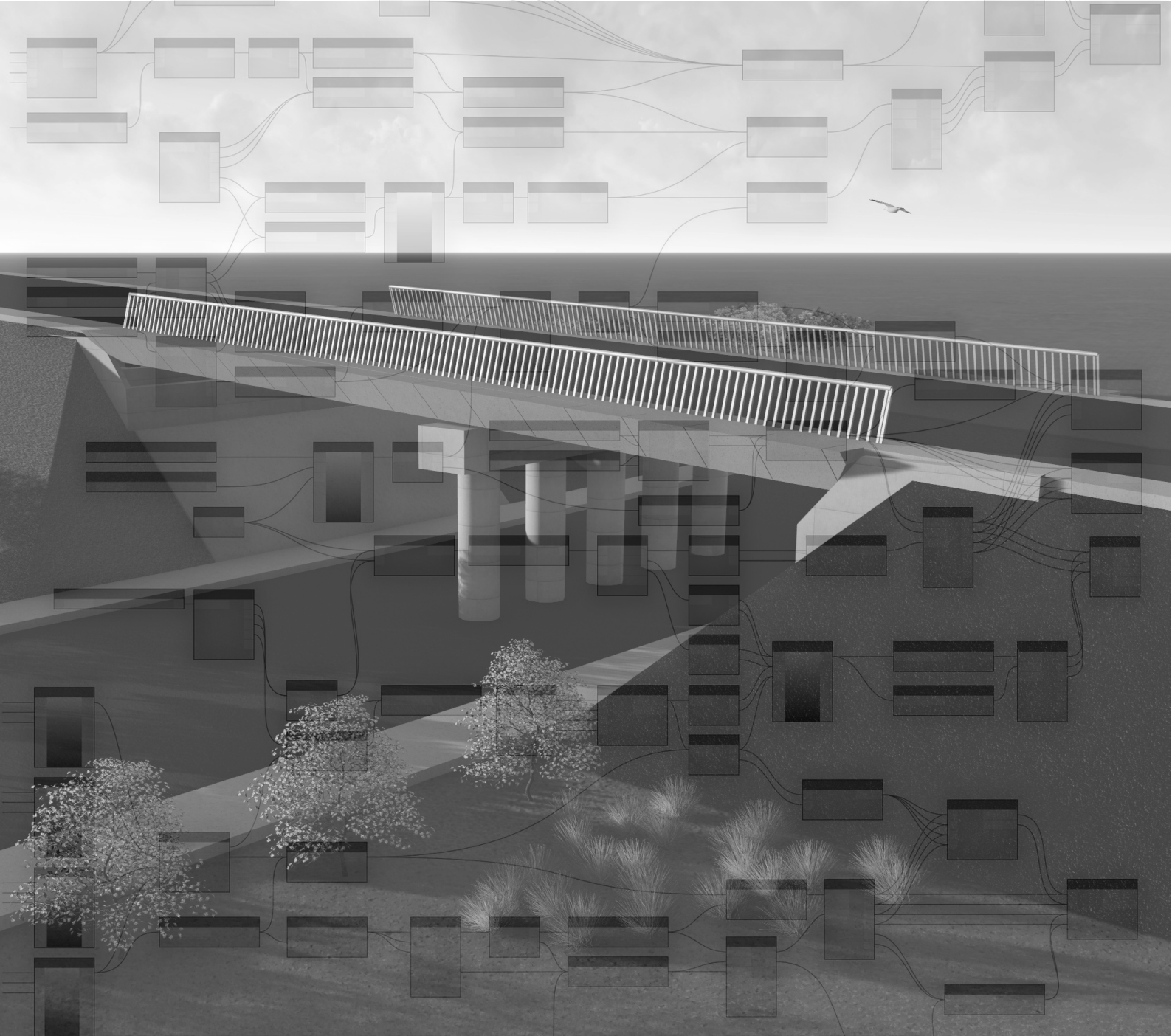


MSc Thesis Report

Knowledge Model for the Parametric Design of Concrete Viaducts

by Maria Gkioka



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MSc OF BUILDING ENGINEERING
FACULTY OF CIVIL ENGINEERING
DELFT UNIVERSITY OF TECHNOLOGY

JUNE 2018

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Abstract

The Architecture, Engineering & Construction (AEC) industry has been traditionally fragmented, with a lot of disciplines specialising in different aspects of a project and encapsulating different knowledge areas. This research project, entitled “Knowledge Model for the Parametric Design of Concrete Viaducts”, investigates the development of a knowledge model around common, prefabricated concrete viaducts and its translation into an integrated, parametric platform and communication medium between architects and structural engineers. This model can be used as a basis of discussion between the architect, the engineer, as well as the client and support a fast decision making process, which is especially useful during the first steps of design.

The main fields of interest for this project are Building Information Modelling (BIM) and parametric/associative design. BIM has revolutionised the industry by providing the practitioners with concepts and tools towards an integrated, object-oriented process. However, the current BIM technologies are often characterised by limited design flexibility. Parametric/associative design promotes the idea of designing structures, as systems of parameters which can generate numerous alternatives. This paradigm facilitates the development of complex geometries, enhances automation and supports optimisation algorithms. In this research, the advantages and limitations of the aforementioned fields, as well as a number of other concepts, such as Object-Oriented Programming, Extreme Programming and Model-Based Systems Engineering are investigated and the results are employed in the development of the model.

In this study, The main parameters of viaduct design are determined and structured in a knowledge model, considering their limitations and typical values. The generic geometry of the components and their interaction is considered, as well as the propagation of design changes through the model. This knowledge model starts with a top-down UML class diagram and gradually evolves into a parametric platform for viaduct design on Dynamo. Due to the complexity of the parametric script, a Python-based User Interface is created to increase the usability of the platform. The parametric model is seamlessly connected to Robot, a structural analysis software, through a Python script, in order to derive instant structural analysis results. The geometry of the deck is transferred to the structural analysis software, along with the properties of the beams, the support conditions and the loads of Load Model 1. A linear structural analysis is automatically conducted and the engineer can directly assess the results in Robot. The link between the applications ensures that both disciplines are working on the same design and merges their different knowledge areas into one model.

The number of parameters considered in this research is 82, and they are divided in 3 categories according to the level to which the designer can influence them on the platform. As an outcome of the standardisation process and the restriction of the scope of the research 51.2% of those parameters require input from the designer, while in the case of a symmetrical design (the same components are used on both sides of the viaduct) this percentage drops to 36.6%. This underlines the potential of such an integrated platform, as automation can significantly reduce the design time and both architects and engineers can focus more on the creative and challenging parts of the design, as well as doing more design iterations. Important issues for the development of the platform are the validation of the results, in order to gain the trust of the user, as well as the limitations of the current parametric platforms. The recommendations for further research include the immediate changes that can be implemented to the algorithm, such as the integration of cost analysis and the increase of the level of detail, as well as ways to unlock the full potential of this platform by considering cloud-based solutions and taking advantage of cutting edge technologies like machine learning.

Acknowledgements

I would first like to thank my thesis mentor dr.ir. Jeroen Coenders of White Lioness, for giving me the opportunity to conduct my final project in the exciting field of computational and parametric design and inspiring me throughout the process. Moreover, he consistently allowed this project to be my own work, while steering me in the right direction whenever I needed it.

I would also like to thank my TU Delft graduation committee: my main supervisor Prof.ir. Rob Nijssen and my university mentors ir. Sander Pasterkamp and dr.ir. Sander van Nederveen for their guidance and valuable input throughout the project.

My research would have been impossible without the aid and support of my company supervisor ir. Arend Rutgers of A&E Architecten and the rest of the team who welcomed me and provided me with insightful comments and useful information regarding my project.

I must also thank the experts of BAM Advies&Engineering, as well as BAM Infra who were always eager to share their knowledge with me, and discuss the challenges they have to face in their practice. My special thanks to Bram Hommen, Mohamad Kayali, Johan Bolhuis, Tiziana Caruana and Wilfred Woudenberg. Without their contribution and interest in my project, this thesis could not have been successfully conducted. Moreover, I would like to thank Spanbeton for the valuable information they offered me regarding prefabricated concrete.

Moreover, I would like to thank my friends in Greece and in the Netherlands for their support and the fun moments we shared during our studies!

Finally, I must express my profound gratitude to my parents for always believing in me and supporting me all those years and especially through the process of conducting this thesis. This accomplishment would not have been possible without them. Thank you.

Maria Gkioka,
Utrecht, June 2018

Preface

This document presents the results of the Master Thesis: “Knowledge Model for the Parametric Design of Concrete Viaducts”. This is the author’s final project to complete the MSc degree of Civil Engineering at Delft University of Technology. This project is carried out at BAM Advies&Engineering in cooperation with White Lioness Technologies. The project investigates the design process of common concrete viaducts and attempts to standardise the knowledge around them. Both the architectural and structural design needs are taken into account. The final output of this research is a parametric platform which according to the designer’s input creates a customisable viaduct and conducts a structural analysis of the design. The role of the companies is explained below:

BAM Advies & Engineering

As one of the major contractor companies in the Netherlands, BAM designs and constructs a large number of projects, building or infrastructure related. Therefore, ways are sought, within the company, to standardise and optimise the design process, so that the knowledge gained from each project can be directly accessed/used during the design of a subsequent, similar project. This can contribute to the reduction of the mundane tasks which are needed for the design of repetitive structures, reduce the design time, as well as be the basis for a communication tool between the different disciplines, involved in the project. Working alongside AEC practitioners, in a professional setting, sets the foundation for a realistic approach on the topic, since all ideas and concepts can be tested and discussed with professionals who work in the fields under investigation. Moreover, being a graduate student at BAM A&E, constitutes a significant opportunity to understand how the design process works in real projects. The interaction with architects and engineers, as well as BIM experts is a powerful tool to grasp the essence of the design process, without relying only to literature.

White Lioness technologies

White Lioness technologies operates in the field of advanced computation, by developing a wide range of customized computational tools for its clients. The main product of the company is Packhunt.io, which is a cloud-based, interactive platform, where data can be stored and processes can be automated. Using this platform as a starting point, solutions for each client are configured. The idea of this research project originates from this company’s practice, as it aspires to transfer the philosophy of the customised, parametric design, widely used in other industries, to the AEC industry. The research project, therefore is developed in cooperation with White Lioness technologies, which provides guidance throughout the project.

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Nomenclature

AEC industry:	Architecture, Engineering and Construction industry
BIM:	Building Information Modeling
IFC:	Industry Foundation Classes
DBFM Contract:	Design, Build, Finance & Maintain Contract
UML:	Unified Modeling Language
API:	Application Programming Interface
UI:	User Interface

1 Introduction

In this chapter, an introduction to the research project and the main fields of interest is given.

1.1 Research Project

This research project investigates the development of a knowledge asset tool with parametric features and the extent to which the knowledge around an AEC project, focused on the infrastructure industry, can be integrated and stored on a parametric platform. The aforementioned aspiration has as a result the development of a parametric tool, through which the architect/engineer is able to access, interpret and act on the available information. The structure under investigation is a bridge, in order to limit the architectural and functional choices that need to be made. To further reduce the scope of the research project, the bridge is considered to be a common concrete viaduct for cars, over traffic. This project type is also chosen due to its repetitive design process. Indeed, special infrastructure projects will always require a unique design approach, therefore, they are not in the scope of this research.

An essential part of the thesis is to define the relationships between the components of the viaduct and the requirements which steer the design and attempt to translate them into an associative, parametric model. Emphasis is given on the design flexibility which the tool aspires to offer to the designer, but also on the integration of the structural analysis of the bridge, so that the design can be more easily communicated to the structural engineer.

Among the main challenges of this project lies the aspiration to translate the knowledge areas around a bridge into an adequate and thorough set of parameters and requirements, as well as consider a suitable hierarchy for those parameters and a certain level of automation. The relationships between the parameters, derived from requirements and other constraints, play a pivotal role in the final product, but undoubtedly the decisions taken by the engineers/architects determine the customised final design. The knowledge model is based on BIM principles, considering associative modelling with local and global relationships between the different component families. A research project is conducted to specify the recurrent steps of the design process and aim to standardise them, while allowing for customisation of each design. The study of the design process reveals also the steps which are not well defined and the parts of the process where information is misplaced or misinterpreted by the stakeholders. The research project focuses on the fields of parametric design, bridge design, structural engineering and BIM in an attempt to create a link between those fields and produce an efficient, computational design approach and a final 3D visualisation of the viaduct.

1.2 Motivation

The motivation for the research project derives from the limitations of the current BIM practices and their insufficient relation to parametric modelling. In common practice, architectural design embarks on design platforms which only represent the geometry of the structure and are deprived of any other information related to the project. The development of a BIM model of the architectural design happens at a later stage of the design process. Moreover, parametric models are usually employed to optimise or automate part of a design and not as an information platform for the whole project.

This situation implies that the designer is not aware of the whole picture of the design and how his actions influence the final outcome. In addition to this, knowledge gained in previous projects is usually not reused in future projects, which means that the design process is not improved. In an attempt to provide perspective to the designer and reuse the already gained knowledge, the goal of the thesis is not to create a mere parametric model but a knowledge model, which can store all knowledge that revolves around a structure and facilitate its assessment. Another issue that is part of the motivation for the research project are the difficulties in the communication between architects and civil engineers. Indeed, both parties develop their own model, without having a common design platform. To tackle this issue, the tool is designed to function as a communication platform between the two parties, by including structural analysis in the parametric model. Indeed, it can be argued that design should be a dialogue between different disciplines, therefore an integrated design platform is needed. Moreover, the tool addresses the need to automate the design of repetitive structures, such as bridges and viaducts for which the same design steps are followed for every new project, even though the knowledge and requirements are similar to the ones defined in previous ones.

The end result of this research is sought to be an integral approach, which results in the development of a knowledge model and its translation into a generic parametric tool, able to design an entire viaduct under the guidance of the architect/engineer. The use of parametric models also facilitates this process, by helping the designer create various alternatives which fulfil the requirements set by the various stakeholders.

1.3 Fields of Importance to the Research Project

In this section, an insight to the fields of importance to the research project is provided. Apart from a mere introduction to those fields, the strong points and limitations of each field are denoted, in an attempt to clarify the scope and the motivation of this research project.

1.3.1 Infrastructure

Bridge History in a Nutshell

Infrastructure projects and especially bridges, have traditionally been associated with human progress, social evolution and financial growth. The concept of bridge construction spans almost the entire human history, since even the early humans had to ensure a safe passage over a river or gorge. Bridge design started from very primitive structures such as simple beam bridges and post and lintel structures made mostly of stone and timber, while at later stages rope and bamboo suspension bridges were devised. This concept is still in use today in different parts of the world such as China, Columbia and Nepal [Parke & Hewson, 2008].

A revolutionary step for bridge engineering was the invention of the arch structure around 4000BC, in the Tigris-Euphrates valley, as a result of trial and error. Hundreds of years later, the Romans employed the arch structure to build their bridges and developed this structural system into art. They increased their knowledge in material science and understood the qualities of different types of wood and stone, as well as developed the voussoir arch structure¹. This structure type enabled a very efficient load distribution and allowed the Romans to build multiple spans (one at a time) without needing substructure. A typical example of this type of structure is given in Figure 1.1(a) and in 1.1(b) an example of elliptical arch structure is illustrated. The invention of the truss system in Renaissance was another revolutionary step in bridge design, which was considered daring at the time, but later replaced the arch in the 18th century. The expansion of the railroads due to the industrial revolution, forced the engineers to reconsider the use of materials (wood, wrought iron, cast iron) and structural systems in bridge design, since more durable structures needed to be built. Through new, cost effective processes steel became a popular material in bridge design halfway through the 18th century, manifesting tremendous advantages over other materials and enabling the construction of long span bridges. New types of bridges appeared, such as the steel truss and the suspension bridge.

The potential of concrete, as a structural material, was discovered by Francois Hennebique, who understood the practical use of reinforcement and later in the end of the 18th century the first concrete bridges were built. Concrete has been used to build most of the world's longest bridges. Its advantages include a lower cost compared to steel, as well as the ability to precast and form prestressed beams.

Those qualities have made concrete an attractive material for bridge design.

¹A wedge-shaped element, made typically of stone, used in building arches or vaults



(a) Pont du Gard - vault arch structure
(Nîmes - France)



(b) Pont Royal - elliptical arch structure
(Paris - France)

Figure 1.1: Typical vault structure and elliptical arch structure

1.3.1.1 Traditional Bridge Design Process

The bridge design process has traditionally been fragmented and linear, in terms of information and knowledge mobility. This indicates that a number of different parties were usually involved in bridge engineering projects, such as the architecture and structural engineering teams without establishing an efficient work and data flow, which lead to an error prone and time consuming process of redefining data on multiple programs and spreadsheets. Moreover, in the traditional design process there is little room for automation and innovation as well as a more efficient data exchange [Day, 2016].

1.3.1.2 Paradigm Change

Thanks to the development of innovative concepts in the AEC industry, such as BIM (Section 1.3.2), the designing process is changing and adopting more integrated methods. A key aspect of infrastructure projects, especially in the Netherlands, is the extensive use of the DBFM contract which requires from the contractor to both design and build the structure ordered by the client. This signifies that the contractor often receives only a list of requirements and is responsible for the right interpretation and realisation of them [Moonen, 2016]. The often abstract nature of those requirements can lead to misunderstandings and increase the work load, since design work which was considered completed has to be redone, in case it does not comply with the new interpretation of the requirements.

Interviews with architects and practitioners of other disciplines conducted within this research project, reveal that the interpretation of those requirements is a time-consuming process, where the initial design needs to be altered multiple times to meet the newly interpreted requirements at every step. The aforementioned condition creates the need to have an integrated approach during the design of infrastructure projects. The possibility to link the physical model to the knowledge behind it, would allow designers to preview design alternatives and induce intelligence into the design from its early stages, by taking into account possible conflicts and constructability issues [Day, 2016].

