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SYSTEMIC DESIGN OF A BRIDGE
DEMOUNTABILITY, INSPECTABILITY AND MAINTAINABILITY

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Abstract— Nowadays, there is a strong attention onto the study of modern buildings and infrastructures to define a paradigm for conceptual design that meets criteria such as demountability, inspectability, and maintainability. Concepts that are common, from the earliest stages, in mechanical engineering and industrial design but still not fully considered in the design of civil infrastructures. These criteria are synergic with modern requirements such as resilience, sustainability, circular economy, and lifecycle analysis.

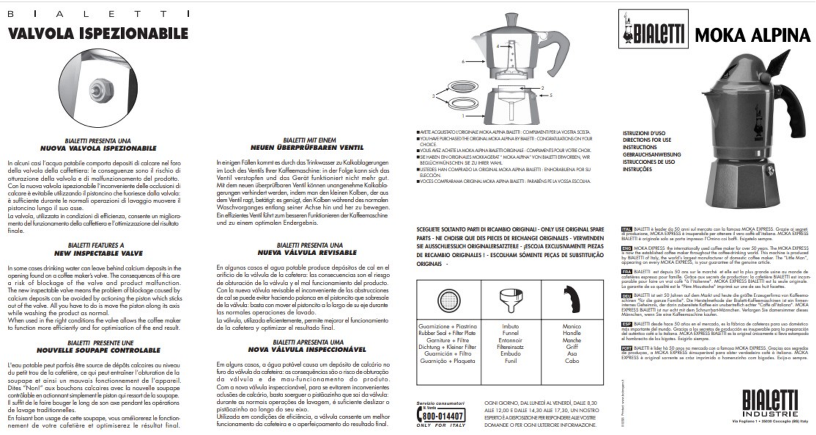
This paper presents the results of an applicative research based on the design of a pedestrian bridge whose concept starts from the above stated principles. Just like a coffee pot, design stems from creativity but is addressed by the above requirements to provide a systemic arrangement of components and simplify the lifelong management stage. By varying the importance of the single criteria, the analysis leads to different results and structural shapes in a range that goes from static redundancy to controlled lability. The paper focuses on the role of demountability, inspectability, maintainability as well as resilience, sustainability, circular economy, and lifecycle analysis, in the context of the conceptual design of a pedestrian bridge project and establishes a set of guidelines for the design principles deriving from this innovative approach. The proposed methodology is the systemic design applied using macro-flow diagrams and synthesis maps that are visual representations of processes, key concepts, relationships between them and their effects on results.

Main findings and observations regard the efficiency of this method in design early stages as well as the simplicity of application in the study of project variations and interactions between the disciplines involved.

Keywords — demountability, inspectability, maintainability, pedestrian bridge, systemic design, structural design, resilience, sustainability, circular economy, lifecycle analysis, creativity, systemic arrangement, and life-long management.

I. INTRODUCTION AND BACKGROUND

Designing a bridge involves a combination of creativity and engineering. Nevertheless, additional design criteria, such as demountability, inspectability, maintainability are also necessary. These factors are common in mechanical engineering and industrial design but are still not fully considered in the design of civil infrastructure. Below, in figure 1 is reported the Bialetti Moka instruction manual where these criteria are clearly defined.



BIALETTI

VALVOLA ISPEZIONABILE

BIALETTI PRESENTA UNA
NUOVA VALVOLA ISPEZIONABILE

In alcuni casi l'acqua potabile comporta depositi di calcare nel foro della valvola della caffettiera: le conseguenze sono il rischio di otturazione della valvola e di malfunzionamento del prodotto. Con la nuova valvola ispezionabile l'inconveniente delle occlusioni di calcare è evitabile utilizzando il pistoncino che fuoriesce dalla valvola: è sufficiente durante le normali operazioni di lavaggio muovere il pistoncino lungo il suo asse.
La valvola, utilizzata in condizioni di efficienza, consente un miglioramento del funzionamento della caffettiera e l'ottimizzazione del risultato finale.

BIALETTI FEATURES A
NEW INSPECTABLE VALVE

In some cases drinking water can leave behind calcium deposits in the opening found on a coffee maker's valve. The consequences of this are a risk of blockage of the valve and product malfunction. The new inspectable valve means the problem of blockage caused by calcium deposits can be avoided by actioning the piston which sticks out of the valve. All you have to do is move the piston along its axis while washing the product as normal.
When used in the right conditions the valve allows the coffee maker to function more efficiently and for optimisation of the end result.

