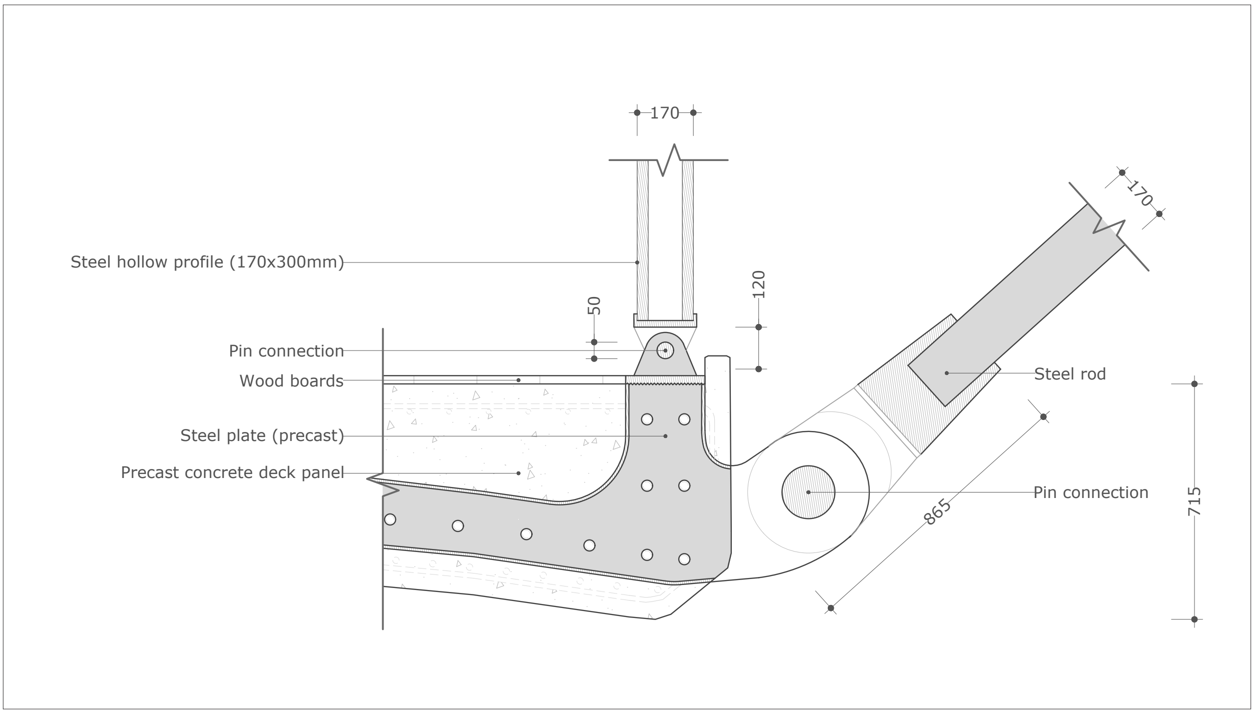


Fig. 113 - *Vertical support and steel rod anchorage to the footbridge*

Footbridge railing

After the entire structure has been built the railings can be mounted in place. The steel railings are connected to the side of the footbridge deck and the handrail runs on the outside of the vertical supports to maximize the usable space for the pedestrians. Two steel cables run along the railing keeping in place a metal net. The lightning of the footbridge is guaranteed by a LED strip placed within the handrail.