1.3.2 Building Information Modelling (BIM)

Building Information Modelling (BIM) has revolutionised the AEC industry, as it aspired to create a common design platform for all construction practitioners, thus limiting the misunderstandings among them. It is described by Autodesk as “an intelligent, 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure” [Autodesk, 2017a]. In general, BIMs are object-oriented information models offering rich geometric, topological, and semantic information of a building, enabling enhanced communication, coordination, analysis and quality control [Nepal, Staub-French, Pottinger, & Webster, 2012]. The former summarizes the ability of a BIM model to visualise the object by giving it dimensions, showing the connections between the different components and assigning materials to the components.

The definition of BIM, usually is a source of confusion and subject to a lot of different interpretations. It is important to understand that BIM is not linked to a specific computational tool, but provides guidelines for an integrated approach to the design of structures. A way to address this confusion, is to define a number of tool/technologies which are **not** BIM-based [Eastman et al., 2011]: (a) 3D models with no object attributes, (b) models without behaviour support, (c) models composed of multiple 2D files which need to be combined to create the whole 3D model and (d) changes in one view are not automatically updated in other views.

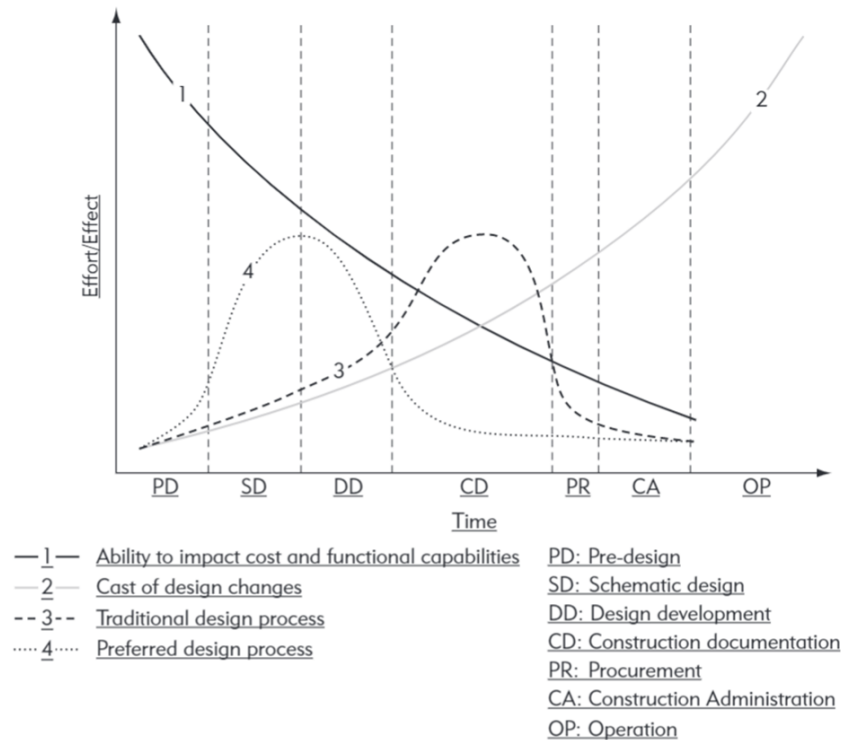


Figure 1.2: Macleamy Curve [Eastman et al., 2011]

The main malfunction of the AEC industry, that BIM sets out to tackle, is that it remains fragmented to a large extent. The term fragmented denotes, that the AEC industry is comprised of a large number of small companies, specialised in a specific role in the process, which need to collaborate to produce built structures [Coenders, 2011]. Moreover, communication still depends on paper-based means, which increases the possibility of errors and omissions and can result in friction between the parties involved, as well as unexpected costs. As Lachmi Khemlani indicates in the BIM Handbook [Eastman et al., 2011], BIM should not be seen as a mere technology change, but also as a process change. Indeed, by allowing an integrated, object-orientated representation of a building, not only the products of a traditional building design process (2-D drawings, visualisations and so on) change, but also the way the industry functions. The requirements of the client are established and used to develop schematic design concepts, and digitally build various alternatives, which are compared to each other in terms of energy use, structural efficiency, architectural quality, cost, constructability and other factors. Moreover, multidisciplinary teams are formed to develop a design based on multiple criteria from schematic design to the construction phase and also the operation and maintenance of the built structure. BIM concepts are becoming essential in the AEC industry. Investing time and effort into creating complete virtual models of the building process can also prevent cost overruns and even lead to an earlier completion of the project, such as the case of the Denver Art Museum by Daniel Libeskind [Garber, 2014].

BIM instigates a full collaboration of the stakeholders from the early stages of the project in order to achieve the desired goals. This paradigm transfers the intensity of the design process from the later to earlier stages of the project [Roundtable, 2004]. This concept is illustrated by the Macleamy curve (Figure 1.2). As can be seen in Figure 1.2, following a BIM workflow can set the foundation of a smooth process throughout

the life cycle of the AEC project and avoid costly changes during its later stages. Indeed, the Macleamy curve reveals the downsides of the traditional design process, where technicians put most effort during the construction documentation phase, where the cost of changes becomes extremely high.

Moreover, the adoption of BIM principles facilitates the explicit representation of information and enables the practitioners to easily ask for spatial and non-spatial queries, and access the data they need at the appropriate detail level or granularity. Therefore, BIM has become pivotal to the AEC industry, since it addresses the need of the practitioners to follow a design process, which is more knowledge-driven and information-intensive.

1.3.2.1 BIM Advantages

The advantages of a BIM strategy have already been mentioned above and they are summarised in this paragraph:

- BIM integrates a large number of disciplines and information fields, such as architecture, structural engineering, mechanical engineering, management, environmental impact, cost and so on, thus leading to well informed decisions and higher efficiency [Polit-Casillas & Howe, 2013].
- BIM allows automatic document generation in 2D and 3D, thus reducing the amount of time needed for mundane drafting and limiting the possibility of errors [Polit-Casillas & Howe, 2013].
- Interoperability allows the users to access and influence BIM data in multiple applications according to each design objective.
- Building information modelling enables the visualisation of multiple design options and alternatives, the identification of clashes between components and facilitates the communication of designs in a 3D context [Garber, 2014].
- BIM supports modularity by enabling an object-oriented design [Coenders, 2011]

1.3.2.2 BIM Limitations

In this paragraph, limitations of the current BIM approaches which are important to the research project are listed:

- A significant limitation of BIM processes is that they confine the design freedom, as they demand a large amount of decisions to be taken from the first steps of the conceptual design. Indeed, BIM softwares, such as Revit demand from the user a lot of information to create a concise model, which is not available in the beginning of the project. They are not interactive enough to support the abstract process of designing, as architects at BAM indicated.
- Another issue which derives from the aforementioned confinement of design choices can be referred to as “catalogue design”. The concern of the architects is that the object-oriented approach in combination with the object libraries reduces the design process to mere combinations of existing components [Coenders, 2011].
- BIM tools provide limited support for the representation of complex geometry, such as NURBS (Non-uniform Rational Basis Splines), mesh etc. The latter constitutes an important hindrance, as contemporary architecture strives for complex and even organic designs, which are not easily developed in a BIM environment [Coenders, 2011].
- While BIM is praised by most corporations in the AEC industry, a closer look at the way information is exchanged between the different parties involved, reveals its inefficiency. BIM is applied by using BIM software, such as Revit, and by exchanging the models which are created on these computational tools. That leads to the exchange of overwhelming amounts of information, between disciplines, most of which is irrelevant to the needs of each practitioner.

1.3.2.3 Resistance of Industry to BIM and New Technologies

Contact to AEC practitioners reveals that they are usually reluctant to explore and embrace new design paradigms, as well as use new designing platforms. The underlying reasons behind this observation can be reduced to a number of issues:

- First, the element of trust arises, whenever a new approach or software enters the market. Indeed, especially in the case of engineers, they want to be certain of the assumptions, theories and computational solutions offered by the new tool. For instance, in case of structural analysis, the engineers need to be 100 % sure that the results are accurate and comply with all norms and theories that must be applied in each case. Therefore, they are sceptical whenever it comes to new tools, as there is a considerable amount of implicit data hidden in the tool's structure, which the user cannot easily access and monitor.
- On the other hand, architects prefer tools that provide them with the needed freedom to design, without being confined in specific paths, therefore the tools that they use for conceptual design need to comply with this prerequisite [Abrishami et al., 2015].
- In both cases though, a very important factor lies in the fact that designers are usually accustomed to one tool and they do not want to make the effort to learn a new computational tool, especially if they are satisfied with the tool they currently use and they master it. This behaviour can also be justified by the fact that valuable time is needed for people not only to learn a new tool, but to become highly skilled in it, so they can use it for work purposes.

The aforementioned observations lead to the conclusion that there is a viscosity in the field of designing, much like in every system, whenever changes and new tools are implemented, which is a very useful deduction for this research.

1.3.2.4 Possible Solution

A possible solution to overcome the natural viscosity of the AEC industry to change is to embrace this behaviour, by focusing on interoperability.

Interoperability: Interoperability is a fundamental attribute of the BIM philosophy, which refers to the ability to transfer and process data on multiple computational platforms. However, data cannot be directly exchanged between computational tools, since each BIM design application has different definitions for its base objects and their behaviours. This problem exists only for parametric elements, as elements with fixed geometry and behaviour can be directly used in multiple BIM platforms [Eastman et al., 2011]. For instance, the most popular interoperability standard, IFC (Industry Foundation Classes) [Building Smart, 2018], is restricted in terms of the complexity of data it can transfer, as it transfers efficiently fixed geometry, but not higher levels of information. In essence, efficient interoperability encourages efficient collaboration between the AEC practitioners.

1.3.3 Computational Design

Computational design has revolutionised the design of structures, equipping the practitioner with all sorts of valuable tools, from Computer Aided Design (CAD) and 2D drawings to complex finite element analysis tools. A broad extent of computational algorithms are extensively used in the AEC industry, as they decrease the needed time for design production, they decrease the reaction time of engineers against design errors, they can support complex optimisation strategies and they enable engineers to explore design options, which otherwise would not be considered [Coenders, 2011].

1.3.3.1 Parametric Design

A great tool offered within computational design is parametric design. This tool empowers the designer, as parametric design is by essence non-destructive, meaning that one model contains all the previously explored solutions, as well as the ones yet to evaluate [Danhaive & Mueller, 2015]. As a result, the designer can investigate countless solutions and choose the most appropriate one. Moreover, parametric design no longer requires extensive programming knowledge from the designer, since visual programming languages have facilitated the creation/extension of the current computational tools. An intermediate paradigm between

coding and visual programming is DesignScript. DesignScript was developed by the Autodesk Singapore Research and Development Centre and it is the computational engine within Dynamo. As is described by Aish & Mendoza [2016], DesignScript is a multi-paradigm domain-specific end-user language and modelling environment for architectural and engineering computation. This language enables the users to become gradually accustomed with more advanced programming concepts, and address the scalability issues which occur when the user tackles a complex system with visual programming. DesignScript is employed in the parametric model created within this study, to reduce the volume of the parametric script. [Aish & Mendoza, 2016]

As Lars Hesselgren mentions, parametric design platforms such as Generative Components (Section 1.3.3.2) and Grasshopper [McNeel et al., 2010], encourage the concept that what the designers are developing is not the object itself, but a system of dependency [Kocatürk & Medjdoub, 2011]. Indeed, parametric design can be seen as a “constrained collection of schemata”, where the designer is responsible for defining the schemata and the constraints [Aish & Woodbury, 2005]. Therefore, establishing the most efficient relationships and dependencies between the components of a system becomes of crucial importance to reach a good design.

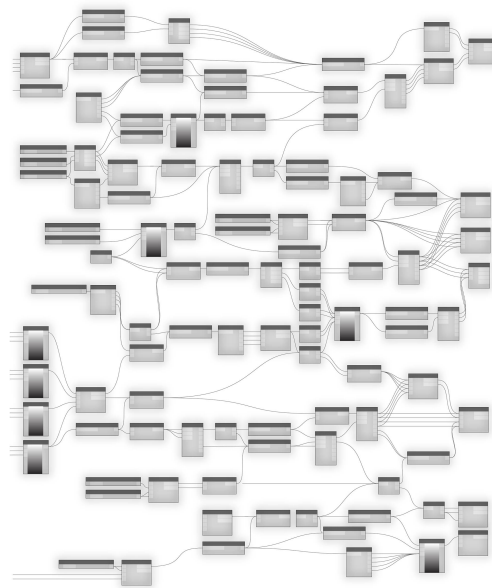


Figure 1.3: Anatomy of Visual Programming [Dynamo, 2016]

Moreover, parametric design aspires to improve the efficiency of any type of AEC project, in terms of architectural value, structural performance, form finding, cost, energy, sustainability, but also create generic models with recurring parameters, present in similar projects, so as to decrease the work load when a number of similar structures have to be designed. Starting from establishing simple relationships between the components of a structure, the density of information can be increased, to create more complex relationships and lead to a more detailed final outcome. A crucial first step in computational design is to define the requirements and expectations around a project and translate them into parameters whose values can be altered. The efficacy of a parametric model therefore, depends on the definition of a suitable set of parameters which express adequately the problem under investigation. Those parameters derive from interpreting information about the project and the relations between its various components. The current philosophy of parametric modelling in the building industry revolves usually around using optimisation techniques, depending on the criteria which are considered most important during the design. However, they do not help the designers grasp the larger impact of the design alternatives on the whole project. Robert Aish states that “(computational) tools embody conceptual knowledge” [Aish, 2011]. They do not only facilitate the design process through automation, but they are also sources of new conceptual knowledge. This dictates that tools should not restrict the designer but offer new possibilities and challenges.

1.3.3.2 Computational Paradigms

In this paragraph, a number of computational paradigms are presented. Those paradigms are used as an inspiration for this research, as they incorporate an integrated approach to designing.

GenerativeComponents

GenerativeComponents [Aish, 2003a], developed by Bentley, is a system whose base principles constitute an inspiration for this research. It is a design tool for exploratory architecture, developed with Microsoft .NET technology and uses object-oriented software engineering to transform user-defined geometric and behavioural design models into new objects. A formal definition of GenerativeComponents is the following: “a model-oriented end-user programming environment which combines direct interactive manipulation design methods, based on feature modelling and constraints, with visual and traditional programming techniques” [Aish, 2003b].

A number of general concepts on which GenerativeComponents is based are listed below [Aish, 2003a]:

- Express conceptual design in an intuitive form.
- Express design rules in a logical form.
- Develop project-specific components (including both intuition and logic) in a re-usable form.
- Model building fabric and the enclosure of space so that it can drive analytical and simulation tools.
- Integrate an exploratory design approach with conventional tools and processes.

GenerativeComponents provides the user with predefined geometric types and relationships, which can be combined to capture complex geometries and relationships. The system does not demand detailed data from the user from the early stages of the design process. Dimensions can be provided to system in numerical form or as references to parameters. A build-in change propagation mechanism enables the designers to explore various geometries and parameter values, with a resulting model being built at different levels of granularity. An important feature of GC is extensibility, which refers to the capacity to extend the available tool set and functionality to accommodate specific design requirements without needing programming skills [Aish, 2003a].

NetworkedDesign

NetworkedDesign [Coenders, 2011] is a design infrastructure which enables the user to model logic, based on a number of paradigms, such as object oriented logic, parametric relationships, and various operations to reach different results. Among the concepts proposed by NetworkedDesign lies multi-directionality, which enhances the concept of bi-directionality, and allows multiple logic flows between input and output. Conceptual links are created between disciplines (structural design and other engineering fields) to improve the usability of computational tools. The latter is achieved by investigating the dynamics of the design process and developing a theory (infrastructure) within which it can further develop. This research focuses in the field of parametric and associative design as the concept of design informed by performance.

StructuralComponents

StructuralComponents is a parametric structural design tool for high rise structures, which has been developed through academic research. It is based on GenerativeComponents [Aish, 2003a] for which extra features have been developed in a .NET environment [Rolvink et al., 2009]. StructuralComponents aims at facilitating the early-stage structural design by instantly analysing its performance. It offers a middle ground between simplified hand calculations and detailed finite element analyses. It is an attempt to address the abstraction of the first steps of designing by using computational tools and analytical methods within an overarching design logic [Van de Weerd, 2013]. This design tool is based on the super-element method, which is well-suited for tall buildings [Van de Weerd, 2013]. Moreover, this tool is based on the parametric and associative paradigm to better address the needs of the design synthesis stage.

1.3.3.3 Current Limitations of Computational and Parametric Design

- Computational methods do not adequately support the design process, which can be of a non-linear, cyclic, chaotic and abstract nature [Coenders, 2011].

- Parametric design can express limited semantics regarding objects and entities, as it is more focused on modelling geometry, based on complex mathematical reasoning (e.g Grasshopper).
- A parametric model is only useful within the logic it is created. If a different design issue needs to be tackled, it is very time-consuming to change the parametric model to address the new problem.
- Parametric platforms are based on a single-directionality concept, which means that there is a specific logical flow from a specific set of parameters to another, which opposes the cyclic nature of the design process [Coenders, 2011].
- The development of a parametric design algorithm is often accompanied by a certain level of abstraction in work. The relationships between the objects in the system need to be explicitly described and if a suitable node to express those relationships does not exist, then it needs to be developed. This induces a higher complexity to parametric design and requires skilled designers [Aish & Woodbury, 2005].

2 Problem Analysis

In this section, a detailed approach to the research project is presented. The main research question of the research project is the following:

To what extent can the design of concrete viaducts be explicitly described in a knowledge model and how can this knowledge model be translated into a parametric tool, facilitating the design process for the architect and serve as a communication tool between the architect and the structural engineer?

In order to answer the main research question, the research project can be divided in two parts:

- The development of a knowledge model (Section 2.2)
- The development of a computational, parametric model (Section 2.3)

The two objectives are linked, as the parametric tool is the computational representation of the knowledge model. More research sub-questions are defined within the following two parts of the project.