BIALETTI PRESENTE UNE
NOUVELLE SOUPAPE CONTROLABLE

L'eau potable peut parfois être source de dépôts calcaires au niveau du petit trou de la cafetière, ce qui peut entraîner l'obturation de la soupape et ainsi un mauvais fonctionnement de l'appareil. Dites "Non!" aux bouchons calcaires avec la nouvelle soupape contrôlable en actionnant simplement le piston qui ressort de la soupape. Il suffit de le faire bouger le long de son axe pendant les opérations de lavage traditionnelles.
En faisant bon usage de cette soupape, vous améliorerez le fonctionnement de votre cafetière et optimiserez le résultat final.

BIALETTI MIT EINEM
NEUEN ÜBERPRÜFBAREN VENTIL

In einigen Fällen kommt es durch das Trinkwasser zu Kalkablagerungen im Loch des Ventils Ihrer Kaffeemaschine: in der Folge kann sich das Ventil verstopfen und das Gerät funktioniert nicht mehr gut. Mit dem neuen überprüfbaren Ventil können unangenehme Kalkablagerungen verhindert werden, indem man den kleinen Kolben, der aus dem Ventil ragt, betätigt: es genügt, den Kolben während des normalen Waschvorganges entlang seiner Achse hin und her zu bewegen. Ein effizientes Ventil führt zum besseren Funktionieren der Kaffeemaschine und zu einem optimalen Endergebnis.

BIALETTI PRESENTA UNA
NUEVA VÁLVULA REVISABLE

En algunos casos el agua potable produce depósitos de cal en el orificio de la válvula de la cafetera: las consecuencias son el riesgo de obturación de la válvula y el mal funcionamiento del producto. Con la nueva válvula revisable el inconveniente de las obstrucciones de cal se puede evitar haciendo palanca en el pistoncito que sobresale de la válvula: basta con mover el pistoncito a lo largo de su eje durante las normales operaciones de lavado.
La válvula, utilizada eficientemente, permite mejorar el funcionamiento de la cafetera y optimizar el resultado final.

BIALETTI APRESENTA UMA
NOVA VÁLVULA INSPECCIONÁVEL

Em alguns casos, a água potável causa um depósito de calcário no furo da válvula da cafeteira: as consequências são o risco de obturação da válvula e de mau-funcionamento do produto. Com a nova válvula inspeccionável, para se evitarem inconvenientes oclusões de calcário, basta soerguer o pistãozinho que sai da válvula: durante as normais operações de lavagem, é suficiente deslizar o pistãozinho ao longo do seu eixo.
Utilizada em condições de eficiência, a válvula consente um melhor funcionamento da cafeteira e o aperfeiçoamento do resultado final.

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- VOUS AVEZ ACHETE LA MOKA ALPINA BIALETTI ORIGINALE : COMPLIMENTS POUR VOTRE CHOIX.
- SIE HABEN EIN ORIGINALES MOKKAGERAT " MOKA ALPINA" VON BIALETTI ERWORBEN, WIR BEGLÜCHWÜNSCHEN SIE ZU IHRER WAHL.
- USTEDES HAN COMPRADO LA ORIGINAL MOKA ALPINA BIALETTI : ENHORABUENA POR SU ELECCIÓN.
- VOCES COMPRARAMA ORIGINAL MOKA ALPINA BIALETTI : PARABÊNS PE LA VOSSA ESCOLHA.

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INSTRUCTIONS
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Figure 1. Bialetti Moka instruction manual

Broadly, these topics are related to requirements such as resilience, sustainability, circular economy, and lifecycle analysis.

Recently, the multifactorial and multiparametric design processes are the subjects of in-depth analysis aimed at defining effective application methods for the evaluation of the different parameters and their influence on the overall system.

Different approaches are available in the literature that allow the study of complex systems in engineering. Among these the most common are the follows.

- Model-based design (MBD).

It is a model-centric approach to systems, using virtual system modeling standards and mathematical models. These methods offer accurate and detailed results in the advanced stages of design but often require an unsustainable design effort when applied in the early stages of the project when the variables involved should be easily governable and adjustable in relation to the different disciplines involved.[1]

- Risk-based design

It is an approach to engineering design that considers the potential risks associated with a project or specific aspects throughout its lifecycle. This method involves identifying potential hazards and assessing the probability and severity of the associated risks. Then, the design is modified to reduce the risk to an acceptable level, based on the level of risk tolerance of the stakeholders.

One of the key benefits of risk-based design is that it helps designers to identify potential hazards early in the design process, before they become costly and difficult to address.