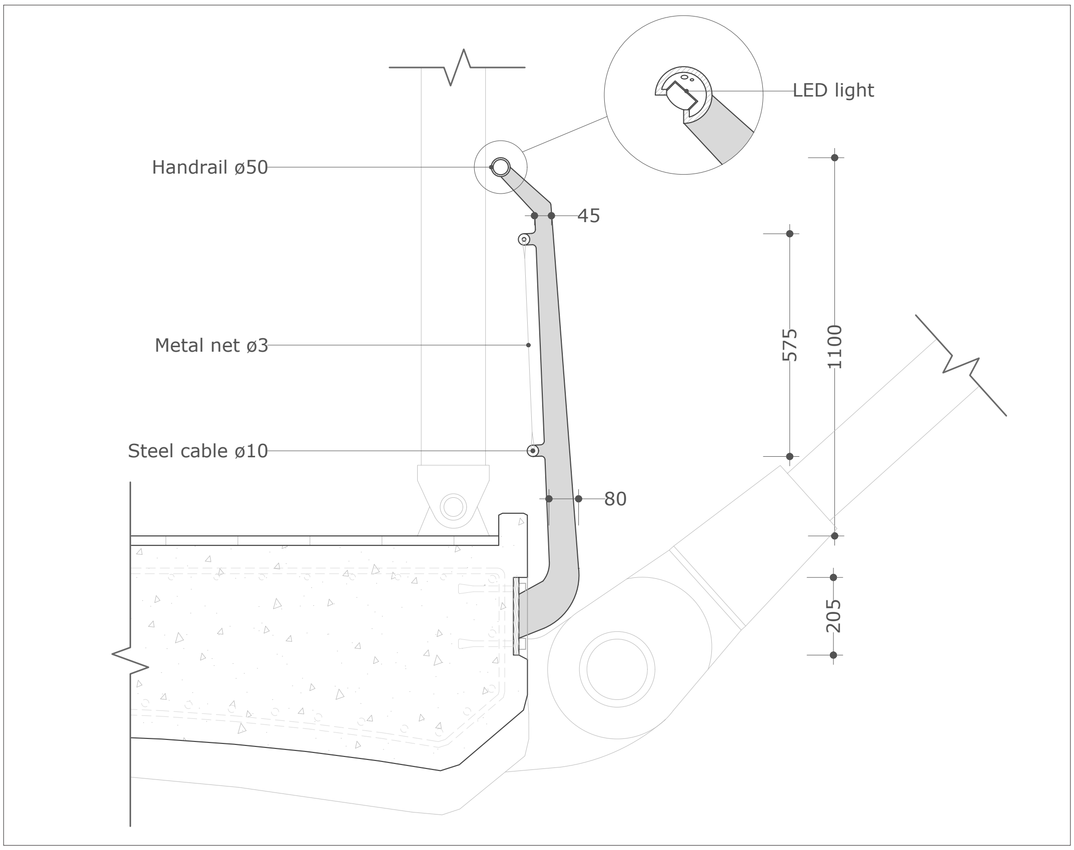


Fig. 114 - *Footbridge railing detail*

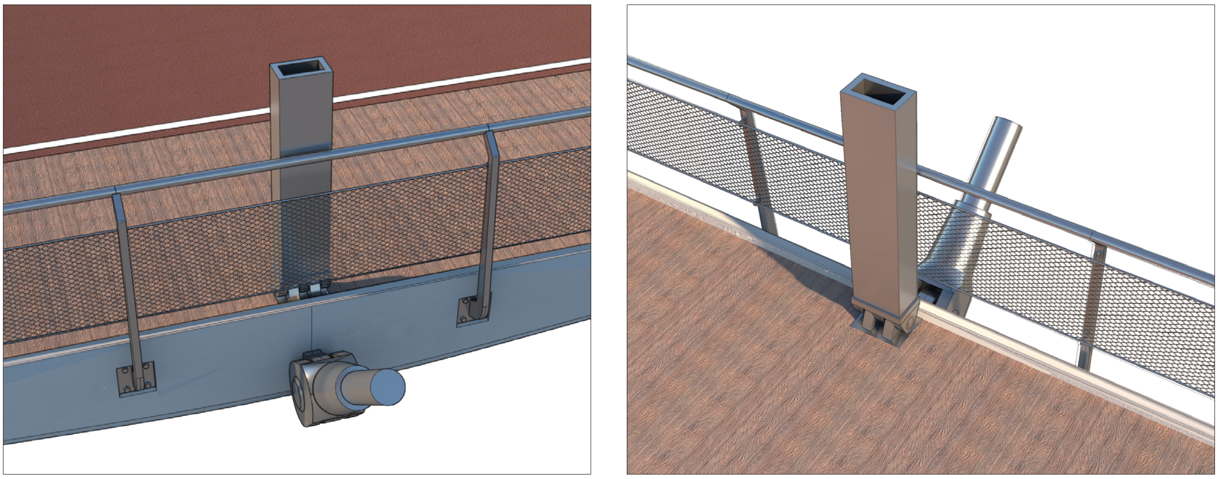


Fig. 115 - *3D models of the footbridge parapet and supports*

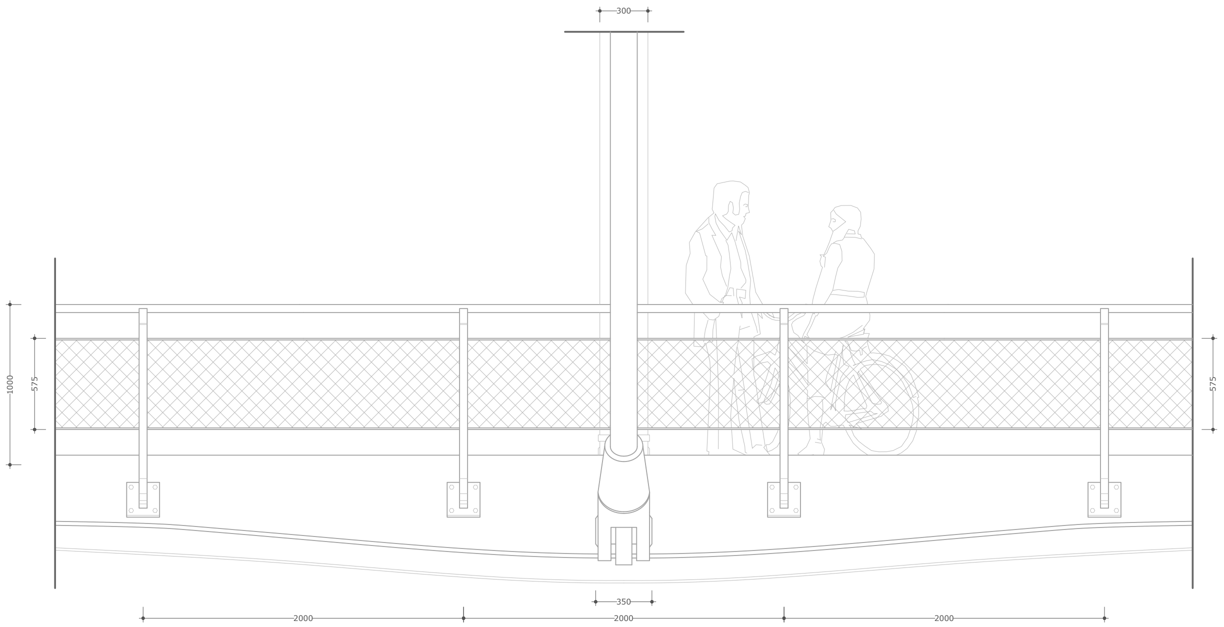


Fig. 116 - *Footbridge railing*

Water drainage

The system used to account for the water drainage on the bridge follows two different strategies.

For the upper deck, dedicated to vehicular traffic, the polluted water is directed towards the edge of the walkways and collected through a fastflow drainage system to PVC pipes embedded in the concrete deck segments (Fig.111).

For what concern the footbridge the water is collected below the porous concrete used for the bike-lanes and directed directly into the river.

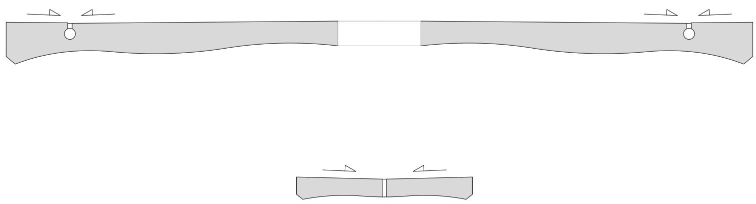


Fig. 117 - *General scheme of the adopted water drainage strategies*

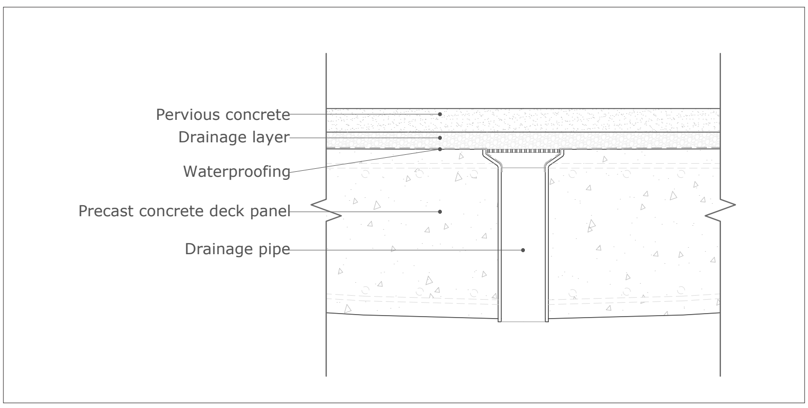


Fig. 118 - *Water drainage on the footbridge*

4 FINAL DESIGN

Hereby the main drawings and 3D impressions of the final design are presented.