2.1 Principles of Research

A number of approaches and concepts are chosen as guidelines and inspiration for this research project. Those concepts are listed below:

2.1.1 Extreme Programming

Extreme Programming is a methodology which is mainly employed in software development. It aims at improving software quality by introducing frequent “releases” to the public and improving them based on the received feedback [Wells, 2006].

※How is it implemented in this research project?

The most important attribute of Extreme Programming which is used in this research is the development of the algorithm in short steps, while consulting architects and engineers about its validity, usefulness and possible improvements. In this way, the final outcome of the research is bound to address adequately the needs of the designers, since they have actively contributed in its development.

2.1.2 Object-Oriented Programming (OOP)

Object-oriented programming (OOP) is a programming paradigm whose fundamental concept is the concept of “objects” which contain data, in the form of fields, also known as attributes and code, in the form of procedures, often known as methods [Wikipedia, 2017b].

※How is it implemented in this research project?

A number of key concepts of object-oriented programming are used in this research:

- **Objects:** The concept of an object is the central idea of object-oriented programming and refers to an entity with specific attributes and behaviour [Coenders, 2011]. Objects can be defined as data structures encapsulating an internal state, which offer conditional access to this state through a set of methods [Pierce, 2002].
- **Classes:** Classes are in essence templates from which objects can be instantiated [Pierce, 2002].
- **Multiple Representations:** An important feature of OOP is the ability of the objects to use different representations, even if they respond to the same set of operations (methods) [Pierce, 2002].
- **Encapsulation:** Encapsulation ensures that the internal representation of an object is generally protected from elements outside the object’s scope [Pierce, 2002].
- **Inheritance:** The ability of classes to derive from other classes and inherit their attributes and behaviours [Pierce, 2002].

2.1.3 Model-Based Systems Engineering (MBSE)

In order to facilitate the mapping of the design process, Model-Based Systems Engineering (MBSE) principles are employed, as MBSE offers a structured method to develop a system that functions in a controlled process and meets the requirements of the stakeholders [Moonen, 2016]. Moreover, it uses models as an integral part of the technical process which includes the requirements, analysis, design, implementation, and verification of a property, system, and product throughout the life cycle of a project [Hart, 2015].

※How is it implemented in this research project?

Systems Engineering principles are not followed blindly in this research, since they are tied to a strict top-down design, which does not comply with the versatility of the expected outcome of this research. In this research project, a combination of top down and bottom up design approaches is considered. A systems Engineering model of the viaduct (knowledge model) and a bottom-up parametric model are developed and the interrelations between them are investigated. The connection between those two approaches and the conflicts which inevitably occur can instigate interesting contradictions and reconsiderations of the attributes and relations between the viaduct's components, leading to possibly radical design strategies. The benefits of the Systems Engineering structured way to deal with information are recognised, therefore some features and principles are employed in this research project. The most important feature of MBSE that is used is the creation of a graphical model, which represents the system of a viaduct.

2.2 Knowledge Model Development

The development of an AEC project and particularly an infrastructure project, involves a large amount of implicit and explicit information. Especially, during the design phase, a large percentage of this information remains tacit and hidden within the project's requirements and the designer's intuition [Bernal et al., 2015]. As can be seen in Figure 2.1, trying to unlock the knowledge behind a design process (Knowledge-Based Engineering) can help the engineer/architect focus on more creative parts of the design process and take well informed decisions based on an extensive knowledge database [Verhagen et al., 2012]. This research project aspires to interpret the implicit information and create a standardised knowledge tool to facilitate the design process. Emphasis is given on semantic completeness [Aish, 2000], which is the basis of a transparent design process.

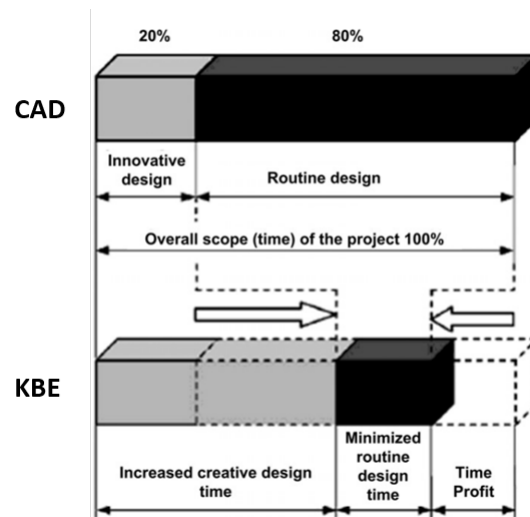


Figure 2.1: Traditional CAD Design Process vs Knowledge-Based Design Process [Verhagen et al., 2012]

Sub-questions within this part of the research are the following:

- Q1. What are the main components/objects of the viaduct that compose the knowledge model?
- Q2. What is the desirable level of detail in the knowledge model?

- Q3. What are the main components of the bridge which the design teams change more often?
- Q4. Which is the appropriate way to design the viaduct 's components, so as to enclose both architectural and structural knowledge?

The knowledge model around a concrete viaduct has the following goals:

- Document the steps of designing
- Define the systems and subsystems of a bridge
- Define and distribute the requirements
- Clarify the parts of the design process which are most often misinterpreted

In Figure 2.2, the steps that need to be followed to develop the knowledge model and its connection to the parametric model are illustrated in a graphical model.

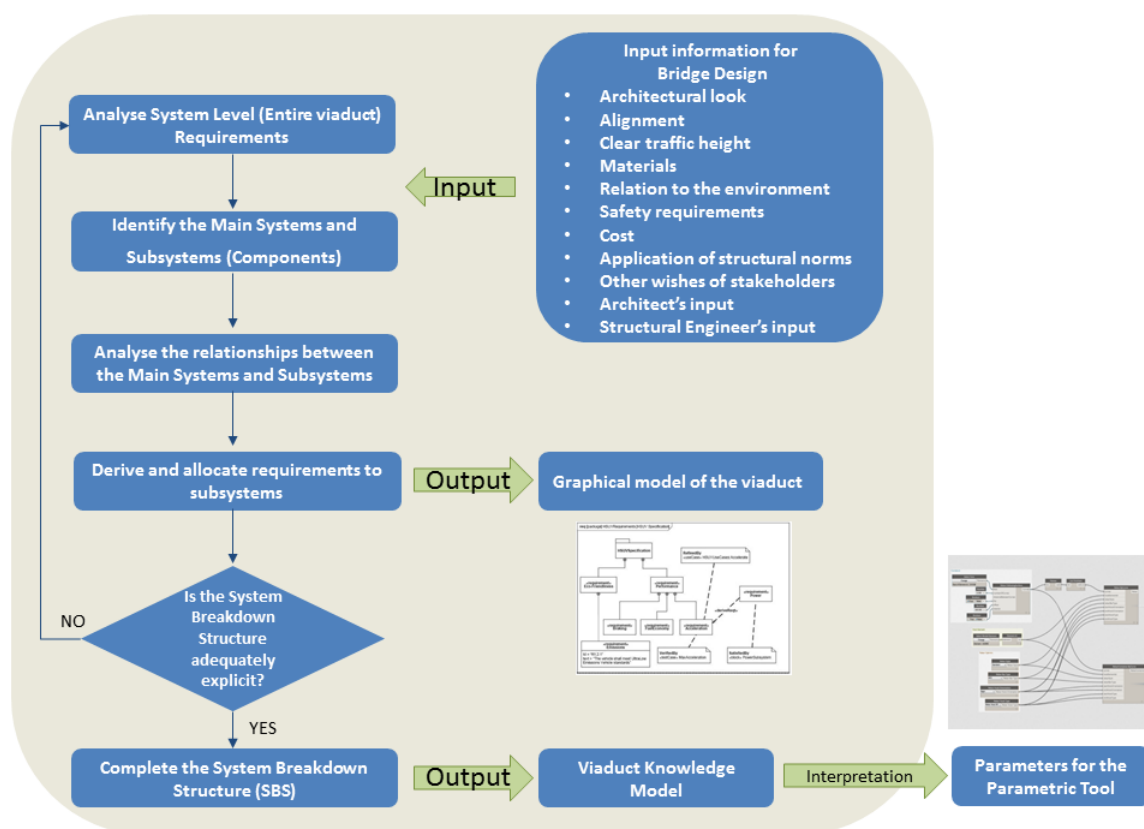


Figure 2.2: Work process for the Development of the Knowledge Model and its relation to the Parametric Model

Understanding the views of architects and structural engineers on the design process is very important, as they are usually different and not integrated. Indeed, since the structural and architectural models are typically developed not only by different disciplines, but sometimes also from different companies, the attributes of the objects and the physical relationships between them are typically not explicit. Undoubtedly, what constitutes a common vocabulary/shared definition for one individual may not be the same for another practitioner. In the knowledge model, emphasis is given on rendering the implicit information from both disciplines into explicit design requirements and steps. Therefore, the knowledge model is comprised of information from both sources.

A crucial part of the project is to understand the steps followed in the design process and define the requirements, which are set in the beginning of the process, and how those evolve throughout the project.

In order to map the aforementioned process, an understanding of the interaction among the stakeholders needs to be established. A detailed stakeholder analysis is not deemed crucial for the current project. The main stakeholders, who are considered in the project, are the architect, the structural engineer and the client. The focus is on developing a flexible system for the translation of the specifications/requirements into a knowledge database which can easily be adapted by the user. The nature and flow of the information which is exchanged between the stakeholders is analysed to underline the weak/poorly defined parts of the process and ways to improve it. Among the aims of this research is to identify recurrent steps and attempt to standardise them by creating a concise knowledge model, linked to a variety of knowledge areas. In bridge design, there are a large number of knowledge areas, some of which are listed below:

- Design requirements
- The Aesthetic quality of the bridge
- The structural model / structural calculations
- BIM considerations
- Drawings
- Risks

Within the research, ways are sought to standardise and automate some domains of those knowledge areas, which do not manifest very abstract design needs, and to improve the influence of the designer in domains, which are of crucial importance to the final design.

Graphical Model of the System

The systematic schematization of the knowledge around a domain is essential to represent information about the domain and draw conclusions from it. An essential first step is to create a simplified version of the complex bridge design process, therefore, create a graphical model of the aforementioned process. That model represents an abstraction of reality through the elimination of unnecessary components. The goals of this model can be summarised below:

- Facilitate the understanding of the process
- Provide aid in decision making
- Explain and control the viaduct components and the relationships among them

Pivotal aspects of that graphical system model are:

- The classes which represent the components of a viaduct
- Properties of the components
- Interconnections between the components
- Structural considerations

The MBSE principles are implemented in the thesis scope by considering the viaduct as an ontology, comprised of various systems and subsystems (components) which have their own requirements and goals in a local level, but are also connected to each other, so as to meet global requirements and goals. As an ontology, the viaduct model includes a set of concepts, entities, properties and functions, as well as their definitions, relationships and semantics [Nepal, Staub-French, Pottinger, & Zhang, 2012]. Following the example of Polit-Casillas et al. [Polit-Casillas & Howe, 2013], who focused in connecting BIM with SysML in the aerospace industry, a graphical modelling language (UML - Section 2.2.1) is employed to create the viaduct's model, understand the design steps and structure the information and knowledge that is gained throughout the process.

Main systems can be denoted within the viaduct knowledge model, which contain a number of subsystems, as can be seen in Figure 2.3. The main systems of a bridge are its main elements, such as the deck, the piers

and the abutments. Those main systems are further reduced to sub-systems which represent more specific components.

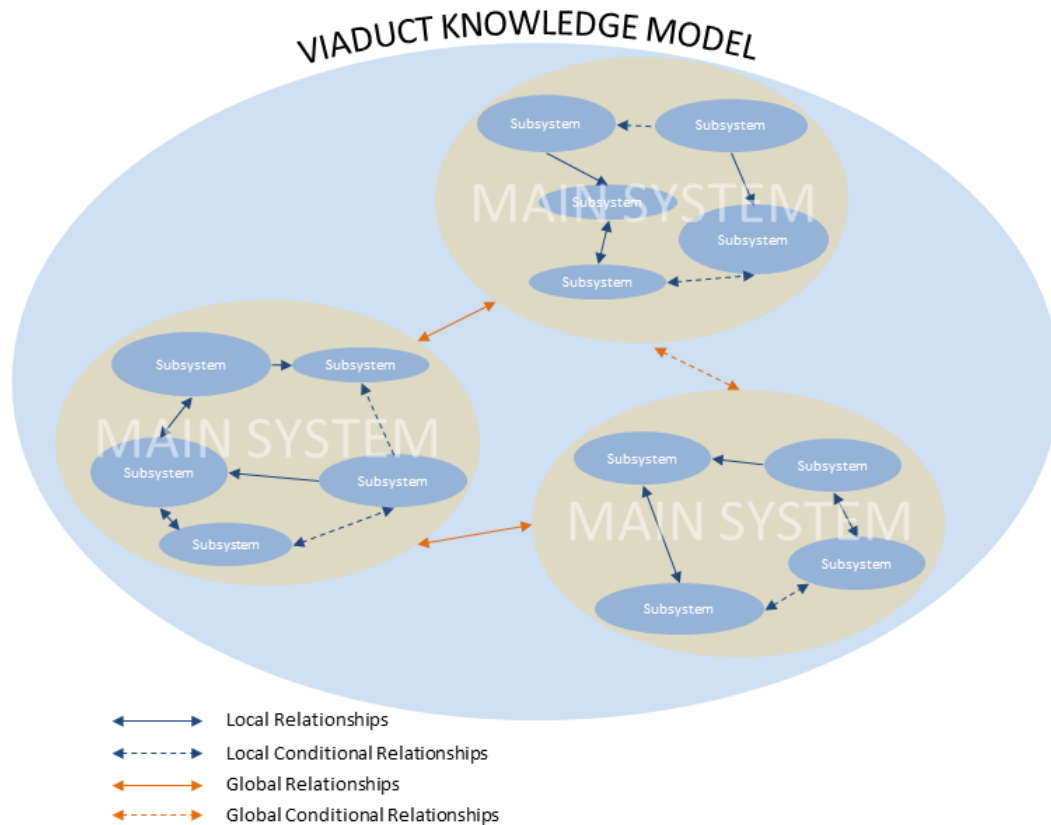


Figure 2.3: Knowledge Model - Schematic View

Three important types of information types are present in the knowledge model:

- **Main system/Sub-system(Component) Features:** This type of information refers to the attributes of each main system or subsystem. Those features can be geometric (spatial) or qualitative (non-spatial), as well as constraints.
- **Local (Conditional) Relationships:** Local relationships refer to the relationships within each main system, namely between the available subsystems. The conditional aspect signifies that the two sub-systems are interrelated only if certain constraints/requirements are present.
- **Global (Conditional) Relationships:** Global relationships refer to the macro features of the viaduct knowledge model, which derive from the interaction among its main systems. The conditional aspect signifies that the two main systems are interrelated only if certain constraints/requirements are present.

To summarise, the knowledge model constitutes a semantic or ontological model, developing a taxonomy or vocabulary of design oriented information, and conceptualising it through the use of relations, constraints or axioms. This model is able to address design specific queries and is comprised of components which are **consistent, unambiguous** and **computer-interpretable** [Staub-French & Nepal, 2007]. This dictates that the components of the bridge should be sufficiently defined, taking into account their geometric, semantic and topological attributes.

2.2.1 Unified Modelling Language (UML)

The Unified Modelling Language (UML) is a general-purpose, developmental, modelling language in the field of software engineering, which provides a standard way to visualize the design of a system [Rumbaugh et al., 2004]. It is a graphical way to illustrate relationships between classes in an object-oriented system. An important advantage of UML is that it is language-agnostic, therefore it is not bounded within a specific programming environment. Indeed, the diagrams created with this approach can be translated to any programming language such as C#, Java, or in the case of this research, Dynamo and Python. UML offers a variety of different diagrams regarding the aim of each project. In the case of this research, the class diagrams are deemed appropriate, as they support an object-oriented approach. A more detailed introduction to the semantics of UML class diagrams which are used in this research is given in Appendix A. The main strengths and weaknesses of UML class diagrams are presented in table 1.

Table 1: Strengths & weaknesses of UML class diagrams

UML class diagrams	
Strengths	Weaknesses
Discovering related data and attributes	Discovering algorithmic (not-data driven) behaviour
Getting a quick picture of the important entities in a system	Finding the flow of steps for objects to solve a given problem
Seeing whether you have too few/many classes	Understanding the app's overall control flow (event-driven? Web-based? Sequential?)
Seeing whether the relationships between objects are too complex, too many in number, simple enough etc	
Spotting dependencies between one class/object and another	

A closer look at Table 1, shows that UML, based on its strengths, is ideal for the development of the viaduct's knowledge model, as it can represent the knowledge in a structured way and reveal the most efficient ways to connect the components. However, the weaknesses of UML reveal that the UML knowledge model is not adequate to represent a real structure with knowledge and data flow in multiple directions. However, this does not constitute a critical issue, since the parametric model of the viaduct, incorporates the missing information from the UML model and simulates the whole structure with both its attributes and behaviour.

Why is a UML model employed before the development of the computational tool?

An initial approach on the topic might lead to the notion that a parametric model is the only product which is expected from this research. However, a more thorough investigation points out that creating first a UML model can facilitate the development and monitoring of the algorithm, before its translation to a parametric model. It offers a way to understand behaviour and relationships outside the context of a programming environment. Moreover, UML offers predefined semantics regarding the systems's structure thus facilitating the creation of an explicit algorithm to represent the viaduct. Indeed, the main purpose of the thesis is not to create a mere computational tool, but to develop a generic, flexible and knowledge-intensive approach towards viaduct design. An important note regarding the nature of UML diagrams is that they describe a top-down design process. In the case of this research however, a strict top-down approach is not desired, as it would lead to a very standardised outcome. The UML diagram is used as a guideline and not as an exact depiction of the system, which in the end is translated into a bottom-up, parametric model.