In structural design are the probabilistic methods that are spreading more and more but that offer the vision only of one aspect of the design without giving the possibility to the designer to evaluate their interaction with other targets or project criteria.[2]

- Systemic-level design

System level design is the process of designing a complex system, which may be made up of multiple subsystems, components, and interfaces. It involves identifying the requirements, functions, and performance criteria of the system and then developing a design that meets these specifications.

The goal of system level design is to create a system that is efficient, effective, and meets the needs of the stakeholders. It requires a multidisciplinary approach that may involve engineers, designers, architects, and other experts who have skills in various discipline interested in the design process.

The method of system level design typically involves the following steps:

-requirements analysis: identify the requirements of the system, including the inputs, outputs, functions, and performance criteria

-architecture design: develop a high-level architecture that describes the structure of the system, including its components, subsystems, and interfaces.

-component design: design the individual components of the system

-integration: integrate the components and subsystems and test the system to ensure that it meets the requirements

-verification and validation: verify and validate the system against the requirements to ensure that it is reliable, effective, and efficient.

When this method is applied in the early stages of a project, i.e., a specific level, where there are still many uncertainties and variables that can change and evolve quickly it implies to recognize the interconnectedness of all elements within a system and seeks to understand the system as a whole, rather than focusing solely on single parts or requirements [3,4]

The process involves mapping out the system, identifying key drivers and variables, and analyzing feedback loops and patterns of behavior.

The goal of systemic design is to identify factors and to create interventions that can positively impact the system, rather than just addressing isolated problems or effects. It involves a long-term perspective and recognizes that solutions must be adaptable and flexible to account for changing conditions and unforeseen consequences.

In this study, we aim to apply this approach to conceptual structural engineering design of a pedestrian bridge, considering the entire structure and its interaction with the environment as a system rather than focusing solely on its individual elements or requirements.

Through this method, the interdependence between different parts of the structure, and the impact of the structure on the architecture, equipment installations and durability (i.e. maintenance and inspection), can be clearly identified and recognised. Therefore, the methodology is well suited to the early stages of project design and can be easily integrated with other methods, including those mentioned, in the later stages of in-depth analysis and where an analytical calculation of the structures is necessary.

By varying the importance of a single criterion, the analysis can lead to to different results and structural shapes in a range from static redundancy to controlled lability. For this reason, the final aim of this work was to identify how conceptual design should be conducted systemically to define multiple criteria that can lead to a target-oriented design.

Specifically, the decisive criteria for this analysis are the followings.

- Geometric limits
- Robustness
- Inspectability
- Maintainability
- Sustainability
- Demountability
- Installation of systems
- Resilience

The last three criteria can be included, as previously stated, in the so-called design for adaptability [5].

II. APPLICATIVE CASE STUDY

We applied the proposed method to a real case study developed by Zanini Gozzi Sagl office: the design competition for a new pedestrian and bicycle bridge at the Delemont railway station in Switzerland [6]

The competition opened in August 2022 and closed at the end of September 2022.

The overall goal was to propose a new pedestrian and bicycle bridge connecting the city centre to an eco-district under development, while also enabling access to the railway platforms by bicycle and on foot (see masterplan and competition area in figure 2)

Several constraints were listed in the competition programme, including the minimum height over the rail tracks, the maximum height below the high-voltage cables, the planimetric position and the required width. One of the most important requirements was that the bridge should be adaptable in the future to railway platform movements.