Fig. 119 - *View of the bridge Approaching it from West*

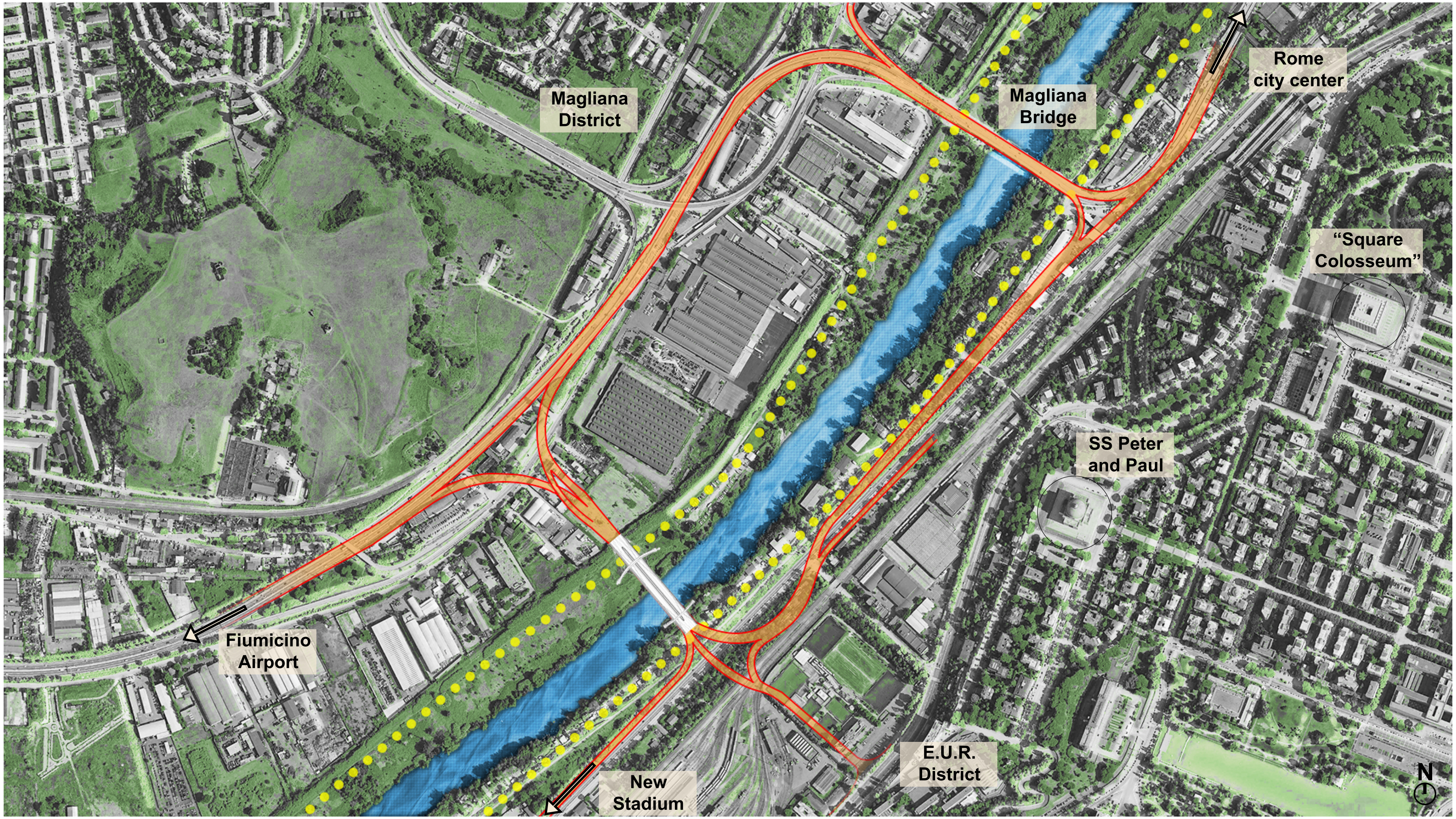


Fig. 120 - *Road system and context*

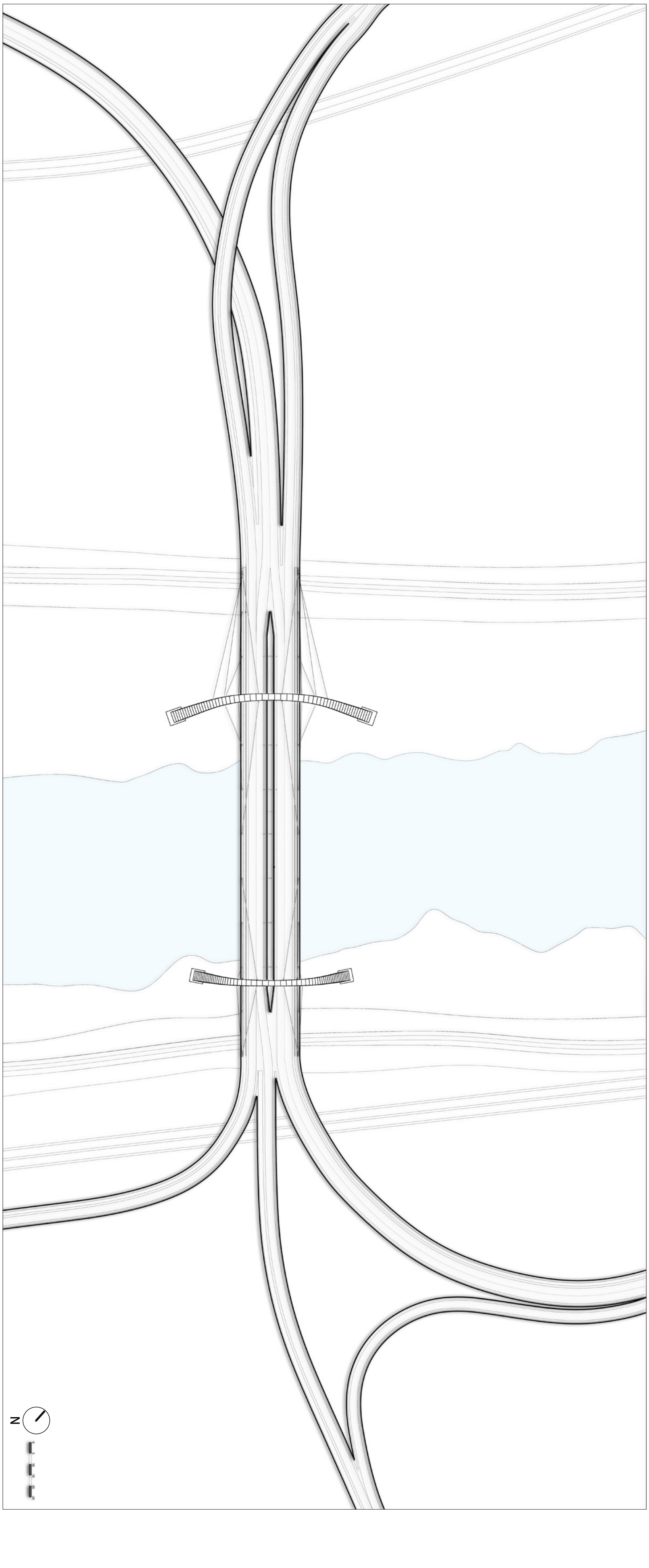


Fig. 121 - *Topview*

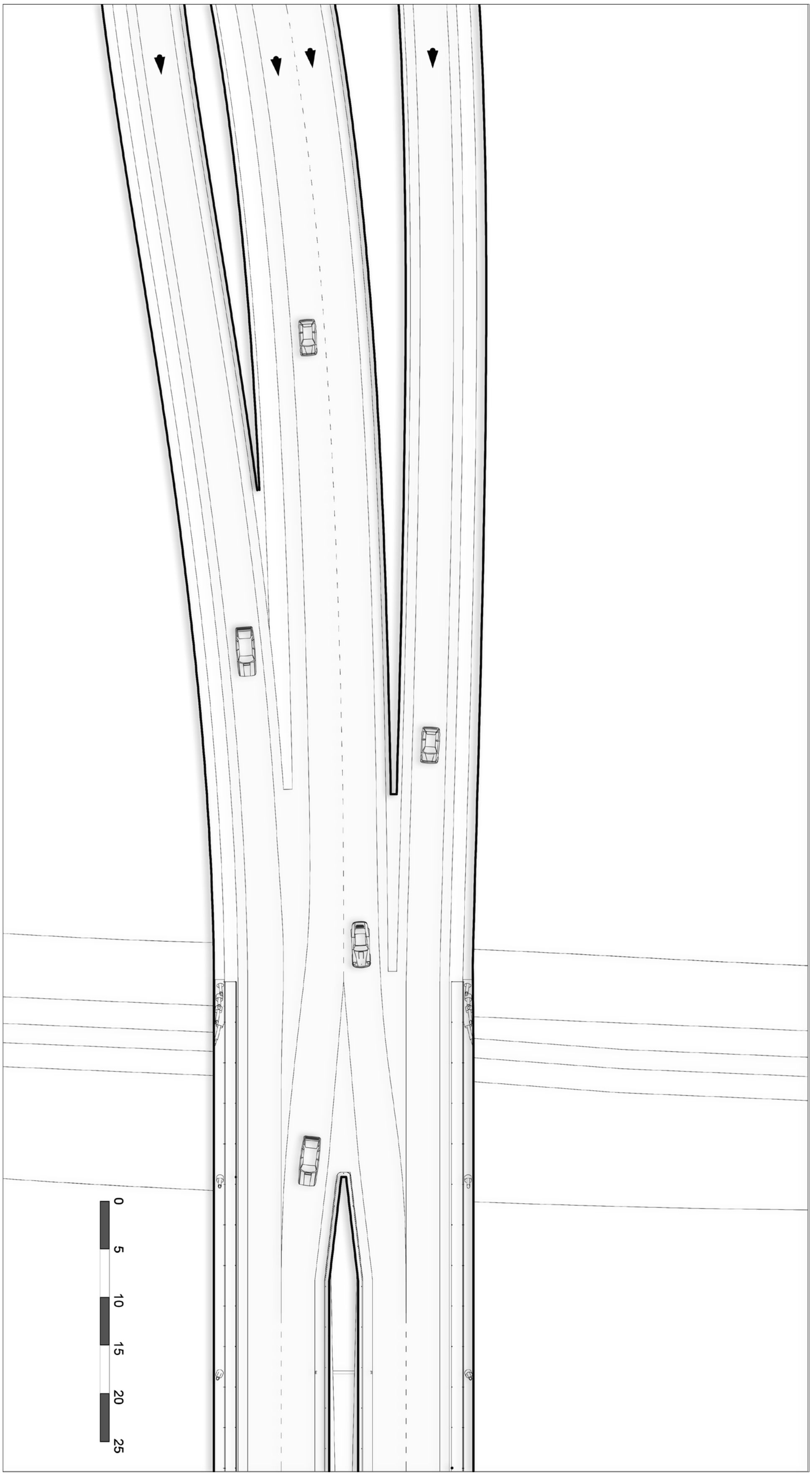


Fig. 122 - *Plan view bridge access*

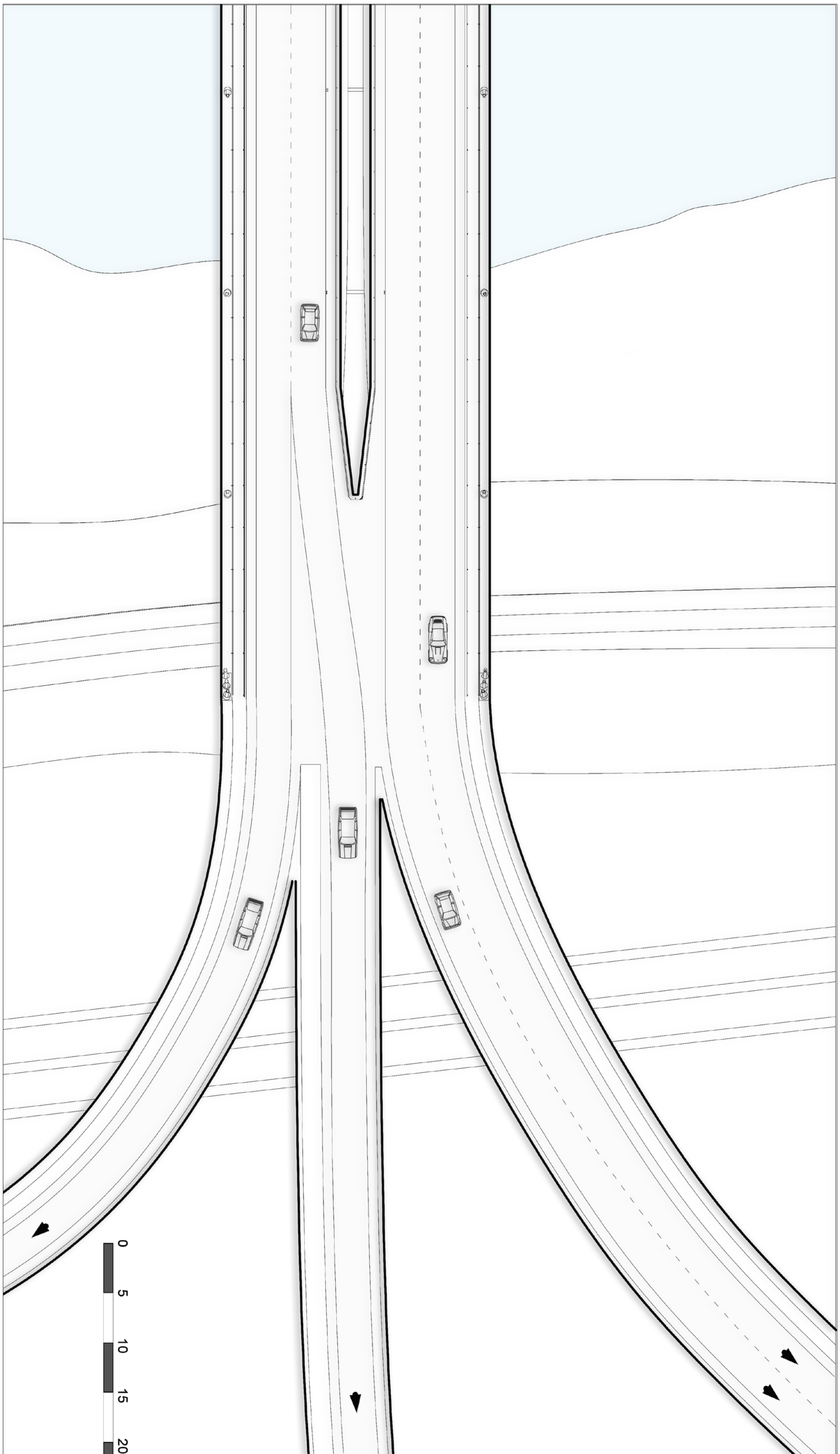


Fig. 123 - *Plan view bridge exit*

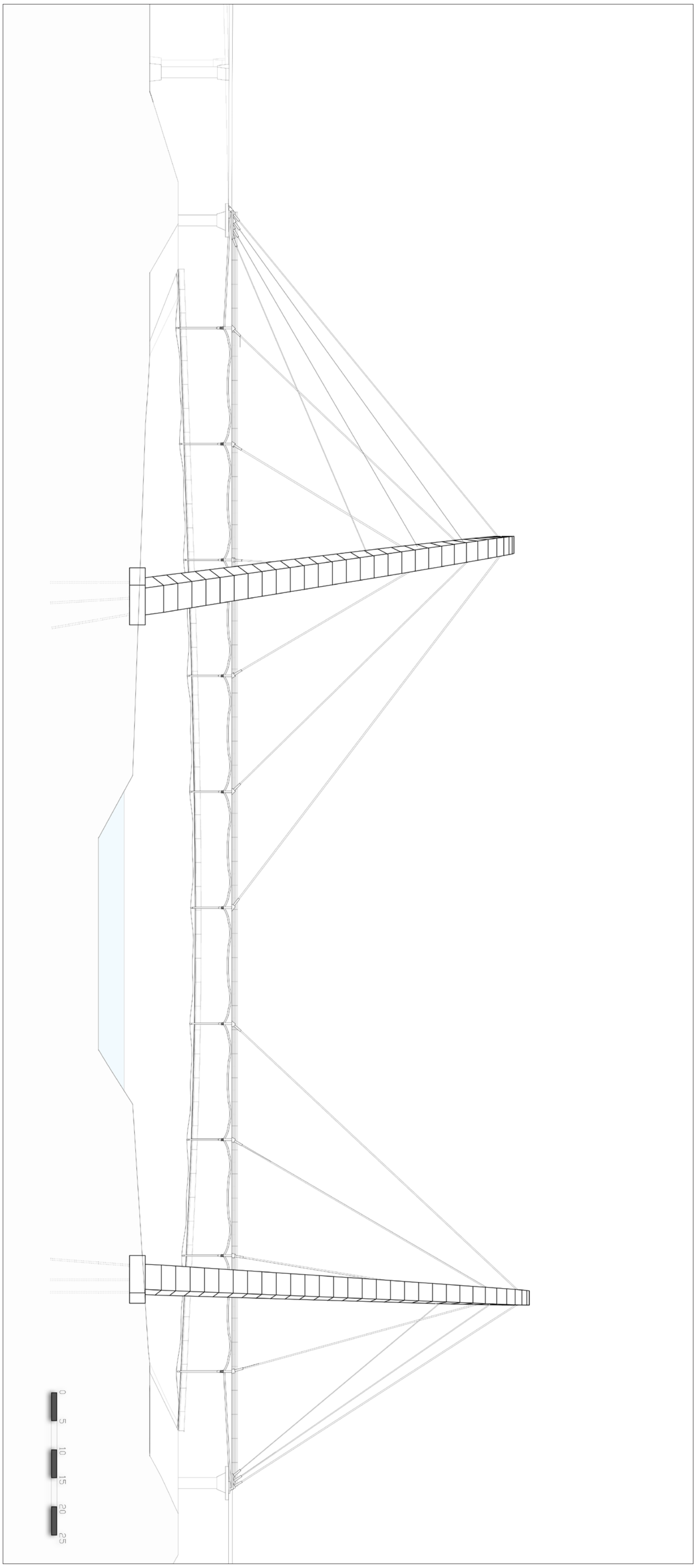


Fig. 124 - *South-East elevation*

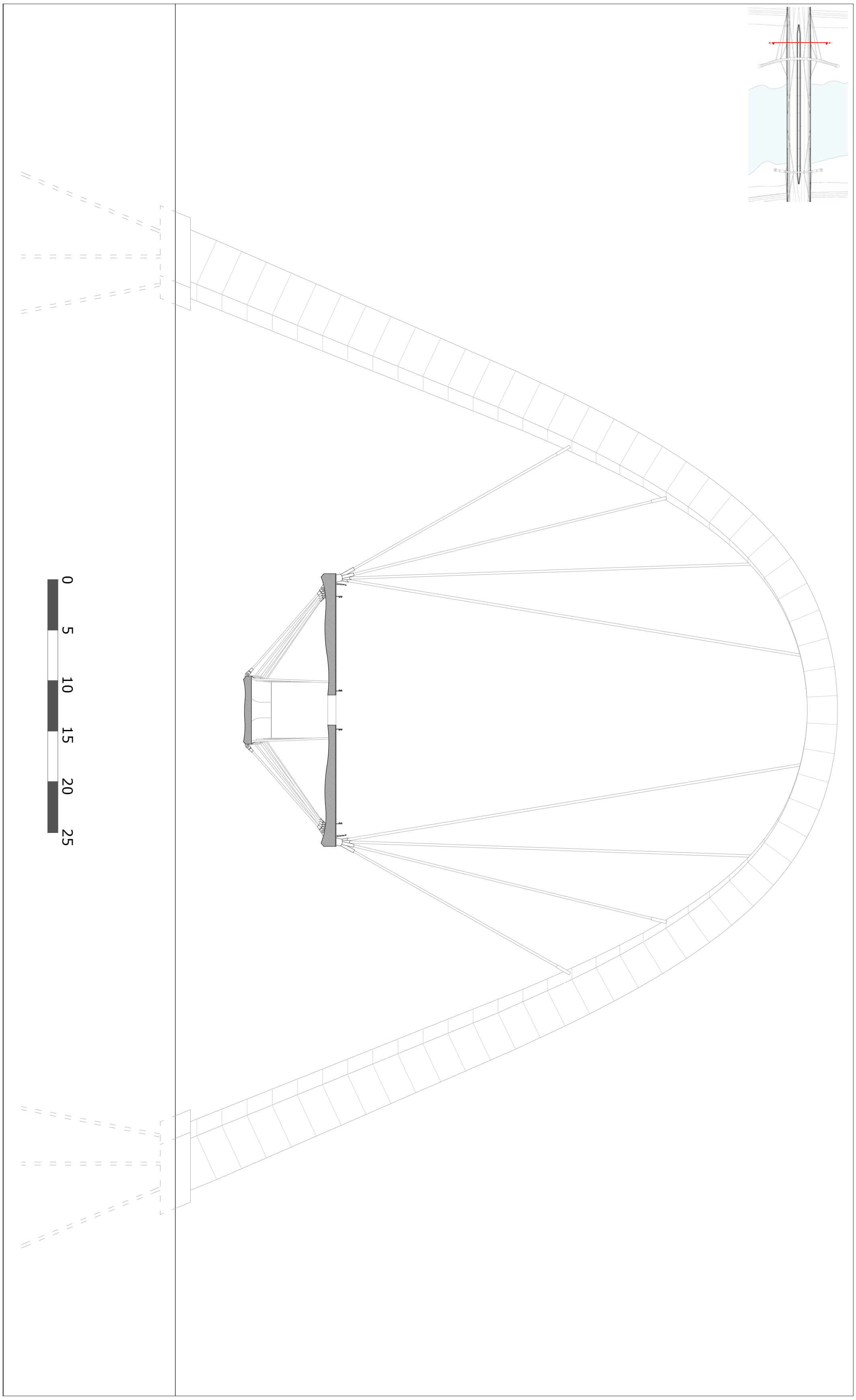


Fig. 125 - *Section A-A'*

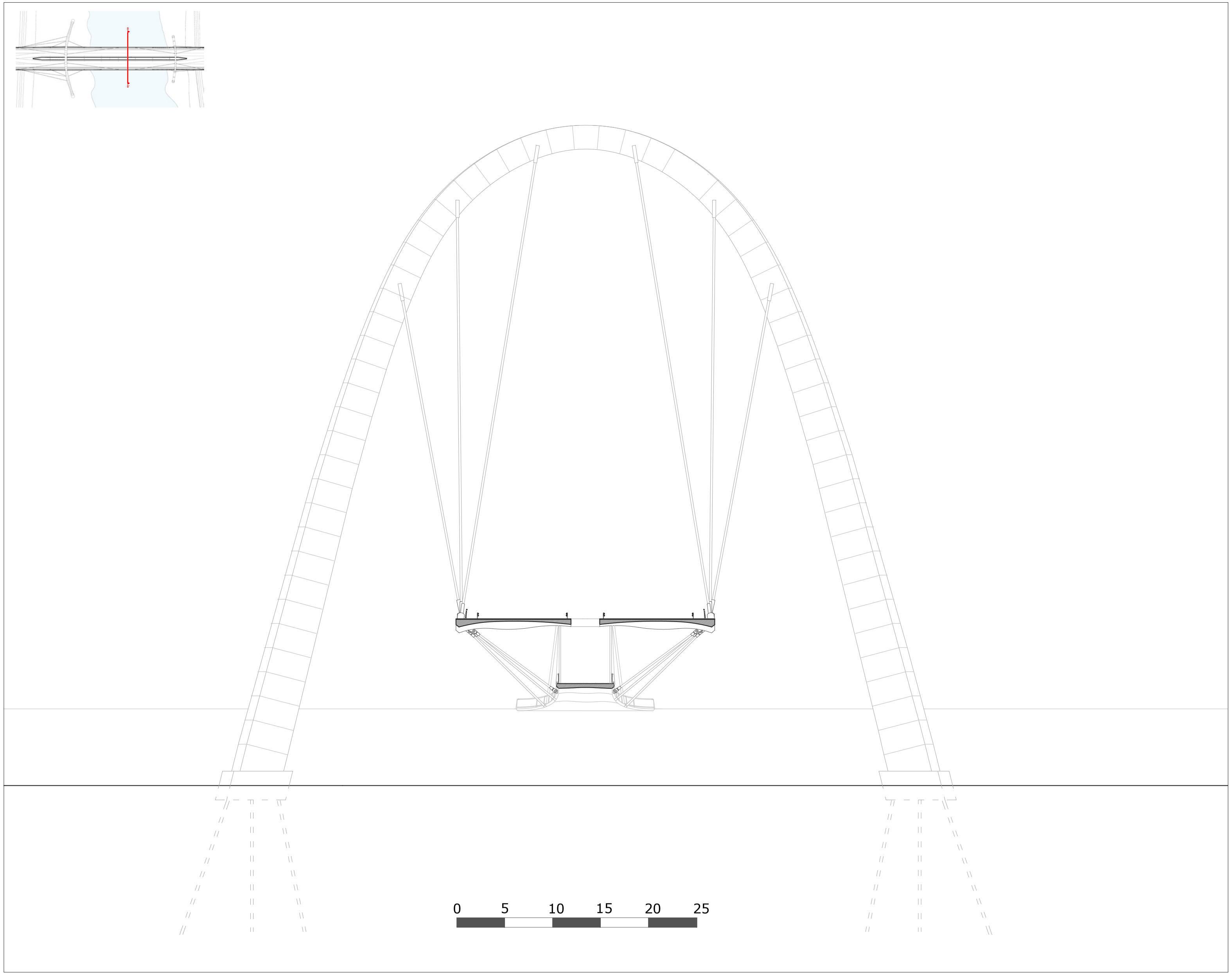


Fig. 126 - *Section B-B'*

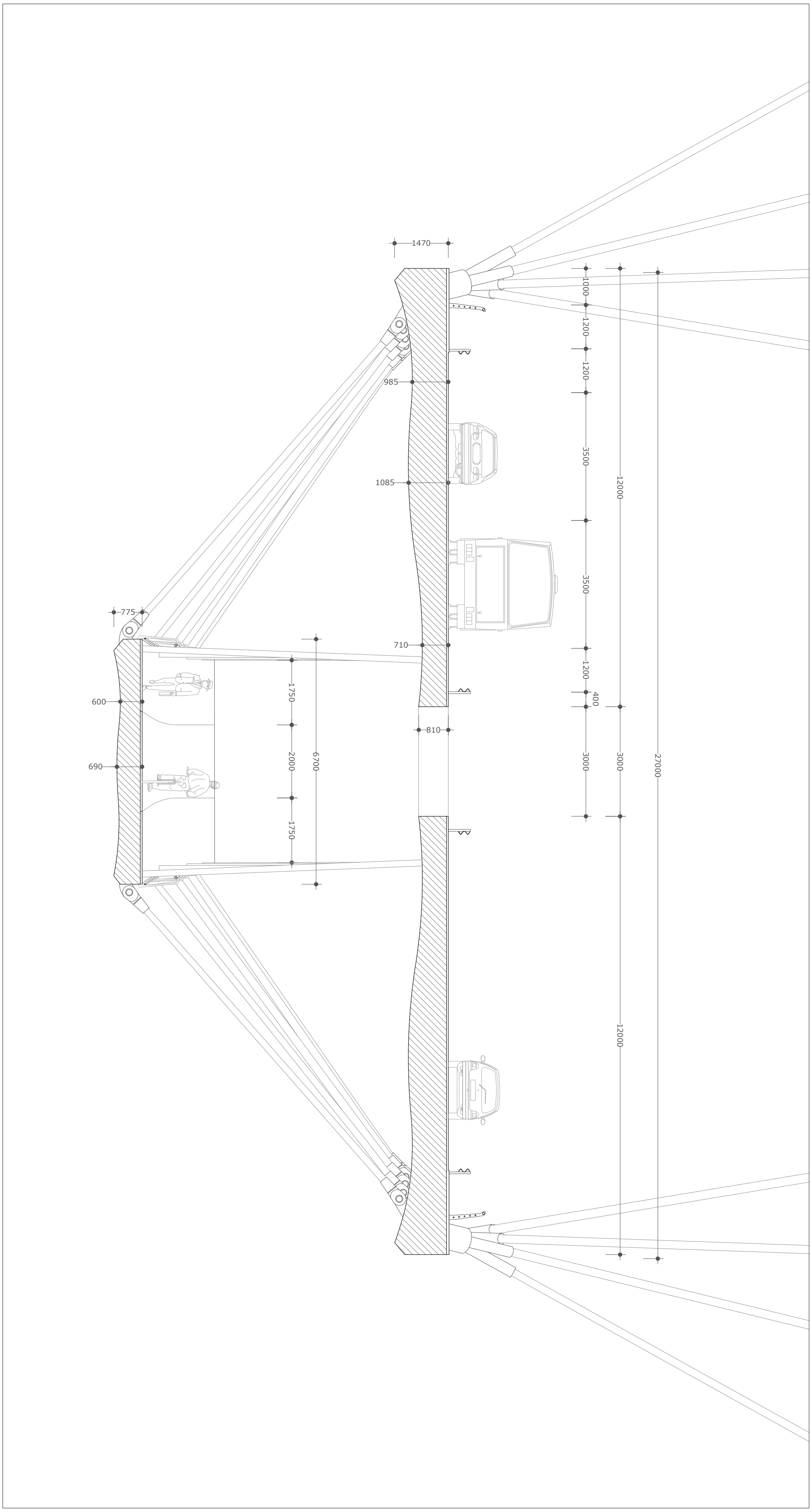


Fig. 127 - *Section A-A’*

5 FINAL REMARKS

In conclusion, a reflection on the final outcome of this graduation project in relation to the proposed research questions is formulated. Lastly, some recommendations for future possible research developments are given while specifying important limitations present within this research.

5.1 LIMITATIONS AND RECOMMENDATIONS

The time available and the complexity of the problem have inevitably led to limitations in the research focus and in the entire process. Recommendations for further research are here proposed.

Background Research Phase

The complexity of the optimization process requires the need for a large amount of information, both as regards the architectural and structural aspects. More detailed research is recommended, especially regarding the definition of the objectives for which the optimisation aspires. To obtain a project that can be considered sustainable, numerous criteria needs to be considered. The effective use of material might be a first step towards it but several different aspects such as the end-life impact of such materials, their recyclability and possible reuse for example need to be considered.

The aspect of the project's economic sustainability, in particular, must consider numerous aspects such as the labour force, the transport of materials, the production processes of the elements belonging to the project, numerous possible maintenance interventions, and traffic management during them.

Materials

In this research, the primary materials used are structural steel and reinforced concrete. Alternative solutions such as wood, stone and plastic have not been considered. In particular, numerous researches have been carried out in the use of FRP solutions. Considering these alternatives is advisable, having more time to define the field of action of the optimization process or limiting the complexity of the problem by concentrating, for example, on a single element of the project.