2.3 Parametric Tool Development

After the knowledge model is composed and explicitly describes the bridge design process, the attributes of the components and the relationships between them, a dynamic relation between the knowledge database and the structure itself is created. This is achieved with the development of a parametric tool, which facilitates the design process. It serves as a communication tool between the architect and the structural engineer,

in an attempt to connect the conceptual design phase with the structural analysis part. It functions as a design platform for both architects and structural engineers, which enables the architects to explore different geometries and shapes, while communicating them to the structural engineers. An important advantage of the tool is that it allows for flexibility in the definition of geometry, without restricting the design at an early stage, thus enabling divergent design spaces [Bernal et al., 2015]. At the same time, it implements the structural design in the process [Danhaive & Mueller, 2015]. A Problem with the current computational methods is that they represent the knowledge around component similarity implicitly in computer code or with just prescriptive statements [Staub-French & Nepal, 2007]. Knowledge should be communicated through the model, therefore it is important to explicitly represent the attributes and relationships of the objects. A number of key attributes of the parametric model are the following:

- Representation of numeric (geometric) properties
- Representation of ranges for numeric properties
- Satisfaction of multiple criteria simultaneously
- Evaluation of the degree of variation consistently and quantitatively
- Support of the customisation of the criteria to address the designer's preferences

The research questions which arise within the parametric tool development are the following:

- *Q5. What parametric plugins can facilitate the integration of the structural analysis in the parametric model?*
- *Q6. How can terrain considerations be implemented into the design?*
- *Q7. How can a user-friendly interface be developed?*

Following the completion of the viaduct breakdown structure in the first part of the project, the challenge in this step is to model the systems and sub-systems of the viaduct, as well as their relationships. Those relationships between the components/subsystems of the bridge can be spatial, which play a crucial role in the whole design process or non-spatial, denoting the attributes of each subsystem. The goal is to create a flexible, explicit modelling tool, without the irreducibility of an implicit approach. A flexible representation of building information facilitates the evolution and adaptation of the design while catering to the needs of designers. Moreover, the integrated knowledge should not confine the design spaces, but enhance the ability of the user to explore new designs, based on the knowledge assigned to them and not through mere drawing tools. Moreover, for the final visualisation of the bridge the location should be taken into account, by virtually positioning the viaduct in the actual environment, thus enabling the designer to have a complete overview of how each choice affects the final outcome.

2.3.1 Parametric Platform

The determination of the parametric platform on which the parametric tool is developed is not a simple choice, considering the plethora of parametric platforms available. However, for the current project the parametric platform is Dynamo [DynamoBIM, 2017] for the following reasons:

- Dynamo is the parametric platform for Revit [Autodesk, 2017b], which is a BIM software, making it ideal for the development of the object-oriented tool under investigation.
- It allows designers and engineers to create geometrical relationships based on rules and logic, rather than traditional sculpting/push-pull commands. Dynamo uses Visual Programming.
- Dynamo offers satisfactory connection to other computational tools, such as EXCEL, Relatics, CAD software etc.
- Structural plugins can be implemented in the Dynamo script, thus making the structural analysis of the design possible. A Dynamo package exists to connect Dynamo and ROBOT [Autodesk, 2017c], a structural analysis software, thus enabling a direct structural analysis of the design.

- The possibilities offered within Dynamo can be extended, by employing a large number of available packages, but also by adding Python code blocks, wherever it is needed, enabling the user to create a fully customised script.
- Revit allows the user to access its API, the application programming interface, that provides a way to programmatically access (using Python) the internal representation of BIM data in Revit. This enables the user to understand and alter the implicit information, hidden behind the Revit object families and redefine the attributes and spatial data of the objects. Gaining access to the way Revit represents objects, enables a more sophisticated and customized algorithm development and the ability to address the needs of the designer for the specific project of viaducts. Moreover, the use of Python code blocks can decrease the volume of the Dynamo script and the number of complicated wires connecting the components, referred to as “Spaghetti Problem”. This solution however, leads to the development of a “black box”, where the logic is concealed in textual coding nodes.
- Revit and Dynamo are extensively used by companies in the AEC industry and also by BAM. Therefore, developing a tool on a platform which is familiar to the design practitioners, to whom the tool is aimed, is of pivotal importance to test its efficiency and usability and also be of use to actual BAM projects.

2.4 Design Dynamics

Bridge design, much like any design process, depends highly on the ability of the designer to visualise the outcome. The aforementioned ability stems from the designer’s creativity, as well as knowledge and experience.

2.4.1 Understanding the Design Process

As mentioned in the “Bridge Engineering Handbook” [Chen & Duan, 2000], the design process can be divided in two steps. The first step is the preliminary design, which results in the generation of a number of alternatives and the second step includes the check of the alternatives. During the preliminary design of a structure, a crucial part of the whole design process takes place, which is the refinement of the design schemas, followed by the choice of the most appropriate one. The choice of a bridge scheme depends on the designer’s intuition, experience and project requirements.

During the design process, a number of constraints always arise. Robert Aish [Garber, 2014] mentions that the design process is subject to three main constraints regardless the task at hand. The first constraint is the level to which the design satisfies the intuition, the ideas and desires of the designer. The second constraint lies in the level to which a design satisfies the requirements set by the other stakeholders and the third constraint lies in the flexibility of the design to adapt itself to new developments. This signifies that a flexible, generic template can be of great value for every design purpose, as it will provide the architect/engineer with a generic design, which can be easily adapted to address the needs, requirements and vision of each project.

2.4.2 From Abstraction to a Concrete Design

Bridge design involves taking a large amount of decisions, in order to reach a final, structurally sound and cost efficient design. The type of the bridge whether it is a pedestrian, a traffic or a train bridge indicates not only a volume for the structure, but also a number of suitable construction methods and materials. Bridges can be constructed using an abundance of materials, such as concrete, steel, FRP and even glass, or a combination of those materials. The most popular materials for bridge construction are concrete and steel. A number of factors determine which material and subsequently which type of construction are chosen, with the most governing ones being the type of the bridge, the cost and the desired shape. Undeniably, steel offers more design freedom compared to concrete, in terms of the shapes that can be achieved. However, this larger design freedom is also accompanied by a much higher cost, in average 2 times the cost of concrete. In this research, in order to limit the scope of the design, only concrete is considered and more specifically prefabricated concrete.

2.4.2.1 Prefab vs In situ Viaducts

For the common concrete viaducts, which are the structures under investigation for this research, two types of construction methods are usually considered: Prefab or In situ. A brief introduction to both construction

methods is given in this paragraph, focusing on the comparison between them.

Prefabricated Concrete Viaducts: In this construction method, the concrete beams of the superstructure, are precast and usually prestressed in the factory of the supplier. The beams are then transferred to the location of the project and put into place. Other components of the viaduct, such as columns and foundation beams, can also be prefabricated, however usually they are cast in situ.

In situ Viaducts: In this construction method, viaducts are completely constructed on site. Sufficient space is required at the location of the viaduct for the equipment needed for construction, such as the temporary scaffolding.

Comparison between methods

The choice for prefab concrete or in situ concrete depends highly on the designer, as the client hardly ever specifies this aspect in the requirements.

A governing factor for the design of the bridge is the environment and the restrictions it imposes on the design, as well as the final cost. A restriction, with respect to the latter, is the relation with the surrounding infrastructure. If a bridge needs to be built over a busy road with the least possible disturbance to the traffic, prefab concrete is a more attractive solution, as it leads to a faster construction. If the traffic disturbance or the construction time are not significant parameters for the project, then in situ concrete is more likely to be preferred, as it is usually more cost efficient. In general, prefab elements are more expensive than in situ concrete, however they allow for a shorter construction time.

With in situ concrete, more labour work at site is required which creates more safety issues and risks, compared to prefab concrete, where most of the work is done in the factory. Moreover, the concrete quality and strength achieved in the factory for the prefabricated beams can be higher compared to in situ concrete, as the environment in the factory is highly controlled and independent of weather conditions.

Prefab concrete will require the use of bearings and capping beams, while in situ concrete, allows the beams to be cast together with the abutments (monolithic connection), without the need of bearings. Therefore, in terms of aesthetics, in situ can be more appealing, as larger bridge components are constructed at once leading to the elimination of any in between seams. Moreover, A complex geometry can be more easily realised with in situ concrete, as the fabrication methods for prefab beams impose limitations on the geometry that can be produced in the factory. In addition to that, the production of special/unique elements can be very expensive as the supplier will need to redesign the available formworks or even construct new formworks to produce the beams.

Choice of Method:

In order to further limit the scope of this study and to be able to insert a level of automation in the structural analysis part, prefabricated beams are only considered, as they have standard properties.

2.4.3 Processing Requirements

Figure 2.4 depicts a simplified view of the requirement processing as described by practitioners at BAM. Initially, the client sets a list of requirements for a project, which then are interpreted by the respective experts (architects, structural engineers, mechanical engineers etc.) of the contractor company. During the internal requirement processing, the contractor either agrees with the initial requirements set by the client or suggests alterations. A discussion between the parties follows regarding the revised requirements, and the client decides whether the changes are approved or not. In the former scenario, the approved requirements are included in the final contract, whereas in the latter scenario, the contractor needs to repeat the requirement interpretation step of the process until there is an agreement with the client.

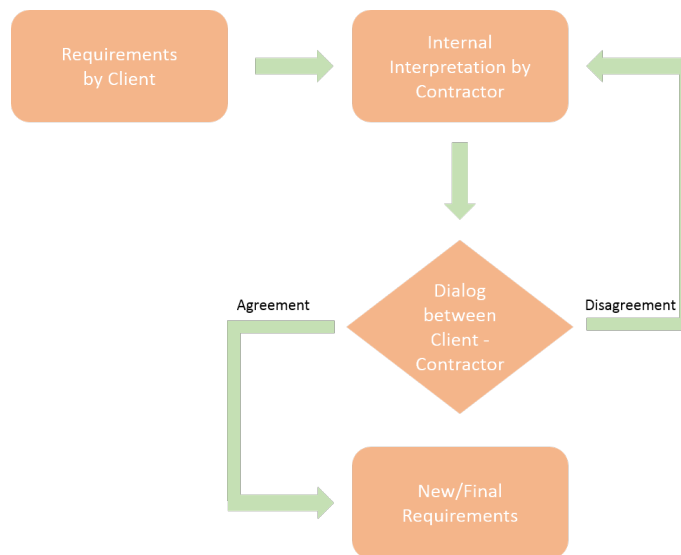


Figure 2.4: Requirement Processing within BAM

As can be easily understood, the aforementioned process can be very time-consuming and lead to conflicts between the parties involved, delay of the project execution, and ultimately cost overrun.

A requirement is an interpretation of a client's need, which can be of an abstract nature. Defining clearly the interaction between the requirements and the needs of the clients is a crucial step for the design process. At first, some of these requirements may only apply to spaces and not specific elements. However, as a space is not a tangible object, these requirements need to be answered by the elements which are contained by the space. For instance, a requirement regarding the acoustic comfort of a room can be interpreted as specific sound insulation requirements for the surrounding walls.

Regarding the assessment of the requirements, an efficient initial approach is to define whether they are SMART or not. SMART stands for Specific, Measurable, Attainable, Realizable and Time bounded. The goal of this process is to make the requirements understandable and eliminate the possibility of misunderstandings [Moonen, 2016].

Some recurrent requirement categories can be seen below:

- spatial
- environment
- technical
- construction
- safety
- sustainability
- material/colours

A requirement analysis can be useful to identify common attributes between different viaduct designs and behaviour patterns of the structure. The requirements of the project Hoevelaken, especially those for the most standard viaduct, are used as a case study for the aforementioned analysis.

A requirement that recurs among the requirements of the Quality Team for the Hoevelaken project is that the design should be composed of smooth lines which are integrated in the environment. The aforementioned requirement implies that the generic viaduct design which is sought in this research project should be able to accommodate not only a rationalised design, but also a fluid and smooth design (Figure 2.5).



Figure 2.5: Smooth, curved bottom deck edges are preferred over rationalised ones - Requirement by Quality Team

2.5 Structural Analysis Considerations

Structural design includes the arrangement and dimensioning of structural systems and their constituent components, so that the final structure is capable of coping with the design loads over a predefined life span within the allowable, by the respective codes, limit states [Parke & Hewson, 2008]. In essence, structural analysis seeks to define the response of a structure under the applied loads by considering a simplified mathematical model instead of the actual structure. Idealisations regarding the material and the structural behaviour of the structure are common practices of structural analysis strategies, due to inadequate data or excessive calculation requirements. Typical simplifications are the following:

- **Idealised physical dimensions** For instance, structures are usually represented by elements of negligible size, while any imperfections are either ignored or idealised.
- **Idealised material behaviour** For instance, the behaviour of steel is considered at first ideally-elastic and then perfectly plastic, while material impurities and local instabilities are usually not accounted for.

2.5.1 Structural Elements

The simple units that comprise any complex structure are termed “members” or “elements” and generally, they can be classified into the following three categories [Parke & Hewson, 2008]:

- Skeletal structures, where the members have one dominant dimension, which is much larger than the other two. Those line elements are named bars, beams, columns or ties.
- Structures with members whose two dimensions (length and width) are much larger than the third (thickness), are named plated structures. A further classification of the plated structures as plates or shells, lies on whether they are plane or curved.
- The third category refers to structures whose elements have all three dimensions of the third order. The analysis of these structures is extremely complex even with simplifying assumptions.

Structural analysis is usually not considered an objective, during conceptual design. Moreover, it is often seen as a constraint for the design, instead of a leading parameter [Coenders, 2011]. However, by integrating structural design during the initial phases of the project, efficient and architecturally expressive forms can be achieved [Danhaive & Mueller, 2015]. The majority of the structural analysis tools do not adequately support the conceptual design phase of a project, since they are mainly focused on producing precise results, rather than generating design alternatives, providing design flexibility, as well as a clear overview over the design concepts [Rolvink et al., 2009].

2.5.2 Structural/ Non-Structural Components

In order to develop a generic structural analysis for viaducts, a separation of the components in structural and non-structural should be made. In table 2, the distinction between the components is shown. For the non-structural components the architectural and functional value is dominant, while for the structural components the structural capacity becomes the crucial factor for the design. Components such as the edge

beams have a dual function, since they have a structural role, but are also chosen based on aesthetical value.

Table 2: Structural and Non-Structural Components

Structural and Non-Structural Components	
Structural	Non-Structural
Deck Beam	Cornice
Abutment	Railing
Bearing	Lighting Pole
Edge Beam	Sidewalk
Foundation Pile	Asphalt Layer
Concrete Slab	Surroundings
Pier Cap	
Wing Wall	
Pier Column	

The knowledge model includes structural information as well, meaning that the choices made by the designer have also an impact on the structural behaviour of the viaduct. However, the complete structural analysis of the viaduct and the exact implementation of the codes is not in the scope of the current thesis, as it would be time-consuming without being innovative. Moreover, following the example of Malsane et al [Malsane et al., 2015] building regulations are not implemented in the design process due to their obscurity and local nature. This research results in a proof of concept which should not be tied to specific regulations. Literature study and interviews with the structural engineers at BAM reveal the main aspects of the structural analysis which need to be tested in the initial design and implement them in the model. The option which is investigated within the model is the use of prefabricated beams, thus creating an actual link between the design phase and the construction phase. Supplier's data sheets provide all information about the prefab elements, including structural performance data, which could simplify the structural analysis part of the project. Therefore, the main questions regarding the structural analysis of the viaduct are the following:

- Q8. What loads should be considered?
- Q9. What are the structural considerations that influence the design?
- Q10. What structural considerations/checks are too detailed and can therefore be omitted?
- Q11. How can the structural analysis be integrated in the model, without restricting the design spaces?

In the current study, the structural analysis will aim at testing the required prestressing of the viaduct's deck. The aforementioned goal denotes that the current knowledge model can be further extended, so as to enable the engineer to calculate a final cost for the viaduct and compare the different solutions, not only aesthetically but also in terms of structural integrity and cost efficiency.

2.5.3 Orthotropy

In bridge engineering, it often occurs that the slabs are not homogeneous and isotropic, thus they do not have the same properties in all directions. A usual simplification of the issue is the consideration of an orthotropic slab, which displays direction-dependent properties. This means that the plate behaves differently in the longitudinal and transverse direction. In this case, the kinematic and equilibrium relationships remain the same, but the constitutive equations change from the homogeneous, isotropic case [Blaauwendraad, 2012].