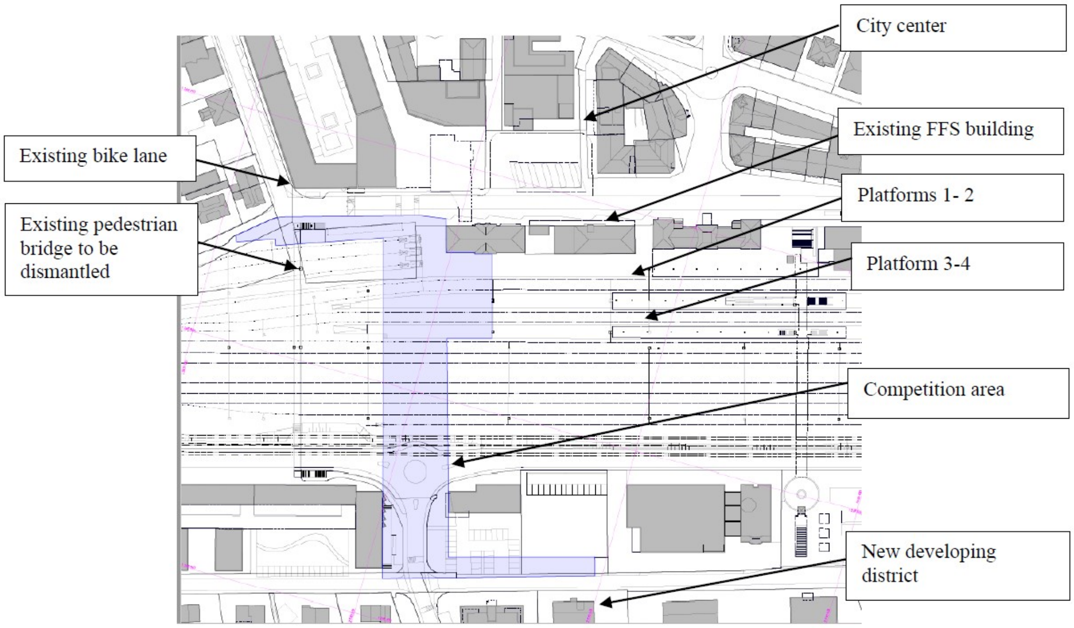

Figure 2. The masterplan and competition area

III. METHOD

The design method we propose in this study reinterprets the steps mentioned for systemic-level design and it follows a precise procedure related to the specific conditions.
It includes the targets we aimed to comply with during the design, which were defined in the early stages of problem comprehension.
The following key steps were developed for the footbridge design.

1. Comprehend and define the function (purpose and requirement).
   The first step was to understand exactly the purpose of the bridge, as well as the requirements it needed to meet. This included factors such as determining whether it was only for pedestrian use or if it was to be cyclable (as in our case), whether a covered or uncovered bridge would be most appropriate, the nature of the connections to the railway platforms (stairs, lift), and the access points, such as stairs and ramps.
   This step also involved obtaining engineering data, such as the maximum load capacity, extreme event conditions, the length of the span and the number of supports, the height of the bridge, and the expected lifespan of the structure [7]
2. Analyse the context.
   The landscape and urban context were analysed to comprehend the needs of the city and the public, as well as to determine how the bridge could be integrated into the existing bicycle-lane system and its future development.
   This analysis then led to a study of local construction culture (baukultur [8]) and the social context.
   In this step, we faced topics such as sustainability, lifecycle analysis, resilience in terms of being adaptable to future transformation (i.e. railway platform relocations, new bicycle lanes, new cities, and public necessities), installation deployability and demountability.
   The first two steps involved mapping out the system and identifying the key drivers and variables.
   These preliminary measures led to the third step, in which we performed the effective design by analysing feedback loops and patterns of behaviour.
3. Systemic design
   At this point, we started to perform the systemic design, considering the seven targets (Figure 3) raised in the earlier design steps and analysing the different structural strategies related to those.
   To more easily manage the various structural strategies and study the static systems, no analytical assessment or FE method was performed. Instead, coherently with the proposed method, we took a visual approach [9] and applied a static graphic study [10].
   We chose this line because early design stages require rapid and efficient analysis so they can be discussed and comprehended by the entire design team, especially the architect, who was particularly interested in the overall shape and footprint in the urban landscape.

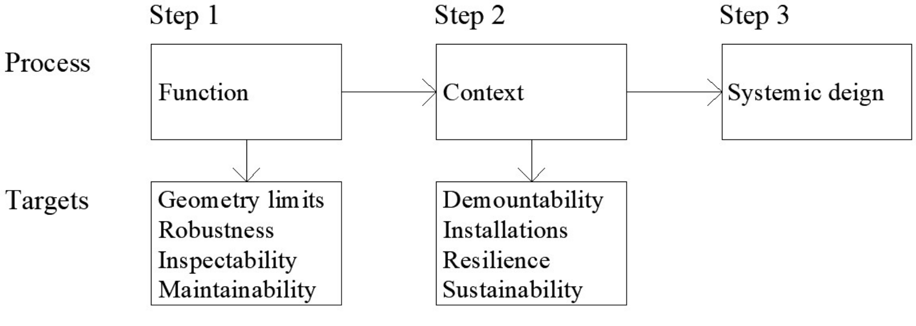

Figure 3. Design process macro- flow diagram

IV. SYSTEMIC DESIGN AS MULTITARGET DESIGN

Here, we describe the synthesis of the systemic approach we adopted in the design process, which can be visualised using diagrams and graphs.
Systemic design can be managed using tools and toolkits that enable and accelerate systems methods for advanced design.