Optimisation Process

The main limitation inherent in the optimization process relates to the time and computational resources available. The calculation time required for evaluating numerous possible solutions made it necessary to define limitations in this sense in terms of the variables analyzed and the number of iterations carried out. Ideally, the best option would be to evaluate as many solutions as possible. This objective can be achieved by simplifying the problem or increasing the resources available in terms of time and computational time. This recommendation has repercussions on the entire research since the time needed to define the optimization process can take precious time from the other phases of the design process.

Kangaroo Form-finding

In this research, the Kangaroo plug-in was used, starting from a configuration obtained after the optimization process was carried out. Ideally, this form-finding process should be included within the optimization process so that the final form and the repercussions it has on the structure can be assessed in relation to the defined objectives. In the time available for this research, this approach has not been possible for two reasons: the exponential increase of the time needed to calculate one solution; and the peculiar behavior of the kangaroo solver, which requires a manual reset in case inputs are changed. As a result of changing the configuration, some of the results obtained by kangaroo, were read as unfeasible within the optimization process, mainly due to errors in the geometry output. To avoid the risk of letting out of the possible solutions potential optimal candidates, the choice was to implement the approach used and described previously in this report. Different solutions can be adopted, such as inserting a timer that resets the solver at each iteration (Piker and Groups, n.d), or stopping the system when the kinetic force achieved is equal to zero (Grasshopper3d.com, 2012). However, preliminary tests of this solutions encountered problems within the communication between grasshopper and modeFrontier and were not used.

Structural Verification