The governing expression for an orthotropic plate is the following:

$$D_x \frac{\delta^4 w}{\delta x^4} + 2H \frac{\delta^4 w}{\delta x^2 + \delta y^2} + D_y \frac{\delta^4 w}{\delta y^4} = q$$

The stiffness matrix for plates with the effect of shear taken into account is shown below:

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \\ T_x \\ T_y \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & 0 & & \\ D_{21} & D_{22} & 0 & & 0 \\ 0 & 0 & D_{33} & & \\ & & & D_{44} & 0 \\ & 0 & & 0 & D_{55} \end{bmatrix} \begin{bmatrix} w_{xx} \\ w_{yy} \\ 2w_{xy} \\ w_x + \phi_y \\ w_y - \phi \end{bmatrix}$$

D_{11} , and D_{22} are the flexural rigidities in the longitudinal and transverse direction respectively. D_{33} is the torsional rigidity of the slab and $D_{12} = D_{21}$ is the off-diagonal rigidity. D_{44} and D_{55} are the shear rigidities [Blaauwendraad, 2012]. Those parameters comprise the stiffness matrix, which is set in Robot to model the orthotropic plate.

$$D_{11} = \frac{E_{c,beam} I_y}{b_w} \quad (1)$$

$$D_{22} = \frac{E_{c,PresLayer} h_x^3}{12(1 - \nu^2)} \quad (2)$$

$$D_{12} = \nu \cdot \min(D_{11}, D_{22}) \quad (3)$$

$$D_{33} = \frac{K_{xy} + K_{yx}}{4} \quad (4)$$

$$D_{44} = \frac{5}{6} \frac{G_y A_{eq}}{b_w} \quad (5)$$

$$D_{55} = \frac{5}{6} G_x h_x \quad (6)$$

$$K_{xy} = \frac{G_y h_y^3}{6} \quad (7)$$

$$K_{yx} = \frac{G_x h_x^3}{6} \quad (8)$$

2.5.4 Material

The material considered for the prestressed beams is C60/75 and for the concrete pressure layer is C35/45. The Poisson ratio for uncracked concrete is 0.2. The concrete is considered uncracked in this study. The properties of the materials are denoted below:

	Strength classes for concrete													
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0
$f_{ctk,0,05}$ (MPa)	1,1	1,3	1,5	1,8	2,0	2,2	2,5	2,7	2,9	3,0	3,1	3,2	3,4	3,5
$f_{ctk,0,95}$ (MPa)	2,0	2,5	2,9	3,3	3,8	4,2	4,6	4,9	5,3	5,5	5,7	6,0	6,3	6,6
E_{cm} (GPa)	27	29	30	31	32	34	35	36	37	38	39	41	42	44
ϵ_{c1} (‰)	1,8	1,9	2,0	2,1	2,2	2,25	2,3	2,4	2,45	2,5	2,6	2,7	2,8	2,8
ϵ_{cu1} (‰)	3,5									3,2	3,0	2,8	2,8	2,8
ϵ_{c2} (‰)	2,0									2,2	2,3	2,4	2,5	2,6
ϵ_{cu2} (‰)	3,5									3,1	2,9	2,7	2,6	2,6
n	2,0									1,75	1,6	1,45	1,4	1,4
ϵ_{c3} (‰)	1,75									1,8	1,9	2,0	2,2	2,3
ϵ_{cu3} (‰)	3,5									3,1	2,9	2,7	2,6	2,6

Figure 2.6: Properties of Concrete [EN1992-1-1(2004), 1992]

The steel class considered for the prestressing is Y1860. Its properties can be seen in Figure 2.7.

steel type	type	tensile strength		fracture strain	0,1% proof-stress	maximum tensile stress			slope discontinuity in the σ - ϵ diagram (ULS)	modulus of elasticity
		f_{pk}	f_{pk}/γ_s			during pre-stressing	during pre-stressing with accurate jack	initial stress		
		MPa	MPa	‰	MPa	MPa	MPa	MPa	MPa	GPa
Y1030H	bar	1030	936	35	927	773	773	773	843	205 or 170
Y1670C	wire	1670	1518	35	1503	1336	1428	1253	1366	205
Y1770C	wire	1770	1609	35	1593	1416	1513	1328	1448	205
Y1860S7	strand	1860	1691	35	1674	1488	1590	1395	1522	195

Figure 2.7: Properties of Prestressing Steel [EN1992-1-1(2004), 1992]

2.5.5 Loading

The dominant loads on bridges are composed of the following:

- Gravity loads due to self-weight
- The mass and dynamic effects of traffic

Apart from the main loads mentioned above, other loads include those due to wind, earthquakes, snow, construction and earthquakes as illustrated in Figure 2.8.

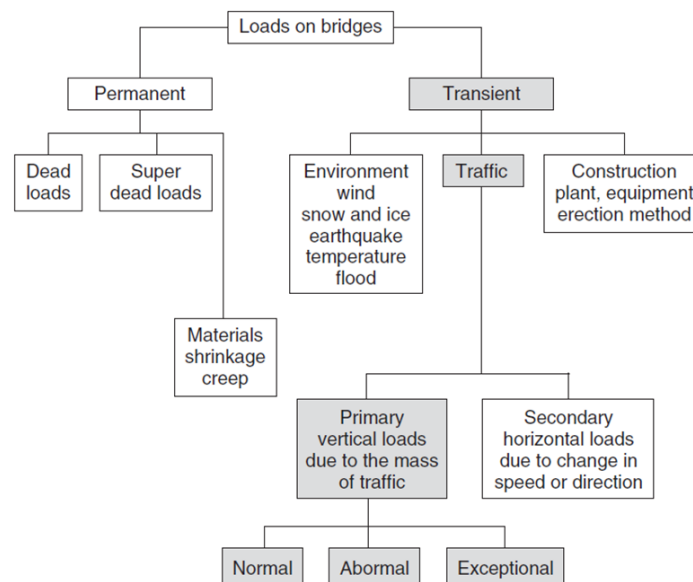


Figure 2.8: Loads on Bridges [Parke & Hewson, 2008]

The loading considerations for the structural analysis of the viaduct derive directly from the EC:1991-2 “Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges” [EN1991-2(2003), 1991]. The load models that are denoted in the EC are shown in Figure 2.9. Load Model 1 is considered for this study, which takes into account general (normal) loading due to lorries or lorries and cars.

Traffic Load Models	Characteristic values	Frequent values	Quasi-permanent values
Road bridges			
LM1 (4.3.2)	1000 year return period (or probability of exceedance of 5% in 50 years) for traffic on the main roads in Europe (α factors equal to 1, see 4.3.2).	1 week return period for traffic on the main roads in Europe (α factors equal to 1, see 4.3.2).	Calibration in accordance with definition given in EN 1990.
LM2 (4.3.3)	1000 year return period (or probability of exceedance of 5% in 50 years) for traffic on the main roads in Europe (β factor equal to 1, see 4.3.3).	1 week return period for traffic on the main roads in Europe (β factor equal to 1, see 4.3.3).	Not relevant
LM3 (4.3.4)	Set of nominal values. Basic values defined in annex A are derived from a synthesis based on various national regulations.	Not relevant	Not relevant
LM4 (4.3.5)	Nominal value deemed to represent the effects of a crowd. Defined with reference to existing national standards.	Not relevant	Not relevant

Figure 2.9: Bases for the Calibration of the Main Load Models (Fatigue Excluded) [EN1991-2(2003), 1991]

In this research project, only vertical loads are considered. LM1 consists of concentrated and uniformly distributed loads, which cover most of the effects of the traffic of lorries and cars. This load model is intended for general and local verifications.

Load Model 1

LM1 consists of two types of load systems:

- Concentrated loads (tandem system: TS): each vehicle axle has a specific weight:

$$a_Q * Q_k$$

where:

α_Q is an adjustment factor equal to 1
and each wheel transfers a load of $0.5 * a_Q * Q_k$

- Uniformly Distributed loads (UDL System), which has the following weight:

$$a_q * q_k$$

where:

α_q is an adjustment factor equal to 1

In Figure 2.10, the characteristic values of the traffic loads are given.

Location	Tandem system TS	UDL system
	Axle loads Q_{ik} (kN)	$\alpha_{Q1} q_{ik}$ (or q_{rk}) (kN/m ²) α_{Q1}
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

Figure 2.10: Characteristic Load Values for LM1 [EN1991-2(2003), 1991]

In order to define the distribution of the traffic loads on the deck of the bridge, the carriageway is divided into notional lanes as is defined in Figure 2.11. In Figure 2.12, the distribution of the notional lanes and the tandem system can be seen.

Carriageway width w	Number of notional lanes	Width of a notional lane w_r	Width of the remaining area
$w < 5,4 m$	$n_1 = 1$	3 m	$w - 3m$
$5,4m \leq w < 6m$	$n_1 = 2$	$\frac{w}{2}$	0
$6m \leq w$	$n_1 = Int\left(\frac{w}{3}\right)$	3 m	$w - 3 \times n_1$
NOTE For example, for a carriageway width equal to 11m, $n_1 = Int\left(\frac{w}{3}\right) = 3$, and the width of the remaining area is $11 - 3 \times 3 = 2m$.			

Figure 2.11: Division of Carriageway into Notional Lanes [EN1991-2(2003), 1991]

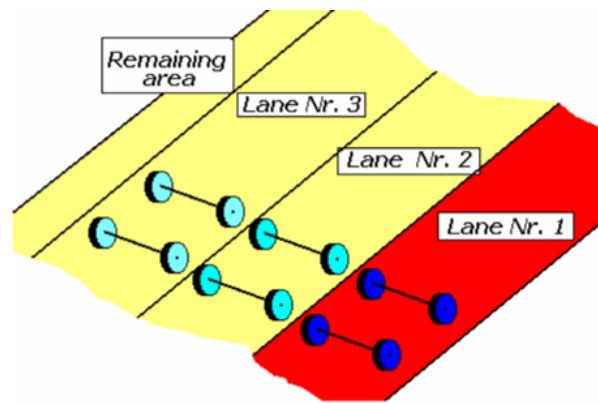


Figure 2.12: Notional Lanes and Tandem System [EN1991-2(2003), 1991]

In Figure 2.13, the dimensions of the tandem system are illustrated, as they are applied for local verifications.

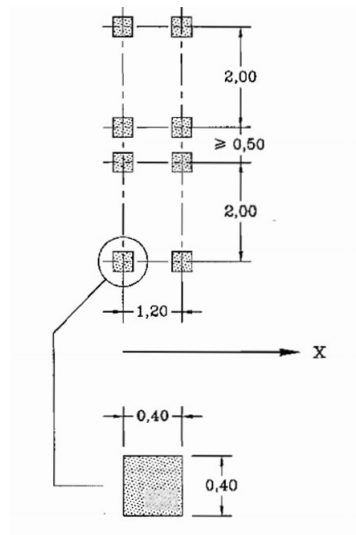


Figure 2.13: Dimensions of Tandem System [EN1991-2(2003), 1991]

Dispersal of the Concentrated Loads

The concentrated loads are transferred to the asphalt layer and the concrete deck under an angle of 45 degrees, as illustrated in Figure 2.14. [EN1991-2(2003), 1991]

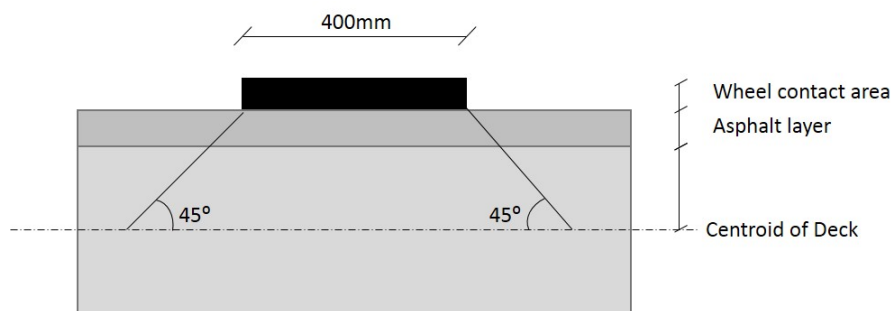


Figure 2.14: Dispersal of concentrated (Traffic) loads

2.5.6 Loads and Load Combinations in the Model

2.5.6.1 Loads

The loadcases and load combinations considered in the model are denoted in this section. The SLS is governing for the prestressing, while ULS is governing for the calculation of shear.

The loads taken into account are the following:

- Self weight of deck
- Self weight of asphalt layer
- Self Weight of the edge beams
- Traffic loads
- Prestressing

During construction, the edge beams are temporarily supported. Once the pressure layer is hardened, the supports are removed and the edge beams function as one composite element with the outer main beams.

2.5.6.2 Load Combinations:

The governing load combinations are considered in the calculations, as shown below [RWS, 2017a]:

Load Combinations for ULS:

$$\gamma_G G + \gamma_P P + \gamma_{Q,1} \psi_{0,1} Q_{k,1} + \gamma_{Q,i} \psi_{0,i} Q_{k,i} \quad (6.10a)$$

$$\gamma_G G + \gamma_P P + \gamma_{Q,1} Q_{k,1} + \gamma_{Q,i} \psi_{0,i} Q_{k,i} \quad (6.10b)$$

where: $\psi_{0,i} = 0.8$ [RWS, 2017a]

The Load Combination 6.10b is considered in the FEA model, since it is governing. The combination becomes: $1.35G + P + 1.35Q_{traffic}$

Load Combinations for SLS:

$$G + P + Q_{k,1} + \psi_{0,i} Q_{k,i} \quad (\text{Characteristic})$$

$$G + P + \psi_{1,1} Q_{k,1} + \psi_{2,i} Q_{k,i} \quad (\text{Frequent})$$

$$G + P + \psi_{2,1} Q_{k,1} + \psi_{2,i} Q_{k,i} \quad (\text{Quasi permanent})$$

where $\psi_{1,1} = 0.80$ and $\psi_{2,i} = 0.4$ [RWS, 2017a]

The Frequent Load Combination is considered in the FEA model, as it is governing for the definition of the prestressing in the SLS. This combination becomes:

$$G + P + 0.8Q_{traffic}$$

3 Model Development

In this section, the model development process is analysed. This includes the assumptions of the knowledge model, the computational approach, as well as the integration of the structural analysis in the process.

3.1 Knowledge Model

The aim of a knowledge model is to capture, formalise and implement the knowledge of the AEC practitioners into a digital design tool, incorporating automated, as well as semi-automated tasks [Sandberg et al., 2016]. Thus, the role of the engineer is upgraded, by removing the repeated, mundane and far from challenging tasks. An important but elusive element which is associated with a knowledge model is the implementation of the AEC practitioners' experience in the final product. This stems from the fact that a tool which is aimed to assist the AEC practitioners in their work, should not be developed detached from an industrial setting. The importance of this observation can be validated by the following example. In a purely academic setting, the length of the viaduct would appear as an essential input for the knowledge model, since it is a parameter which is crucial for the design. However, through discussions with practitioners at BAM, it was established that the actual length of the viaduct is never a parameter that the designer can specify in the conceptual design, since it actually derives from the specification of other parameters of the longitudinal profile of the viaduct.

The current research aspires to investigate the viaduct design process, while considering the latter a system and investigating its behaviour. The output of this approach is a generic viaduct design template which serves as a starting point for similar projects. In the aforementioned template, the client's needs and requirements can be converted into functional and technical input. Indeed, it is sought to establish fundamental relationships between the components of the viaduct and visualise them. The parameters defined in this chapter are specified after discussion with practitioners at BAM, which led to interesting conclusions regarding the definition of standard values.

As was mentioned in Section 2.2, one of the objectives of the knowledge model is to document the steps of designing. The importance of this objective lies in defining which information is relevant at which part of the design and therefore request the right amount of input from the designer. For instance, in preliminary design the choice of the type of the prefab beams for the deck is not an objective, as it would require the user to take too many decisions at a very early stage.

The three main components of a viaduct are the following: the deck, the abutments and the pier. Each of those three main components has its own design needs, which influence the design needs of the other components (Figure 3.1). The knowledge model provides insight into the interaction between those components by introducing a generic viaduct design, which includes all possible designs within the set design space.

In this section, the main parameters and assumptions about the components are presented, schematically or directly from the Revit Model which is created in this study.

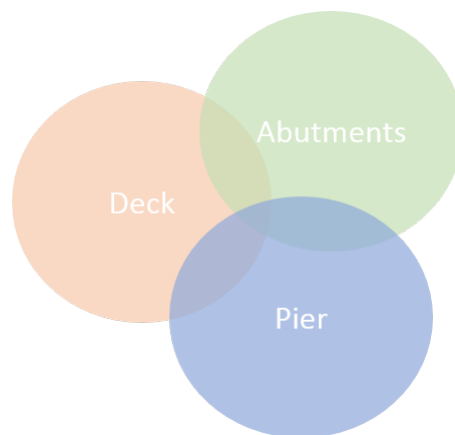


Figure 3.1: Influence Areas of Changes in the Main Components of a Viaduct

3.1.1 Abutments

The abutments are part of the substructure of the viaduct and are also referred to as end supports. The type of the abutments can vary depending on the objectives of the design. Solid or closed-end abutments are common, but not desirable in terms of aesthetics as they restrict the line of sight of traffic. This type of abutment is employed when there is no available space to create slopes at the sides of the road underneath the viaduct. In that case, the abutments need to be placed on high abutment walls next to traffic. Skeletal abutments as well as mass concrete bankseats (open-end) are chosen when a wide open area is required for the traffic flow beneath the bridge [Chen & Duan, 2000]. The bankseat is situated on the top of a cutting slope and can rest on simple footings or on a pile foundation (most common in the Netherlands). This type of abutment can allow an easier future widening of the road underneath by adjusting the ratios of the slopes, but also leads to longer deck spans and extra earthwork.

The choice among the available types of end supports lies primarily on the financial impact that it will have, as well as the characteristics of the surroundings. In general, open-end abutments are a more economical and attractive solution.

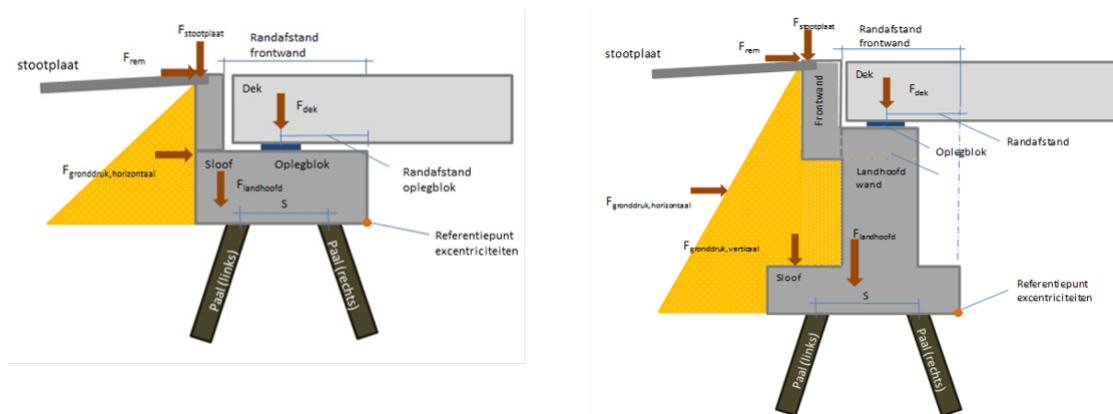


Figure 3.2: Types of Abutments (a) Bankseat - High Abutment (open-end) (b) Full-Height Abutment - Low Abutment (closed-end) (images by BAM Infra)

Considering the geometrical freedom for the abutments can facilitate the creation of more efficient parametric algorithm. The main factors determining the shape of the abutment and its subcomponents are:

- The design requirements
- The applicable codes
- The experience of the Engineer/Architect

3.1.1.1 Generic Geometry

Following the input of BAM engineers the geometry illustrated in Figure 3.3, is chosen for the design considering some basic design needs. A tolerance between the abutment and the end of the prefab beams is always considered to accommodate the thermal expansion of the aforementioned elements. An offset from the edge of the slope to the abutment should exist to guarantee the stability of the slope. Moreover, an (optional) open area for maintenance is considered. This allows the engineers to maintain the bearings. It is interesting to point out that there is not a unanimous agreement among the interviewed engineers regarding a standard geometry for the abutments. Indeed, the geometry can vary highly depending on the project at hand. For instance, the maintenance space can be ignored if there is sufficient space next to the end of the slope, so that maintenance can still be conducted. The width of the abutment depends on the arrangement of the foundation piles, which is not investigated in this research. Moreover, the top of the abutment is aligned with the top of the slab, therefore the height is not an independent parameter.