Generally, the most common tools used are gigamaps, introduced in 2009 by Birger Sevaldson at the Oslo School of Architecture and Design [11], and synthesis maps [12], which represent the evolution of conceptual maps.

These tools are effective for synthesising and defining the process, but for the structural design, we considered the synthesis map to be more efficient because they are more representative of the precise pattern and flow of the target's importance and connected effects.

The synthesis map is shown in Figure 4. This explains how each target influences the final shape and how the targets are related to each other, as well as identifying material of choice.

The beam and truss solutions were analysed, except for the structural elements that did not satisfy the geometric limits and robustness criteria.

Both satisfied the basic requirements, but since resilience was essential in this case, due to the competition regulation requirements for access to the railway platforms and the division between pedestrian and bicycle use, the truss solution was excluded.

The support arrangement was analysed, including two or four supports.

This analysis invoked both resilience and sustainability. When resilience was considered the priority, the two support solutions were more interesting, but when sustainability (i.e. material use and structure cross-section) was the priority, the four support option won.

Maintainability, inspectability and installation were more connected to the bridge cross-section, involving the selection of one box girder or two separated beams. In terms of installation deployability, two separate beams were more efficient because they could be integrated with the surrounding equipment.

Furthermore, they could be easily connected to the pillars using a 'V' shape, since this could accept either vertical or horizontal loads (robustness).

The material that could efficiently satisfy each target was steel, this is also in line with the choice of material that best meets sustainability requirements. Several studies show that this is the construction material is suitable for disassembly and reuse with an hight potential to reduce the CO2 footprint in new structures. [13,14]

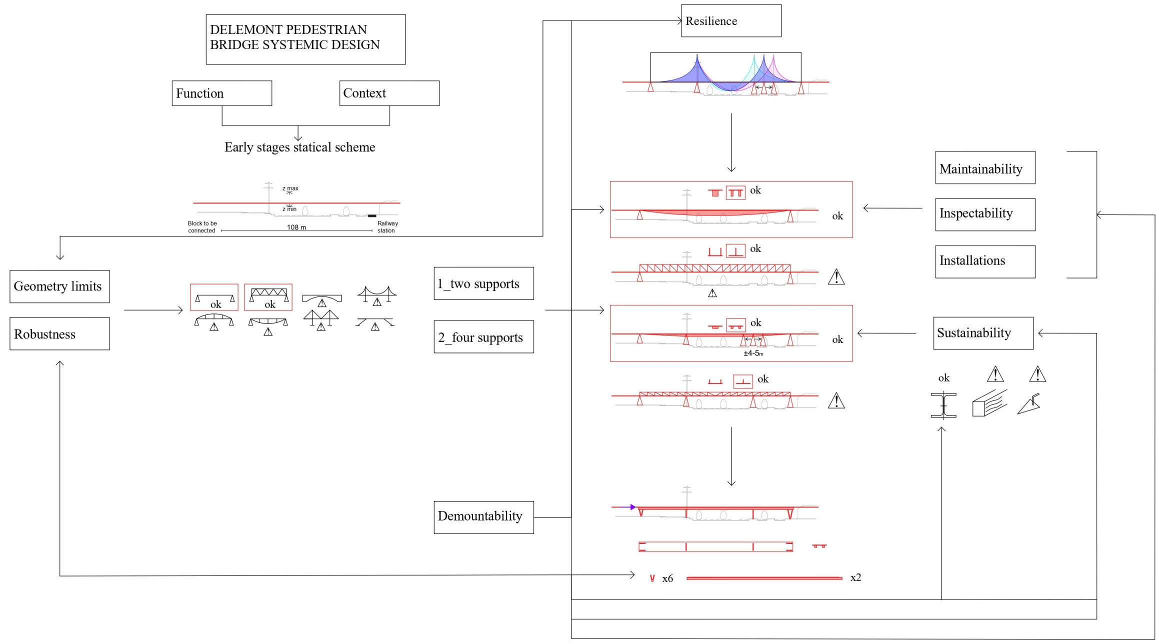

Figure 4. Systemic design synthesis map

The system was composed of a kit of defined elements that could be arranged in different positions. according to the actual requirements and could be changed in the future.

In Figure 5, we illustrate the different arrangements.