Perhaps the most critical part of finding an optimal design for a bridge is to validate its capability to support design loads. Within the time available for this research, it was considered sufficient to validate the structure for the load case prescribed by the Eurocode. However, in practice, it is necessary to consider situations in which the load cases can be even more onerous for the structure, for example having one lane subject to a load of 9KN / m ^ 2 and the remaining ones without any load instead of the 2,5KN / m ^ 2 used. The arrangement of point loads can vary as well, and an extraordinary wind intensity should be considered as well. Dynamic actions were also excluded from the structural verification. The main recommendation for a correct structural verification is to implement a nonlinear analysis to superimpose several load cases and optimize the structure accordingly.

5.1 CONCLUSION

This research had the goal of exploring how multi-objective optimization processes can influence and potentially improve the design process of a bridge aiming towards an effective use of the materials as a first step towards an improved sustainablity.

If used correctly, the computational design tools made available to the designer can prove to be a powerful means by which to improve the design process. In the specific case of bridge design, where aesthetics and structure go hand in hand, it is essential to use these tools knowing that initial settings of a parametric model based on aesthetic choices have substantial repercussions on the design's structural behavior and final outcome. Nonetheless, some choices regarding the design can and must be made before relying on optimization processes; This is necessary not only to give limits to the optimisation process but to consider as well that the computed solutions could be distant from the desired yield in aesthetic terms. In the case of this research, for example, the arched shape of the pylons was decided beforehand conscious of the fact that if more freedom was given to the optimisation process to space between different shapes, one attributable to an arch would have been difficult to overcome other traditional ones in terms of performances.

It is essential to reiterate that usually in practice optimization processes are carried out at the end of the design process to improve already established solutions. In this research, an attempt was made to relocate the optimization process within the design process and use it as a means of exploration to evaluate different options. Such an approach can theoretically be used in practice, but the amount of information and considerations to which optimization must respond requires a more significant and precise definition then what proposed in the time available for this research.