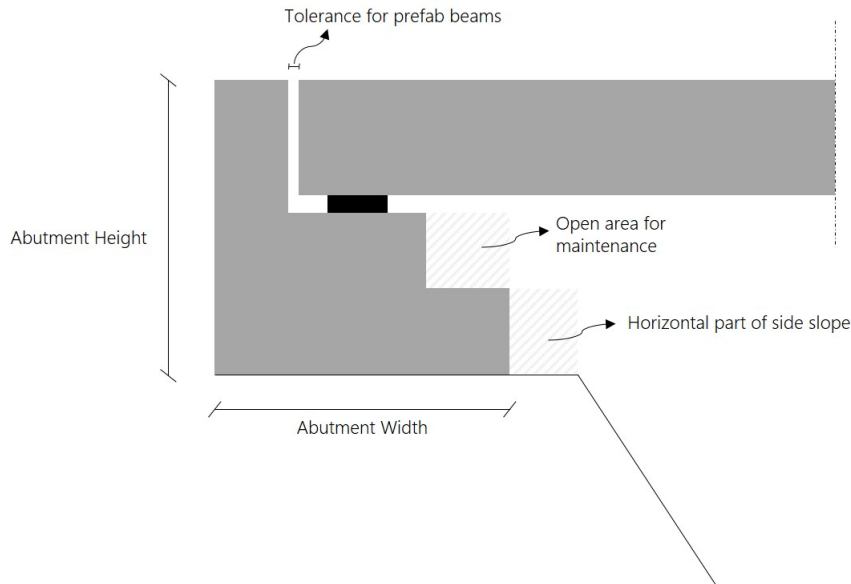


Figure 3.3: Generic Abutment Geometry

3.1.1.2 Tolerances

The consideration of tolerances is a crucial part of the design, as allowing differential movement between the components reduces the stresses at the connection areas. In this study, the tolerances between the bankseat and the deck slab, as well as the tolerances at the area of the pier have been considered.

The magnitude of the tolerances and some of the dimensions at the abutments are given by Spanbeton for the SJP-FLEX beams. Those can be seen in Figure 3.4. The exact position of the bearings on the abutment depends on the angle of skewness, in order to guarantee minimum distances of the ends of the beams and the bearings (Table 3). Those dimensions are set to default in the parametric platform, as they are not needed for the conceptual design.

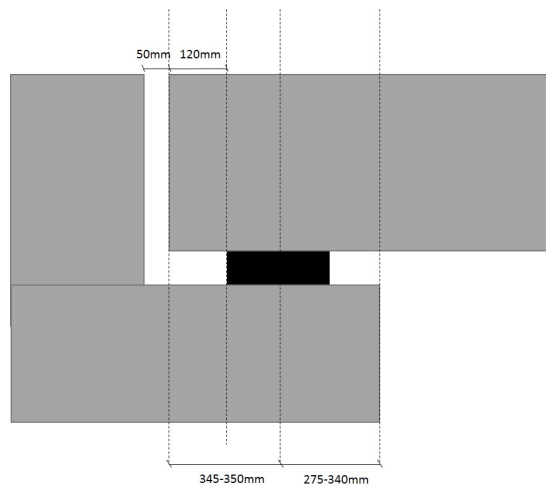


Figure 3.4: Dimensions at the abutments

The approach slabs are positioned on the abutments, by considering a cut at the top of the abutment to ensure that all components are aligned. The position of the approach slabs is illustrated in Figure 3.5. The height of the cut depends on the thickness of the approach slabs and the width is considered 300mm.

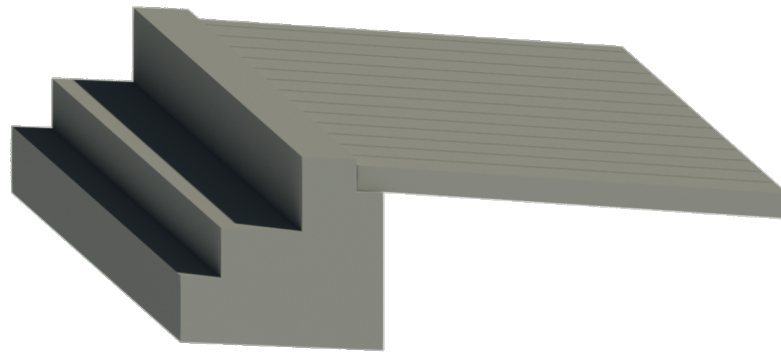


Figure 3.5: Abutment with Approach Slabs (Revit Model)

3.1.1.3 Wing Walls

Wing walls are retaining structures, designed at the sides of the abutment, to prevent the abutment backfill soil from sliding in the transverse direction. Moreover, the settlements at the area of the abutments are reduced by ensuring the horizontal stability of the ground. The geometry of the wing wall can vary depending on the topography of the site, the construction restriction and the construction sequence [Hambly, 1979]. Wing walls can be both structurally independent and dependent from the abutments. In this research, the case of a structurally dependent wing wall, the cantilever wing wall is considered (Figure 3.6). In Figure 3.7, the generic geometry of the abutment, considered in this study is illustrated.

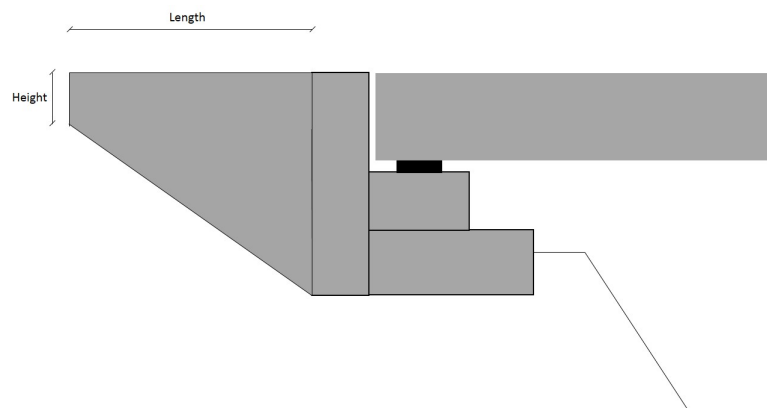


Figure 3.6: Cantilever Wing Wall Geometry

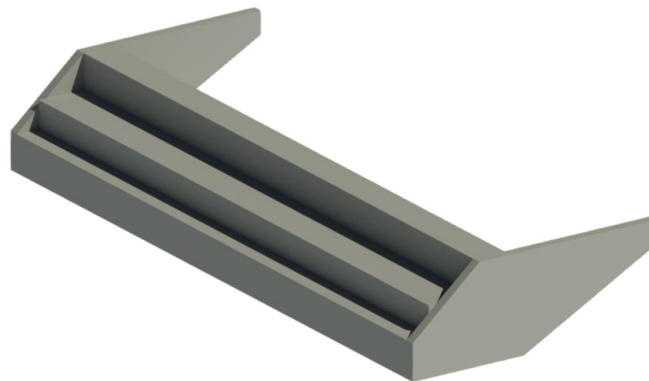


Figure 3.7: Generic Abutment Geometry (Revit Model)

3.1.1.4 Approach Slabs

The approach slabs are needed to ensure a smooth transition between the road and the viaduct. The surface beneath the road is softer (soil) compared to the superstructure of the viaduct (concrete deck), therefore without approach slabs there could be a bump in the road, as vehicles passed by. The approach slabs are designed, aligned with the road and they are usually prefabricated with their length depending on the road type. For highways, where the design speed is higher than 80km/h, the minimum length is 5m [RWS, 2017a]. Typical dimensions (considered in this study) for the approach slabs are the following:

- Length: 5m
- Width: 1m
- Thickness: 0.35m

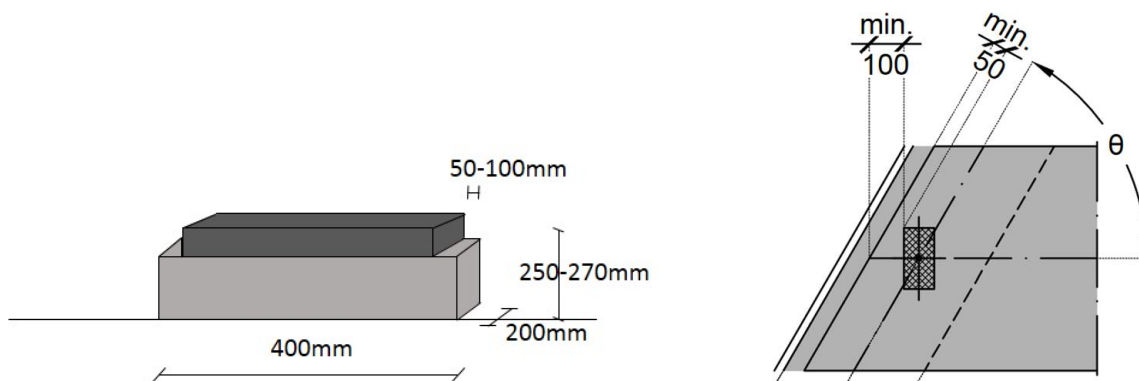
3.1.1.5 Cutting Slopes

A cutting slope is normally used to overcome the height difference between the viaduct's structure and its surroundings. Other functions of the slopes are the water drainage and the integration of the viaduct in the landscape. The maximum slope up to which no reinforcement is required in the ground is 1:2 and a usual value for the slopes is 2:3.

3.1.1.6 Bearings

The structural bearings are designed with a life expectancy of 50 years. Typical dimensions for the bearings are shown in Table 3, along with the minimum distances between the bearings and the ends of the beams.

Table 3: Typical Bearing Dimensions [Spanbeton, 2018]



3.1.2 Deck

The deck of the viaduct is one of the main top classes of the model. The design assumptions for the deck slab and the subsystems of the deck are mentioned in the paragraphs below. The main attributes of the viaduct's deck are:

- The geometry of the slab
- The height of the slab which is defined by rules of thumb based on its span (see Section 3.5.2).
- The road profile
- The road furniture
- The edge beams and edge elements
- The rationalisation of the deck edges, which indicates whether the deck is curved (follows the curved alignment) or straight.

3.1.2.1 Deck Geometry

In this research, the viaduct's superstructure can have three possible geometries as illustrated in Figure 3.8. While the designer has the freedom to design a curved superstructure, the structural analysis is not available for this option, as a curved superstructure would require another type of prefab beams or in situ concrete and more complex considerations. In this research, the angle θ is advised to be up to 20 degrees and the beams are considered straight. This ensures that a valid structural analysis is conducted. Moreover, the abutments are considered parallel in this study, which is a cost efficient design, as all beams in the deck have the same length.

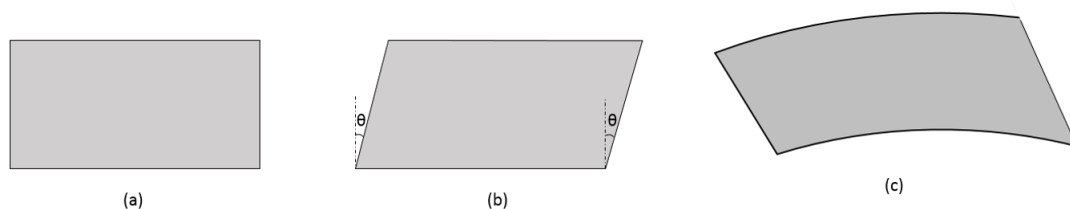


Figure 3.8: Possible Slab Geometry (Top view) - (a) Rectangular slab (b) Skewed slab (c) Curved Slab

3.1.2.2 Road Categories and Types

The Dutch road design regulations [CROW, 2013a], employ a road classification system, based on the location and function of the road, within the “Sustainable Safety” (Duurzaam Veilig) concept [Wegenwiki, 2017]. Three categories are distinguished within the road network: Expressways, distributor roads and access roads. The details of the aforementioned distinction are not further discussed in this research, as they are not directly pertinent to project. A further classification of the roads is employed to define the transverse profile of the road, namely the number of carriageways and the numbers of the traffic lanes per carriageway (The respective numbers can be seen in the parentheses next to the types). The aforementioned distinction is applicable only for the roads outside the urban areas. Within the “Sustainable Safety” concept, each category and type of road is associated with a maximum allowable speed, as seen below:

Expressways:

- max speed: 100km/h
- Type I (2x1)
- Type II (2x2)

Distributor Roads:

- max speed: 80km/h
- Type I (2x2)
- Type II (1x2)

Access Roads:

- max speed: 60km/h
- Type I (width: 4.50m to 6.20m)
- Type II (width: up to 4.50m)

The layout of the road depends on the following parameters:

- The road category, which indicates the function of the road
- The requirements in relation to road safety

- The height clearance
- The requirements in relation to the environment
- The requirements in relation to management and maintenance

A crucial aspect of the design of the deck is the definition of the number of traffic lanes. While the choice of the number of traffic lanes and their width remains parametric in this study, guidelines are employed to associate the type of road with the respective number of traffic lanes and widths. Those guidelines are provided by the “Handboek wegenontwerp 2013” [CROW, 2013a]. The normal width of a traffic lane is 2.75m as specified in the aforementioned publication.

For the generic design of the viaduct, the road is considered a distributor road of type I, which entails that there are two carriageways with 2 traffic lanes each. For this type of road, it is advised to always keep the traffic lanes and the bicycle lanes completely separated, because of the big difference in speed and mass [CROW, 2013b]. Therefore, bicycle lanes will not be incorporated in the model.

The minimum horizontal curvature for Distributor Roads is given by the following equation [CROW, 2013b]:

$$R \geq \frac{v^2}{127(f_z + \frac{i}{100})} = 295m \tag{9}$$

where:

$v = 80\text{km/h}^2$ (the maximum speed for Distributor Roads)

$f_z = 0.14572$ (lateral friction coefficient)

$i = 2.5\%$ (crossfall)

The transverse cross section considered in the model is illustrated in Figure 3.9, along with the values of the asphalt thickness and the kerb dimensions.

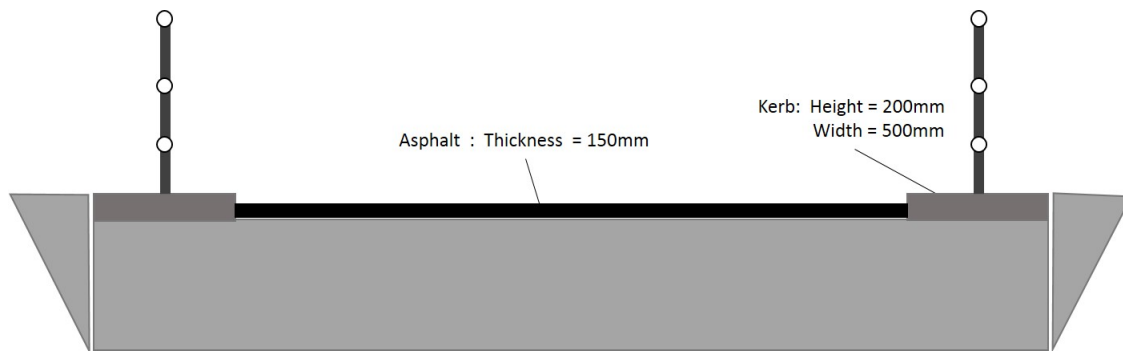


Figure 3.9: Viaduct Cross Section in this Study

3.1.2.3 Crossfall

In order to guarantee the proper drainage of the viaduct, a crossfall is always considered. In usual practice, the prefab beams are arranged with an inclination as shown in Figure 3.10. This arrangement is cost efficient, since the asphalt layer has a uniform thickness. However, in this study in order to decrease the complexity of the parametric model, the crossfall is realised through the asphalt layer.

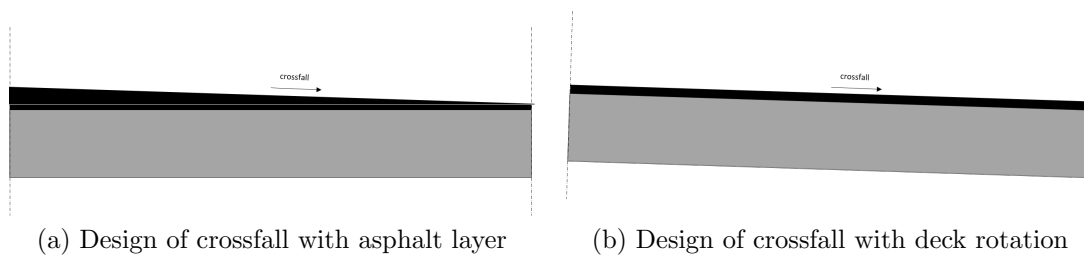


Figure 3.10: Crossfall Design

3.1.2.4 Railings

Regarding the railings on the sides of the viaduct, the available options stem from the standard viaduct details, as designed by RWS [RWS, 2017b].