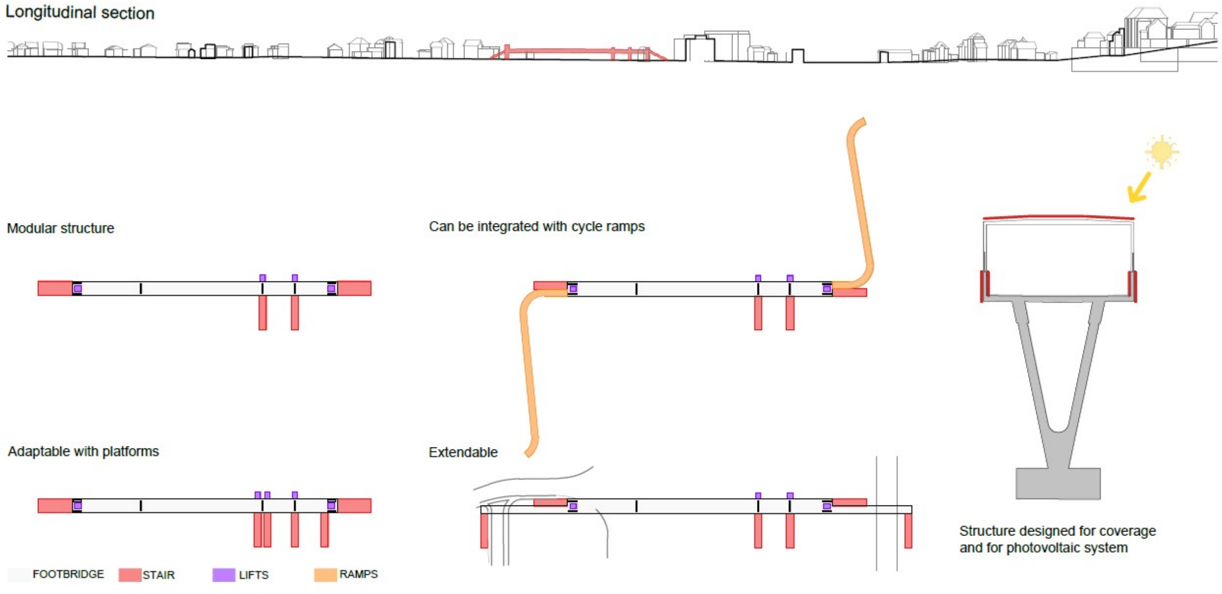

Figure 5. Demountable system and different arrangements

In addition, this system efficiently satisfied the provisional arrangement during construction without stopping the rail traffic and avoiding complex site facilities as much as possible.
The construction phases are shown in Figure 6.

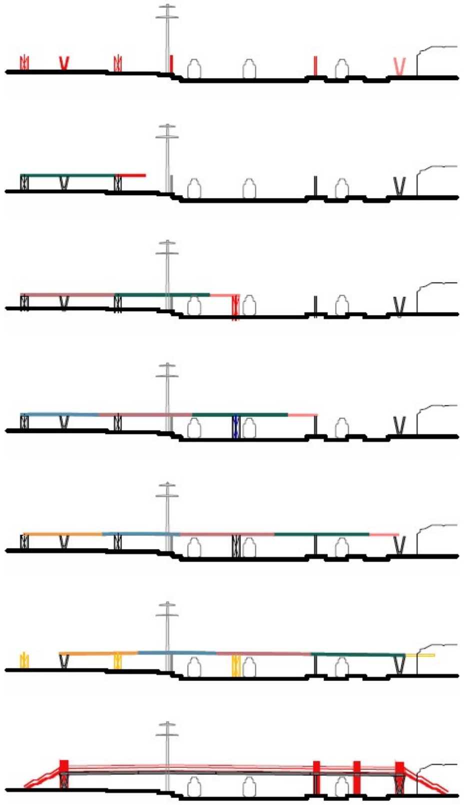

Figure 6. Montage system

The final solution is shown in figures 7 and 8. In figure 9, the more-detailed drawing explains some technical details that were studied and shown to be coherent with the overall conceptual design.