Concerning the main research question stated at the beginning of this graduation project: "*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 can be considered promising in terms of the effective use of the material and early exploration of different solutions. The comparison of different options for the given problem has made it possible to direct the choice towards a design that could be considered a first step in the choice of a configuration that could potentially lead to an improvement of the bridge sustainability under the aspect of effective use of material. The final design development was carried out having in mind its need to be functional, structurally sound and aestetically appealing as the primary objective. Naturally the sustainability as a whole it is still far from be achieved, since numerous criteria were left out during this research and some traits of the design were changed according to the desired architectural language.

An interesting finding was how and to what extent the designer can influence the optimization process and remain in control of the finished result. The designer's decision and personal preference can and must be able to control the process so as not to sacrifice the desired architectural rendering in favor of a blind follow-up of the optimization results. In this research, it was possible to note how multi-criteria decision-making methods can partially help the designer have substantial control over the preference of one solution over another.

It is also noteworthy that the optimization process implemented, due to its complexity and the fact that it was developed during the course of this research, took away time from other important phases in the entire process that could have led to a more in depth inclusion of the available information and subsequent design development.

In conclusion, it is possible to state that the use of optimization processes in the exploratory phase of design does not guarantee a single optimal solution, but can guide the design in the right direction. To make the best out of an approach similar to the one used, given the complexity of the problem, the amount of information taken into consideration in the process must be as extensive and detailed as possible. So as not to exclude potential optimal solutions and simultaneously guarantee its correct analysis in terms of relationship with the set objectives and feasibility. Alternatively, such an approach should be used for less complex design problems.