3.1.2.5 Cornices - Edge Elements

The cornices are the external lining of the edge beam of the bridge. This component can be used as a permanent formwork, and its function is to protect the concrete, steel or cast iron bridge components against chemically active, aqueous solutions. Moreover, The cornices at the sides of the viaduct are important architectural entities.

The position of the edge elements in this study, is fixed as shown in Figure 3.12. The cornice is placed at the edge of the deck, with its top point on the top of the kerb and the bottom point on the bottom of the deck slab. The edge elements are segmented based on the length and the tolerance provided. The platform calculates the number of the whole elements that fit at the edge of the deck and splits the difference at the ends. The division of the cornices can be seen in Figure e3.11.

$$L_{end} = \frac{L_{edge} - \frac{L_{edge}}{L_{cornice}}}{2}$$

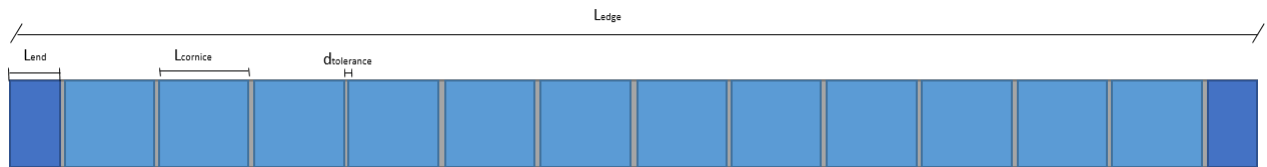


Figure 3.11: Division of Cornices along Deck Edge

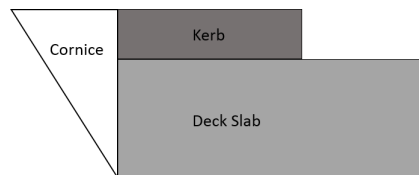


Figure 3.12: Position of Cornice

In case, the edge elements are intersecting with the wing walls, they are cut as shown in Figure 3.13, in order to avoid clashes in the abutment area.

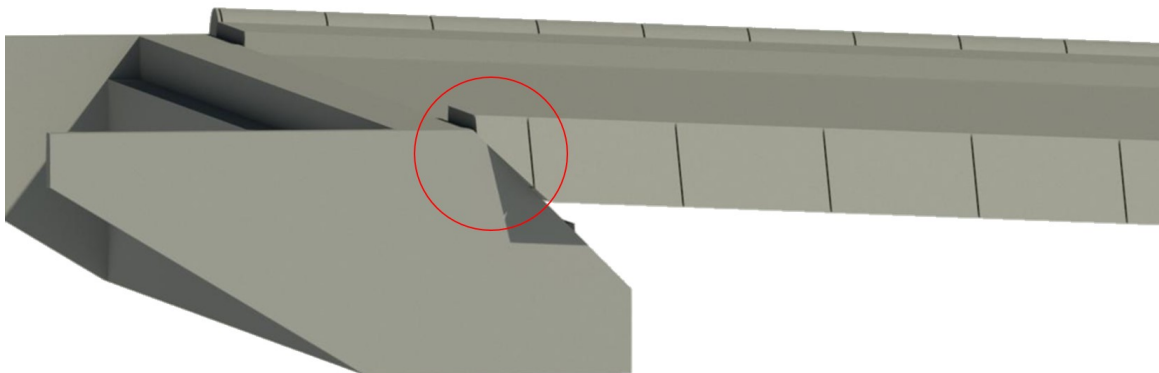


Figure 3.13: Cut of Edge Element at Wing Wall (Revit Model)

3.1.2.6 Rationalisation

In this study, the deck can have either straight or curved edges. This option is included in the model, since the curvature of the deck is an important design choice. Choosing a straight geometry can decrease the design complexity of the viaduct, while leading to a lower cost, since standard, prefab beams can be employed.

However, a curved deck usually has a higher architectural value, as it allows for a smoother and more integrated design. Therefore, in this study the designer has the option to model a curved deck as well, however without the possibility of a structural analysis, as this would highly increase the complexity of this study, by introducing significant torsion on the beams. In this study, structural analysis is only available for the case of a straight deck, since the SJP-FLEX beams, which are considered in this study, cannot be curved. In this study, structural analysis is only available for the case of a straight deck, since the SJP-FLEX beams, which are considered in this study, cannot be curved. Moreover, employing curved beams increases the complexity of structural design, since torsion becomes of crucial importance.

In Figure 3.14, the two options for the deck are illustrated. As can be seen in this figure, rationalisation affects also the kerb, whose outer edge is aligned with the edge of the deck.

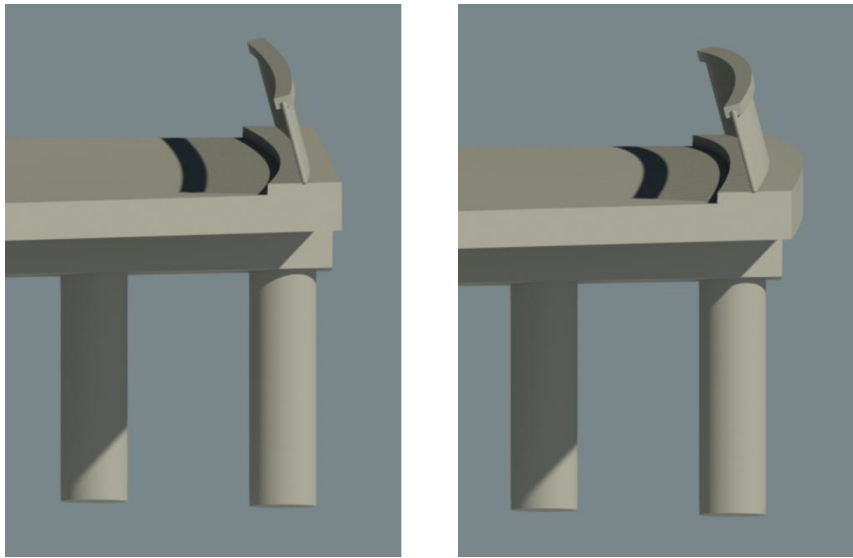


Figure 3.14: (a) Straight Deck (b) Curved Deck (Revit Model)

3.1.3 Pier

In this research, the option to consider an intermediate support is available to the designer. Whether a pier is considered or not, depends mostly on two parameters: aesthetics and cost. Adding a pier every 15m of span, as was mentioned by engineers at BAM, can help reduce the height of the deck beams and lead to a more economic solution. The choice of in situ or prefab concrete can determine the geometry of the standard solution. The overall design of the pier in this study derives from the general design guidelines for prefab concrete, which indicate that a beam is present at the top of the pier, as seen in Figure 3.15 in the Revit model.

3.1.3.1 Pier Beam

In the case of a skewed deck the beam of the pier is aligned with the edges of the viaduct, as is illustrated in Figure 3.15. The minimum width of the pier beam depends on the tolerances at the area of the pier, which are defined by Spanbeton graphs [Spanbeton, 2018].

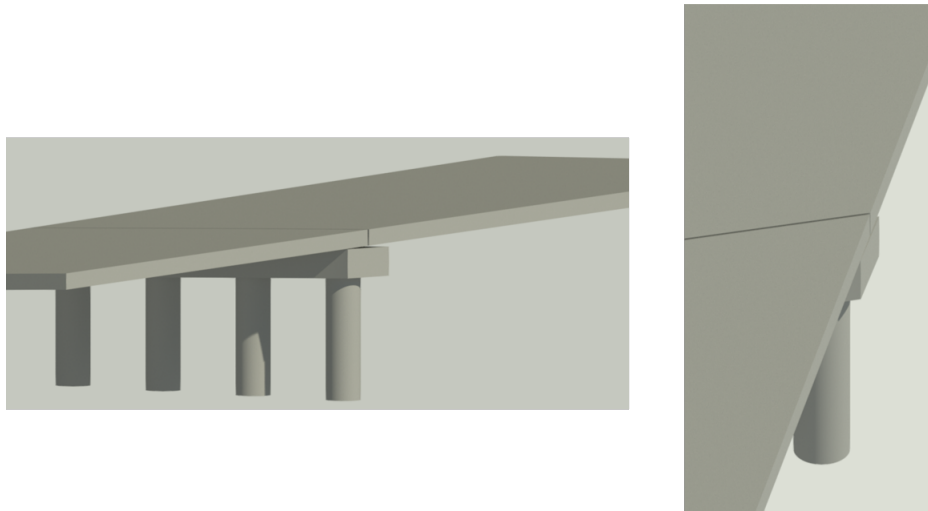


Figure 3.15: Pier Beam Aligned with Deck Edges (Revit Model)

3.1.4 Soil - Structure Interaction

The piers and the abutments support the deck of the bridge, and are supported by foundations resting on the soil. They are termed the substructure and the calculation of their stiffness and structural behaviour is of crucial importance to safety of the design. Settlements of the supports can yield secondary effects (large displacements) and cause a redistribution of the forces in the bridge deck, especially if it is continuous. A careful design of the substructure is therefore needed to guarantee the stability of the whole structure. The foundation is not considered in this conceptual study, however it is advised to include it if an extension to the knowledge model is considered (Section 7).

3.2 UML Model

A UML model is employed to control the complex design process. The components and their design parameters are sorted into a top-down model. An important step in establishing a connection between the UML model and the parametric/associative model is to clarify the semantics of the relationship between them.

The development of the UML model is based on a cyclic process, which resembles the actual designing process. The steps are shown in Figure 3.16 and are the following:

- **Step 1:** Define classes (tangible objects. e.g bearings are a class, alignment not a class). Also, an object is denoted as a class when its description becomes too complicated.
- **Step 2:** Define which classes are abstract and which are concrete
- **Step 3:** Define the attributes of the classes. Four attributes are denoted for every concrete class: “name”, “familyName” (through “familyName” the shape of the component is defined), “material”, “structural”.
- **Step 4:** Define whether a class is structural or not.
- **Step 5:** Define the relationships between the classes
- **Step 6:** Define methods

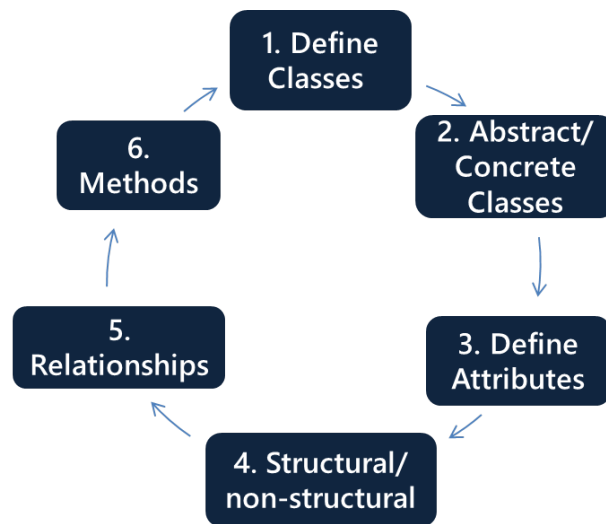


Figure 3.16: Cyclic process of UML model development for this research

3.2.1 Relation between UML semantics and Knowledge Model

UML provides the user with a restricted field of semantics (specified in Appendix A), which facilitates the analysis of the problem at hand. Moreover, this contradiction between the abstract nature of the design process and the structured UML can yield interesting conclusions. The UML semantics are used in the development of the knowledge model as shown below:

- An entity is denoted a class when it becomes too complicated to be considered an attribute, relationship or constraint.
- Entities that are not specific, tangible objects and cannot be described with specific values to consider them attributes, are denoted as restrictions for the design (e.g alignment).
- Abstract classes cannot be instantiated. That means that when a class is denoted as abstract, the subclasses can differ and have their own attributes in addition to the ones defined in the superclass (abstract). This enables the designer to consider for instance, abutments with a different geometry at each side, thus allowing a non-symmetrical design.
- Static attributes, which are denoted in the class “Viaduct”, as well as the superclasses “Deck”, “Abutment” and “Pier”, are given by the user in the beginning and do not change throughout the design process (e.g width of viaduct). This creates a distinction between the parameters in a local level, which only affect particular classes and the parameters which affect the global design and require a redesign of the whole viaduct.
- The attributes specified in the superclasses, are the input that is required by the user to reach a generic viaduct design (using also rules of thumb).
- An attribute named “structural” is defined only in concrete (not abstract) classes as it refers to specific components of the viaduct. There is no setter method for this attribute, in order to ensure that the user will not denote components which are not structural as structural. This consideration can be seen as a form of encapsulation for the whole logic of the model.
- Encapsulation is considered in the definition of every attribute, by defining the type of the expected value (e.g float, string, boolean etc.)

3.2.1.1 Composition and Aggregation

- Composition relationship means that the subclass can be automated and the freedom of the designer is restricted. Subclasses cannot exist outside the context of the superclass, therefore they have no special

design needs. For example, in order to model the asphalt layer we need to define 2 main parameters, the thickness of the layer and a host component (concrete slab of the deck).

- Classes which are connected to superclasses through composition relationship, have a “host” attribute, to specify on which class they rely. There is no setter method for the “host” attribute. It is predefined in the model. Moreover, some classes have also an “offsetFromHost” attribute, as they may aligned but not attached to a specific component. This attribute has a setter method, so that the user can specify the exact offset of the component in the model.
- Aggregation relationship means that the subclass is an important/distinct entity which exists on its own and has special design needs, therefore it is partly automated and the design of this component is facilitated on the Revit/Dynamo model.

The UML model can be used to clarify the relationships between the components of the viaduct. For instance, it can help establish what will happen in case the designer wants to change the width of the viaduct or its function. Two important questions that should be addressed are the following:

- Which components are affected by a specific change?
- Which parts of the design need to be reconsidered and which parts can maintain their initial design?

To answer these questions, the UML model can offer some guidance. The parameter “width” is an attribute of the “Viaduct” class, which indicates that a change is made on a global level, creating an extensive chain reaction to the model. Therefore, the whole viaduct should be redesigned. However, this does not indicate that the user should reconsider the design of the entire viaduct, since the previous design choices are maintained and adapted to the new width of the viaduct.

A change in a local level though can yield changes in its surrounding components, namely the components with which a direct relationship is established, without affecting the global design of the viaduct. For instance, if a change in the edge beam is needed, this will affect the components which are connected to the “EdgeBeam” class.

As can be seen in Figure 3.17, The class “EdgeBeam” is a child class of the class “DeckBeam”, which means that the edge beams inherit the attributes of the latter class, but also bear their own attributes and have their own design limits. A change in the edge beams therefore does not directly cause changes in the deck beams, however, the design freedom of the child class is limited by the choice of the parent class.

Another class associated with the “EdgeBeam” class is the “Cornice” class. Cornices are non-structural, aesthetical elements, which are attached to the edge beams of the viaduct. The aforementioned relationship implies that a change in the edge beams can inflict a direct change on the cornices, since the size of the cornices may need to change or other attachment methods should be considered. As can be easily understood, the reinforcement of the edge beam changes according to the shape and size of the edge beams. In the UML model, the relationship of the two components is denoted as a composition relationship, since the calculation of the reinforcement depends highly on the definition of the edge beams. An overview of the UML model is shown in Appendix B.

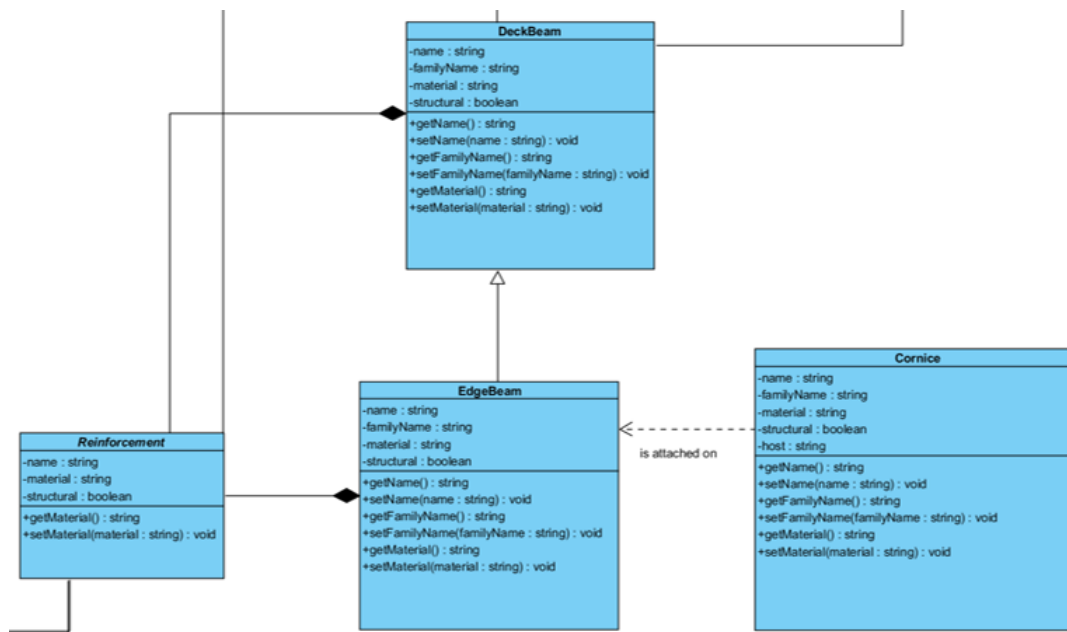


Figure 3.17: UML “EdgeBeam” class and the classes related to it

3.3 Dynamo Model

The top down approach of the UML model is sought to be translated into a parametric tool based on a bottom up approach. Indeed, while UML offers a structured way to divide the entire viaduct in main components and subcomponents, a reverse way of thinking needs to be employed in the development of the Dynamo model.

The variation of the parameters that specify the shape and qualities of each component is specified, so as to address the design needs of the viaduct. A generalisation of this issue is illustrated in Figure 3.18. On a 2D canvas, four points can create a variety of shapes, however there maybe ways to narrow down the number of possibilities by understanding the function and interrelations of those points. For instance, if in every possible design scenario those points need to form a square then the user needs to specify only one parameter, the length of the sides. In Figure 3.18, variations (a), (b) and (c) require more information from the user in order to create the final shape. Therefore, the relationships between the parameters of the design should be identified, in an attempt to reduce the amount of the input.