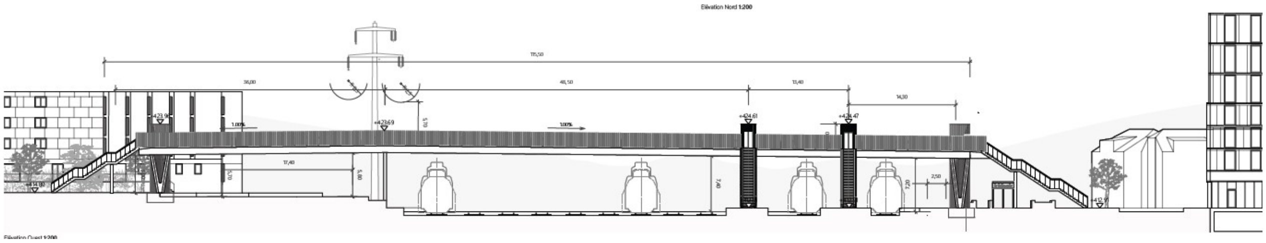

Figure 7. Final solution front view

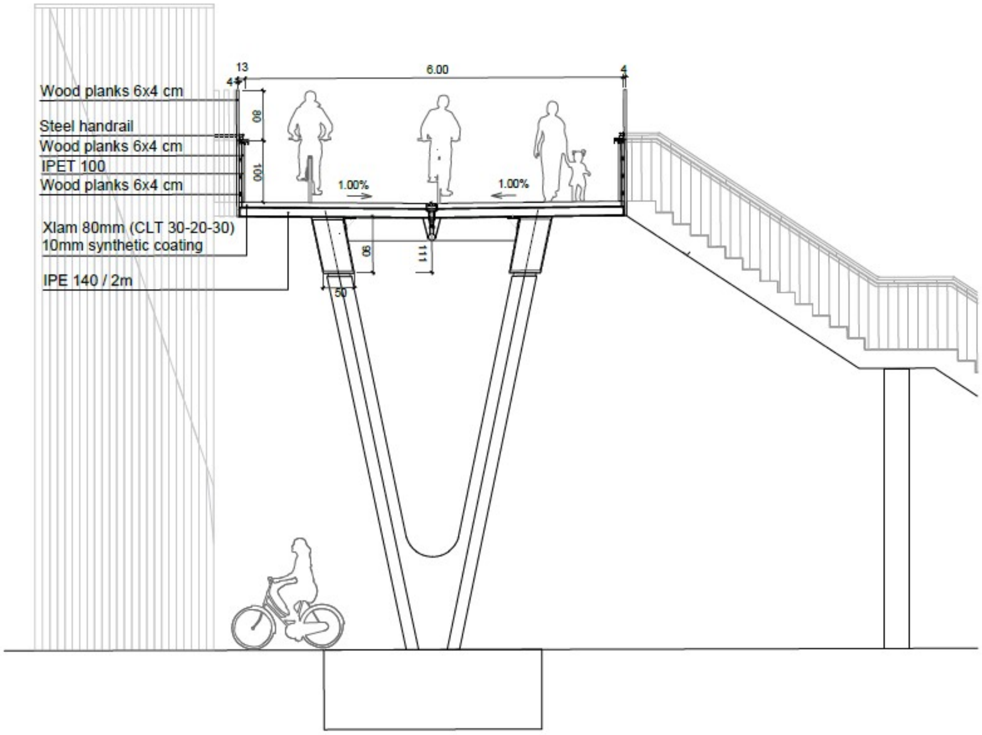

Figure 8. Final solution section

Figure 9. Final solution render

V. DEMOUNTABILITY, INSPECTABILITY, AND MAINTAINABILITY FOCUS

The concepts of demountability, serviceability and maintenance were included as essential design targets from the outset. The design concept also considered the choice of individual elements that could be easily assembled and disassembled.

The decision to split the beams allowed the intermediate space, in which the floor bracing was provided, to be used as a laying area for the installations, making them easily accessible and inspectable.

The profiles of both the beams and the V-pillars were closed-box-shaped and airtight.

The support details and connections were all bolted and accessible for visual control and periodic tightening according to the maintenance plan.

The static concept of shifting supports meant the structure was dimensioned according to robustness criteria.

The same is efficient when considering the overall structure as made of compartmentalised zones according to each single part of the composition.

In this way, delocalised failures are contained in the elements, avoiding progressive failure accomplishing to robustness requirements.

The concept also meets maintenance requirements as well facilitating element substitutions involving transient situations in the static scheme.

The possibility of installing equipment made it possible to provide an integrated monitoring system from the outset.

The footbridge is in fact equipped with dormant accelerometers to be activated according to the maintenance and control plan.

These will be periodically activated for dynamic identification to check the overall stiffness.

VI. CONCLUSIONS

In the overall context of construction design, this type of approach is introduced as a method that allows to simply control and manipulate the different design paradigms that can guide an efficient project. It wants to answer to necessity to manage a high complex process, giving a method that can be easily controlled and understood by the involved actors reducing the risk of chaotic as well as inefficient design.