REFERENCES

Amiri, A., Arya, C., Vassie, P.R. (2009). A model for appraising the sustainability of bridges. Building a Sustainable Future, Feb 2009 S*ymposium: Concrete 21st Century Superhero, London.*

Amiri, A., Arya, C., Vassie, P.R. (2010). Embedding sustainable development into structural design teaching u*sing sustainability appraisal tools. University College London.*

Balali, V., Mottaghi, A., Shoghli, O. and Golabchi, M. (2014). Selection of Appropriate Material, Construction Technique, and Structural System of Bridges by Use of Multicriteria Decision-Making Method. Transportation Research Record: Journal of the Transportation Research Board, 2431(1), pp.79-87.

Bare, J. (2012). Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) - Software Name and Version Number: TRACI version 2.1 - User's Manual. Washington, DC: US EPA.

Bilec, M., Ries, R. and Matthews, H. (2007). Sustainable Development and Green Design—Who Is Leading the Green Initiative?. Journal of Professional Issues in Engineering Education and Practice, 133(4), pp.265-269.

Biraghi, M. (2008). Storia dell'architettura contemporanea I 1750-1945. Piccola Biblioteca Einaudi, p.331.

BMVBS, I. (2020). Informationsportal Nachhaltiges Bauen:. [online] Nachhaltigesbauen.de. Available at: https://www.nachhaltigesbauen.de/ [Accessed 25 Gen. 2020].

BRE Global Limited (2019). CEEQUAL Version 6, Technical manual, International Projects.

Bucci, F., & Mulazzani, M. (2002). Luigi Moretti: Works and Writings. New York: Princeton Architectu*ral Press.*

Bucci, F., and Mulazzani, M. (2000). Luigi Moretti: Works and writings. New York: Princeton Architectural Press, p.21.

Capuano, A. (2005). Temi e figure nell'architettura romana 1944-2004. Rome: Gangemi Editore spa, p.267.

de Leur, M. (2017). Breaking Barriers: A parametrically optimised bridge design crossing the Nieuwe Maas. MSc thesis, TU Delft 2017.[Online] Available on: http://repository.tudelft.nl

DEFRA - Department for Environment, Food and Rural Affairs. (2008). Guidelines to DEFRA's G*HG Conversion Factors, 2008.*

EPA. (2012). Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (*TRACI) – User's Manual. Washington, D.: US EPA.*

Ernst, M.K. (2017). Green-linking Rotterdam Zuid. MSc thesis, TU Delft 2017.[Online] Available on: http://repositor*y.tudelft.nl*

ESTECO. (n.d.).Optimisation Algorithms [online]. Available at: https://www.esteco.com/technology/optimization-algorithms

Etymonline.com. (2019). bridge | Origin and meaning of bridge by Online Etymology Dictionary. [online] Available at: https://www.etymonline.com/word/bridge [Accessed *28 Dec. 2019]*

Furuta H, Maeda K, Watanabe E. (1995). Application of genetic algorithm to aesthetic design of bridge structures. Microcomputers in Civil Engineering, 10(1995), 415–421.

Gervásio, H. and Simões Da Silva, L. (2012). A Probabilistic Decision-Making Approach for the Sustainable Assessment of Infrastructures, Expert Systems with Applications, Elsevier, 39(8), 7121–7131.

Granta Design. (n.d.). CES EduPack. [online] Available at: https://grantadesign.com/it/education/ces-edupack/.

Grasshopper3d.com. (2012). Reset Simulation Override - galapagos etc. – Grasshopper. [online] Available at: https://www.grasshopper3d.com/m/group/discussion?id=2985220%3ATopi-c%3A744129.

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., . . . Huijbregts, M. (2002). Handbook on life cycle assessment. Operational guide to the ISO standards. Dordrecht, Netherlands: Kluwer.

Highways Agency. (2002). Evaluation of maintenance costs in comparing alternative designs and maintenance schemes for highway structures (draft). The Highways Agency, London, Advice Note BA 28/XX, Departmental Standard BD 36/XX.

IPCC. (2013). Climate Change 2013: The Physical Science Basis. Geneva, Switzerland: IPCC.

Langdon, D. (2009). SPON'S Civil engineering and highway works price book. Taylor & Francis, 24 edition.

Lute, V., Upahyay, A., Singh, K.K. (2011). "Genetic algorithms-based optimization of cable stayed bridges." J. Software Engineering & Applications, 4, 571-578.

Magrone P., Tomasello G., Adriaenssens, S. Gabriele, S., and Varano, V. (2016). "Revisiting the form finding techniques of Sergio Musmeci: The Bridge over the Basento River", in Structures and architecture, Paulo J. da Sousa Cruz ed., Taylor & Francis, London. pp. 543-550.

McIsaac, G. and Morey, N. (1998). Engineers' Role in Sustainable Development: Considering Cultural Dynamics. Journal of Professional Issues in Engineering Education and Practice, 124(4), pp.110-119.

Moretti, L. (1971). "Ricerca Matematica in Architettura e Urbanisticâ." Moebius IV no. 1, p.30-53. Republished in: Bucci, F., and Mulazzani, M. (2000). Luigi Moretti: Works and writings. New York: Princeton Architectural Press, p.701.

Mosavi, A. (2012). “Decision-Making Models for Optimal Engineering Design and their Applications,” Dissertation University of Debrecen. hdl.handle.net/2437/171847.

Munasinghe M, and Cruz W. (1995) Economywide Policies and the Environment: Lessons from Experience. World Bank Environment, paper no. 10. The World Bank, Washington, DC, pp. 8−9.

Navarro, I., J.V. Martí, J.V., and Yepes, V. (2018). Multi-criteria decision making techniques in civil engineering education for sustainability. Conference: ICERI2018,the 11th annual International Conference of Education, Research and Innovation. At: Seville (Spain)

Nikolic M. (2019. Computational Design: Computationally optimised bridge design. MSc thesis, TU Delft 2019.[Online] Available on: http://repository.tudelft.nl

OECD (2014). SMART PROCUREMENT Going green: best practices for green procurement - NETHERLANDS.

Penadés-Plà, V., García-Segura, T., Martí, J. V., and Yepes, V. (2016). A Review of Multi-Criteria Decision-Making Methods Applied to the Sustainable Bridge Design, Sustainability, MDPI, 8(12), 1295.

Piker, C. by D. and Groups, V. (n.d.). Kangaroo. [online] www.grasshopper3d.com. Available at: https://www.grasshopper3d.com/group/kangaroo?commentId=2985220%3AComment%3A611966&xg_source=activity.

Quartz. (2020). Open data for a healthier, more sustainable future. [online] Available at: http://quartzproject.org/ [Accessed 25 Gen. 2020].

Rajpurohit J., Sharma T.K., Abraham A., Vaishali (2017). Glossary of Metaheuristic Algorithm. International Journal of Computer Information Systems and Industrial Management Applications, 9(2017), 181-205.

Regione Lazio (2012). Tariffa dei prezzi 2012. Available at: http://www.regione.lazio.it/binary/rl_testChannel/tbl_contenuti/INF_DGR_412_06_08_2012_Tariffa2012.pdf

Rossi, P., Gatti, I. (1991). Roma. Guida all’architettura moderna 1909-1991, Laterza.

Tensacciai. (n.d.). Stay cables. [online] Available at: https://www.tensacciai.it/technologies/stay-cables

Terzidis, K. (2003). Expressive form. London: Spon Press, p.70.

van Baalen S. (2016). Topology optimised pedestrian bridge. MSc thesis, TU Delft 2016.[Online] Available on: http://repository.tudelft.nl

Weston, R. F. (1994). “Towards understanding the idea of sustainable development, the role of engineering in sustainable development: selected readings and references for the profession.” M.D. Ellis, Ed., American Association of Engineering Societies, Washington, D.C., pp. 40-43.

Wood, W. H., III, and A. M. Agogino. (1996) Case-Based Conceptual Design Information Server for Concurrent Engineering. Computer-Aided Design, Vol. 28, No. 5, pp. 361–369.

Wortmann, T., & Nannicini, G. (2017). Introduction to Architectural Design Optimization.In City Networks - Planning for Health and Sustainability (Karakitsiou, A., Migdalas, A.,Pardalos, P. M., & Rassia, S., Eds.). Springer International Publishing.