The main idea of this paper is to apply the method in the context of conceptual design of structures that is the substance of the design process and when the fundamental decisions are agreed between the stakeholders. It regards experience, technical approaches combined with intuition and sensitivity towards the different involved discipline and requirements.

This analysis highlights the fact that traditional paradigms such as form follows function [15] and form follows forces [16] today are reductive although remaining criteria that can be contained within the process and can be related to other project requirements that are defined in the applicative case study of a footbridge, and it explains how these criteria relate each other as well to the overall system in the final design result.

The main findings are basically two. First, we propose a precise procedure raised from a concrete and applicative example showing the main steps preliminary to the effective systemic design.

The procedure is fast and efficient for the early stages because it involves visual and conceptual analysis instead of long analytical and mathematical assessments that can be integrated in the successive steps.

Secondly, we produce the synthesis map that is a concrete result of the specific case study in the early stages of conceptual design and summarize the process until the final design proposal.

The synthesis map is an effective tool that can be used by the designer (engineers, architects, and specialist) to easily change the importance of various factors as well as their effect on results; that toll should be kept updated and coherent throughout the whole design process.

Since it can be used by each designer involved in the process, it can be enriched or changed until the final solution, showing interesting results and potentials that deserve to be deeper investigated.

In literature the approach includes more than solely technical aspects but also social, economic, cultural, and environmental factors that affect the system.

For that reason, this specific study should be furthermore developed adding, to the cited target, social and cultural aspects, that in the competition were not defined, but they can be integrated when specialists on the topics are involved in the team process.

One important potential to be considered is undoubtedly that the proposed approach is not reduced to the useful life of the designed structure, but by meeting sustainability and life cycle requirements, this can indorse very actual structure requirements such as design for adaptability, disassembly, reassembly, future re-use of both the entire constructed complex and individual elements, offering a visual result of future situations.

Another possible future development is to extend the systematic design to more complex infrastructures such as road bridges and viaducts to offer practical and operational design guidelines considering the different targets required today for a new structure as well as retrofitting of existing constructions.

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2006. Master's degree in civil engineering at Politecnico di Torino

Academic career

2014 - Research assistant, Academy of Architecture, University of Italian Switzerland (USI)

2020 - Associate professor DACD Department of Environment Constructions and Design, University of Applied Sciences and Arts of Southern Switzerland (SUPSI)

2021 - Responsible for interdisciplinary summer school '22 on conceptual design, engineering, and architecture USI-SUPSI

2022 - Doctoral researcher at Politecnico di Torino and SUPSI

Scientific activity

Author of many internal publications in USI on subjects of structural engineering and conceptual design of structures.

2019 - Editor of engineering at architectural magazine Archi and editorial group Espazium. www.espazium.ch/de

Author of many essays about construction culture and structures and some chapters of engineering books.

Responsible author and curator of some magazine numbers. 2021 - Responsible for an editorial series of articles and essays on conceptual design of structures, publishing from Feb. 2022.

Professional career and consulting activity

2007 - Structural engineer and project manager of many projects in international environments.

2014 - Structural consultant for USI and SUPSI internal projects, architectural atelier, bachelor, and master thesis.

2022 - Founder of the consultancy firm Zanini Gozzi in Lugano:

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1991. Master's degree in civil engineering at the University of Bari
1995, PhD in Structural Engineering at Politecnico di Torino

Academic career

2002 - Full Professor of Structural Engineering in the Faculty of Engineering at Politecnico di Torino

2005 - 2012 Vice-rector for Education and Member of the Board, Politecnico di Torino

2010 - Dean of the Faculty of Engineering, Uninettuno

2012 - 2015 Member of the Evaluation Board, PoliTo

2015 - 2018 Vice-rector for International Affairs, PoliTo

2018 - Head of the Competence Center SISCON 'Safety of Infrastructures and Constructions' at PoliTo.

Scientific activity: Research and awards

Author of more than 190 scientific publications on subjects of Structural Engineering, Materials Engineering and Fracture Mechanics. In particular, 85 papers have been published in the most important journals of the field.

In 2012 he was awarded the ACI Wason Medal for Material Research by the American Concrete Institute for his research on structural concrete.

In 2014 he was named Honorary Professor in structural mechanics at Henan University of Technology (Zhengzhou, China).

Consulting activity

2004 - Founder of the consultancy firm ARCOS Engineering in Torino (Italy): http://www.arcos-engineering.it. Presently a member of the Board of Directors of the firm.