Yanarella, E., Levine, R. and Lancaster, R. (2009). Research and Solutions: “Green” vs. Sustainability: From Semantics to Enlightenment. Sustainability: The Journal of Record, 2(5), pp.296-302.

FIGURES REFERENCE LIST

[1] Encyclopædia Britannica - https://www.britannica.com/technology/bridge-engineering#/media/1/79272/149100

[2] Encyclopædia Britannica - https://www.britannica.com/technology/bridge-engineering/Truss#/media/1/79272/18376

[3] By JaGa, own work - https://commons.wikimedia.org/wiki/File:New_River_Gorge_Bridge.jpg

[4] By Glabb, own work - https://commons.wikimedia.org/wiki/File:Chaotianmen_Yangtze_River_Bridge.JPG

[5] By Mrs Logic, Flickr: Calm before the storm - https://commons.wikimedia.org/wiki/File:Calm_before_the_storm,_Infinity_Bridge.jpg

[6] Encyclopædia Britannica - https://www.britannica.com/technology/bridge-engineering#/media/1/79272/18374

[7] By Joe Underwood - https://bridgehunter.com/photos/20/39/203942-L.jpg

[8] By Sakowski - http://highestbridges.com/wiki/images/b/b8/LabajinConstructionView11.jpg

[9] Banagherprecast - https://banagherprecast.com/wp-content/uploads/2011/12/P1010375-1024x768.jpg

[10] By Cherrybomb - https://commons.wikimedia.org/wiki/File:Concrete_box_girder_bridge.JPG

[11] By Damien du Toit / https://commons.wikimedia.org/wiki/File:Gouritz_River_Bridges2.jpg

[12] By Brian McKee - https://bridgehunter.com/photos/16/57/165744-L.jpg

[13] Encyclopædia Britannica - https://www.britannica.com/technology/bridge-engineering#/media/1/79272/18375

[14] By STA3816 - https://commons.wikimedia.org/wiki/File:Ikitsuki_Bridge.jpg

[15] Encyclopædia Britannica - https://www.britannica.com/technology/bridge-engineering/Truss#/media/1/79272/18378

[16] By Andrew Bell - https://commons.wikimedia.org/wiki/File:Bb-forthrailbridge.jpg

[17] Encyclopædia Britannica - https://www.britannica.com/technology/bridge-engineering/Truss#/media/1/79272/18377

[18] By Tysto - https://commons.wikimedia.org/wiki/File:Akashi_Bridge.JPG

[19] Encyclopædia Britannica - https://www.britannica.com/technology/bridge-engineering/Truss#/media/1/79272/18379

[20] By Tizio - https://en.wikipedia.org/wiki/Cable-stayed_bridge

[21] By Баяков Алексей Александрович - https://commons.wikimedia.org/wiki/File:%22Russian_bridge%22_in_Vladivostok.jpg

[22] X

[23] X https://i.ytimg.com/vi/74NpV3cc87s/maxresdefault.jpg

[24] By Storfix - https://commons.wikimedia.org/wiki/File:Itztalbruecke_2005-07-24.jpg

[25] By OSJB - http://www.orsc.co.jp/english/tec/images/d/roa_02.jpg

[26] By Protezione Civile Italiana - http://www.protezionecivile.gov.it/resources/cms/documents/A3_class20150416_r.pdf

[27] British Standards Institution. NEN-EN 1991-2:2003. Eurocode 1: Actions on structures– Part 2: Traffic loads on bridges. 2003

[28] By Johann “nojhan” Dréo, Caner Candan - https://commons.wikimedia.org/wiki/File:Metaheuristics_classification.svg

[29] Italian Regulations, NTC 2018 - https://www.gazzettaufficiale.it/eli/gu/2018/02/20/42/so/8/sg/pdf

[30] Bucci and Mulazzani - Luigi Moretti: Works and Writings. New York: Princeton Architectural Press.

[31] By Johann “nojhan” Dréo - https://en.wikipedia.org/wiki/Metaheuristic#/media/File:Metaheuristics_classification.svg

[32] Mosavi A. - “Decision-Making Models for Optimal Engineering Design and their Applications,” Dissertation University of Debrecen. hdl.handle.net/2437/171847.

[33] By LucanoPz - https://commons.wikimedia.org/w/index.php?curid=46391221

[34] Ney and Partners - https://archinect.com/neyandpartners/project/footbridge-in-knokke#&gid=1&pid=3

[35] Furuta H, Maeda K, Watanabe E. - Application of genetic algorithm to aesthetic design of bridge structures. Microcomputers in Civil Engineering, 10(1995), 415–421.

[36] Lute, V., Upahyay, A., Singh, K.K. - “Genetic algorithms-based optimization of cable stayed bridges.” J. Software Engineering & Applications, 4, 571-578.

[37] Momir Nikolic. Computationally optimised bridge design. MSc thesis, TU Delft 2019.[Online] Available on: http://repository.tudelft.nl

[38] Quartz - http://quartzproject.org/methodology#Impact_Assessment_Methodology

[39] Amiri, A., Arya, C., Vassie, P.R. - Embedding sustainable development into structural design teaching using sustainability appraisal tools. University College London.

[40] By Piero Tucci - http://inbiciperoma.blogspot.com/2014/09/questa-volta-la-magliana-fa-parlare-di.html

[41] By Antonio Bevilacqua - https://db82kmzzne7f2.cloudfront.net/ghost-blogit/2018/04/EUR1.jpg

[42] By Blackcat - https://upload.wikimedia.org/wikipedia/it/0/07/20110307_Roma_Palazzo_della_Civilt%C3%A0_Italiana_fronte_-_lato_sx.jpg

[43] By Starless74 - https://upload.wikimedia.org/wikipedia/commons/2/29/PonteMagliana2019.jpeg

[44] By Jastrow - https://commons.wikimedia.org/wiki/File:Ponte_Fabricio_Rome_Pierleoni.jpg

[45] By Blackcat - https://commons.wikimedia.org/wiki/File:2012-05-15_Roma_ponte_Cestio_da_ponte_Garibaldi_2.jpg

[46] By Livioandronico2013 - https://commons.wikimedia.org/wiki/File:Ponte_Sisto_and_Dome_od_St._Peter_at_night.jpg

[47] By Giuseppe Primoli - https://www.flickr.com/photos/dealvariis/3833587945/

[48] By Lalupa - https://commons.wikimedia.org/wiki/File:Tevere_-_ponte_Industria_1030875.JPG

[49] By Lalupa - https://upload.wikimedia.org/wikipedia/commns/5/5/Tevere_-_PonteRisorgimento1.JPG

[50] By Lalupa - https://upload.wikimedia.org/wikipedia/commons/6/6a/Tevere_-_Ponte_Duca_d_Aosta_03.JPG

[51] By Livioandronico2013 - https://commons.wikimedia.org/wiki/File:Bridge_of_the_Music_2.jpg

[52] By Blackcat - https://it.wikipedia.org/wiki/File:Roma_Ponte_Ostiense_003.jpg

[53] Politecnico di Torino - Analisi e valutazione degli aspetti di trasporto del progeto del nuovo stadio di Roma.
[54] Municipality of Rome - Relazione tecnica D-EG-01-B-Rel-Gen.
[55] Capuano - Temi e figure nell'architettura romana 1944-2004.
[56] Strade e Autostrade - https://www.stradeeautostrade.it/notizie/2017/roma-bocciato-il-progetto-del-ponte-dei-congressi/
[57] Studio Transit - http://www.studiotransit.it/project-view/congressi-bridge/
[58] By Ilfattoquotidiano -https://st.ilfattoquotidiano.it/wp-content/uploads/2018/08/20/PonteMagliana675.jpg
[59] By cesar-eur.it - https://66.media.tumblr.com/27c5a07fa4037d005e705615b2f1b8c3/tumblr_mfhp6mmRSd1r4vadxo1_500.jpg
[60] By QuartzProject - https://quartzproject.org/p/CP170-a05/q/concrete
[61] By QuartzProject - https://quartzproject.org/p/CP000-a02/q/rebar#cp
[62] By QuartzProject - https://quartzproject.org/p/CP017-a03/q/structural+steel#cp
[63] By QuartzProject - https://quartzproject.org/p/CP174-a04/q/cables#cp
[64] By clearriceedu - https://www.clear.rice.edu/mech403/HelpFiles/FEA_Buckling_analysis.pdf