Extending this simple logic to the problem at hand, it is clear that understanding the possible variations and possibilities that the tool should offer to the user is vital in developing an efficient approach to parametric viaduct design. The possible object shapes in a viaduct can be specified through the study of design requirements and input from the AEC practitioners (see Section 3.1).

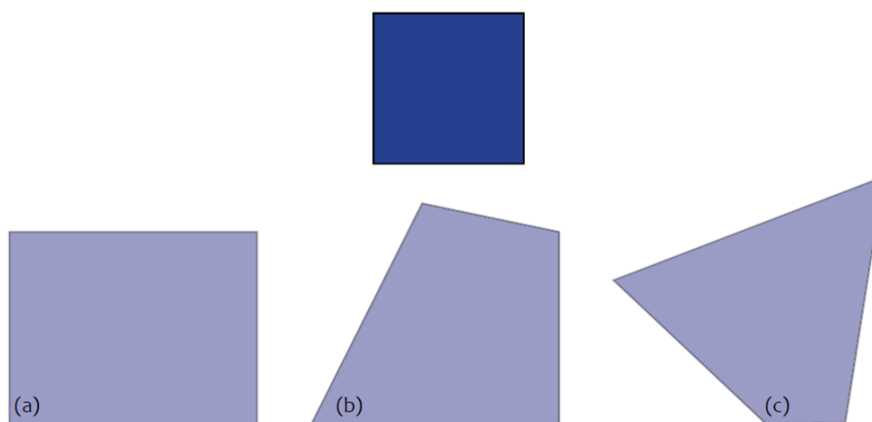


Figure 3.18: Example of 2d object variations

3.3.1 Dynamo Script

In the Dynamo script, it is sought to create a fully parametric design algorithm, where the user will be able to create numerous designs, within an expandable design space. The whole model of the viaduct is built around two alignments, the 3D alignment of the bridge and the 2D alignment of the road underneath, which are part of the initial input of the tool. This signifies that the visualisation of the viaduct can be placed in any environmental context, as long as the Autocad lines, which represent the alignments are placed in a 3D model.

The concept of topology [Wikipedia, 2017a] is considered in the development of the Dynamo script, in order to ensure a fully parametric, and accurate interpretation of the parameters. The main goal of the parametric algorithm is to develop a script, whose outcome is not tied to any points in space and can be easily manipulated by the user. To achieve the latter, the topological interdependencies of the component volumes are sought, so as to achieve an associative design. The development of the script is incremental, in order to ensure that the complexity is gradually introduced to the model and ensure the credibility of the final parametric model. Three mediums are employed:

- Visual Programming
- DesignScript
- Python

3.4 Main Geometrical Challenges

A number of crucial geometrical irregularities that need to be addressed during the design of the bridge are the following:

- **Spatial Independence:** The parametric model functions for any given alignment (within the curvature limits) without any ties to specific geometric points. This entails, that a large number of logic checks is required to ensure that the components are developed and positioned in the appropriate positions in relation to the others and the alignment.
- **3D Curved alignment:** The alignment of the viaduct is assumed to have a longitudinal and a horizontal curvature. The 3D curvature of the alignment of the bridge increases the complexity of the parametric algorithm, since the location of the edges of the viaduct cannot be instantly defined in the parametric model. The solution for this issue is shown in Appendix C.
- **Skewed superstructure:** The skewed angle of the deck is defined by the position of the abutments, as illustrated in Appendix C.

3.5 Design Levels

Design levels are defined in the parametric tool to ensure that an abundance of solutions can be created, without restricting the design freedom of the user. In order to achieve this, the design levels start from a generic design, where the user inputs basic information about the viaduct and a generic design is developed, mainly focusing on creating the viaduct's volumes. A further design step is the structural analysis of the deck.

3.5.1 Global Design Parameters

At the beginning of the design process, a generic set of important global parameters are considered. Those parameters are illustrated in Figure 3.19 and are the following: The length of the road and the sidewalks underneath the bridge, the clearance height, which is the minimum height of the viaduct, and the inclination of the two slopes (inc1 and inc2).

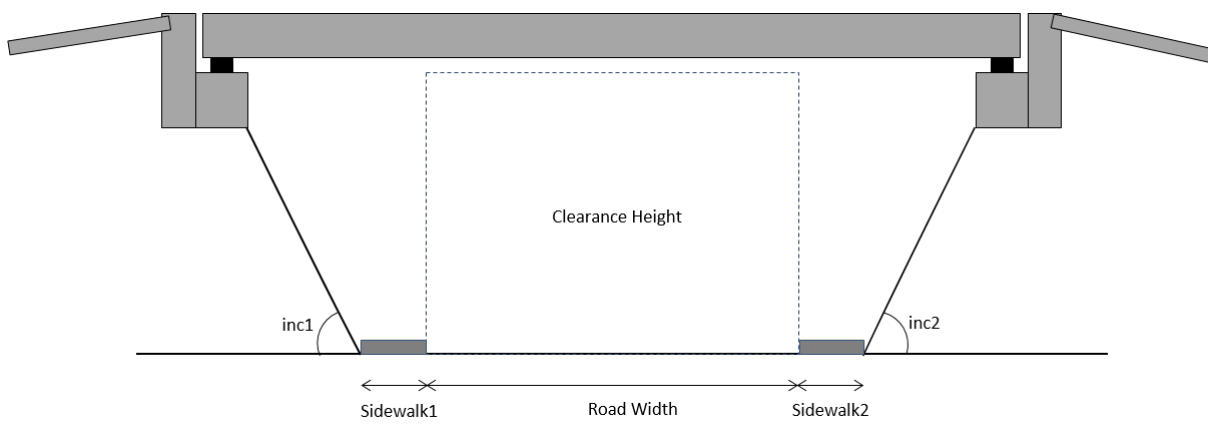


Figure 3.19: Longitudinal Section of the Viaduct for the Generic Design

The length of the viaduct, even though it might seem as a basic parameter, it is not crucial for the design. Discussion with AEC practitioners showed that the length is a property of the viaduct which derives from the definition of the parameters specified above. Therefore, the length of the deck is calculated as a result of the generic design and then used to calculate the thickness of the deck based on rules of thumb.

The set of parameters which constitutes the input for the Generic Design level can be seen in the abstract “Viaduct” class of the UML model (Figure 3.20). The attributes of this abstract class are public and shared with all the classes in the model. Getter methods are specified for every attribute, so that the parameters can be used by other classes. Setter methods are also defined for every attribute, except from the Length of the viaduct, allowing the user to set the respective values. As mentioned above, the length of the viaduct derived from the definition of the other attributes, therefore there is no setter method defined. The use of the setter method facilitates the creation of the user interface, as it indicates where input is needed. In Figure 3.20, another important parameter can be seen, the alignment of the viaduct. Indeed, the entire viaduct is built around the alignment, which can be a straight line consisting of two points, or a curve defined by a larger number of points.

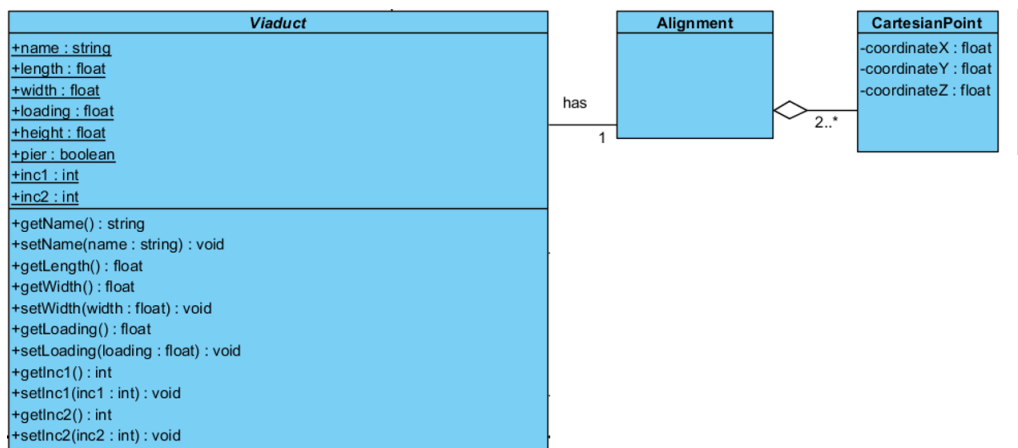


Figure 3.20: UML “Viaduct” class - Attributes and Methods

In the “Viaduct” class, as illustrated above, global attributes are specified which refer to the viaduct as a whole. However, this information is not sufficient, since more parameters should be specified on a main components level. The extra information that is needed, in order to create the deck of the viaduct as illustrated in Figure 3.21. The attribute “name” is associated with the name of the viaduct, so as to provide a unique identity for each component in each design iteration. The thickness of the slab is automatically calculated, based on rules of thumb as denoted in Section 3.5.2. The “rationalisation” attribute is a boolean parameter, which signifies whether the geometry of the slab should be maintained, as it derives from the alignment of the bridge (offset) or whether it should be rationalised into a rectangular or skewed geometry.

The “rationalisation” attribute allows for the investigation of free form solutions, which will follow the curved alignment of the viaduct. The angle of skewness has no ”setter” method, since it depends on the alignment and the position of the abutments.

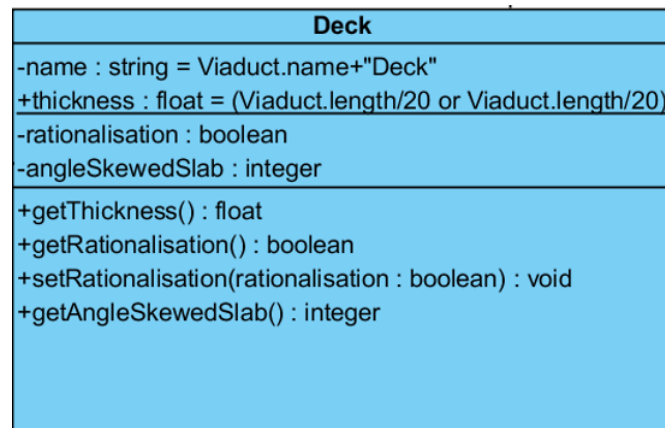


Figure 3.21: UML “Deck” class - Attributes and Methods

3.5.2 Rules of Thumb for the Calculation of the Deck Thickness

Rules of thumb are employed to calculate the thickness of the slab, during the generic design. The 1st design level does not incorporate a sophisticated structural analysis of the viaduct, but includes an indication of the actual thickness of the deck. The rules of thumb used in the algorithm are shown below:

- Reinforced slab: $\frac{L}{20}$
- Prestressed beams: $\frac{L}{30}$
- Prefabricated Beams: SPANBETON graphs

where: L is the span of the viaduct as defined in section 3.5.3.

3.5.3 Span vs Length of viaduct

The span of the viaduct is defined by the centerlines of the bearings. The main parameters which determine the span of the viaduct are the width of the road underneath, the inclination of the slopes and the geometry/location of the abutments. The span derives from the sum of the distances illustrated in Figure 3.22: d1, d2a, d3a, d2b, d3b.

- $d1 = w + \tan(inc1) * h1 + \tan(inc2) * h2$
- d2 = offset of abutment location
- d3 = distance between the end of the abutment and the centerlines at the bearings

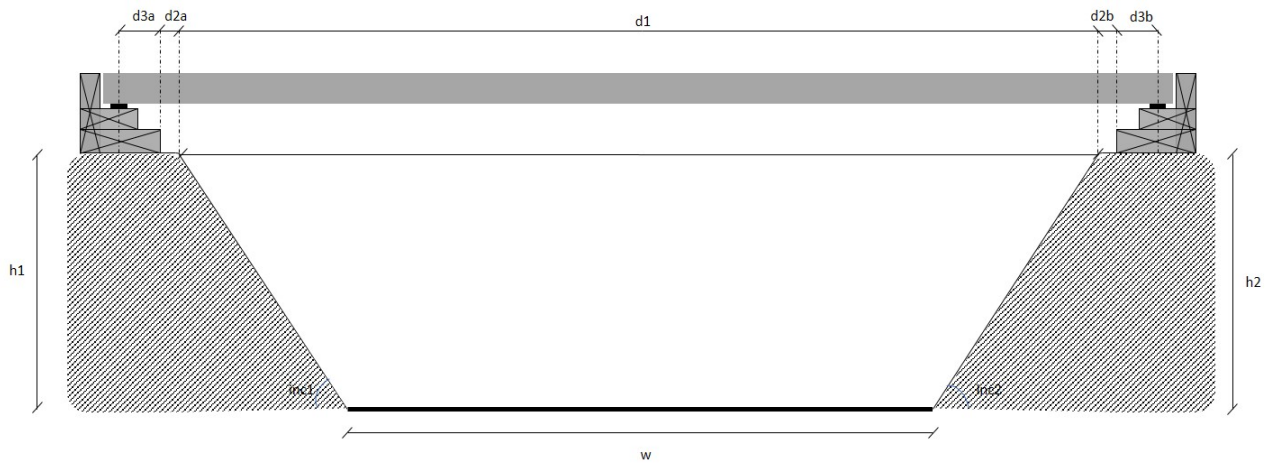


Figure 3.22: Definition of span

The length of the viaduct is defined by the length of the beams. The difference between the length and the span is shown in Figure 3.23. This Figure shows a statically determined system. In Figure 3.24, dimensions are given from Spanbeton for SJP-FLEX beams ([Spanbeton, 2018]).

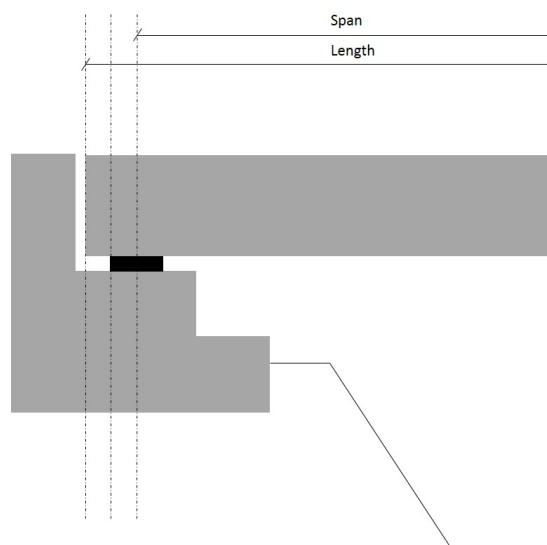


Figure 3.23: Definition of length

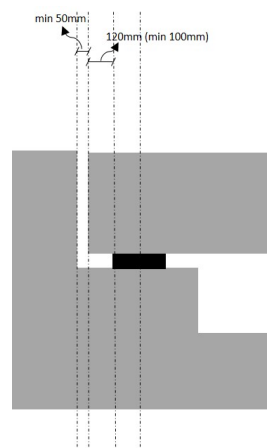


Figure 3.24: Detailed edge

3.5.4 Width of Viaduct

The width of the viaduct is specified by the user, since it is one of the parameters in this research. However, since the solution which is investigated is prefabricated concrete, the final width of the viaduct will depend on the number of beams which fit in this width. The formula for the definition of the final width of the viaduct is shown in Figure 3.25 and is:

$$(n + 0.5) * 1200$$

where n is the number of SJP-FLEX beams that fit in the indicated width.

In this research, the number of beams is chosen so that the final width is slightly larger than the one specified. For instance, if the specified width is 12m, the prefabricated viaduct deck will have a width of:

$$(10 + 0.5) * 1200 = 12600\text{mm}$$

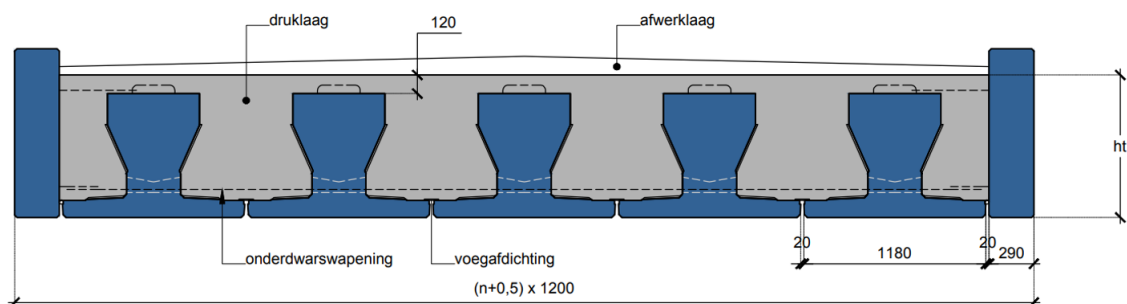


Figure 3.25: SJP-FLEX prefabricated beams and concrete in situ deck [Spanbeton, 2018]

During actual projects, a cost analysis is conducted to specify whether increasing the seams between the beams or adding extra beams is the most appealing solution to reach the desired width. Increasing the width of the seams between the beams is less appealing in terms of aesthetics as the seams are more visible, while the height of the beams increases, so that they can carry the weight of the extra concrete between them. However, adding extra beams and extending the width of the viaduct can lead to higher costs.

3.6 1st Design Level - Interface

The 1st design level of the viaduct is considered in this study, which refers to the definition of the main parameters of each component. The information is provided by the designer through a user interface, which provides a structured environment for the input. Initially, a user interface based on Excel was created in order to facilitate the input process. However, the link between the parametric model and the excel appeared to slow down the execution of the algorithm, therefore the creation of a UI using Python is preferred. The

need for a UI derived from the aspiration to make the platform usable and not discourage the user. A preview option is available at different levels of the UI, so that the user can see what they are designing. A number of the key programming principles mentioned in subsection 2.1.2 are used to create the UI. For instance, the encapsulation principle is present in the UI, by ensuring that the right parameter types are passed to the model. If the user inserts text (string type), where a number is expected, a warning appears on the preview window. (See Appendix C)

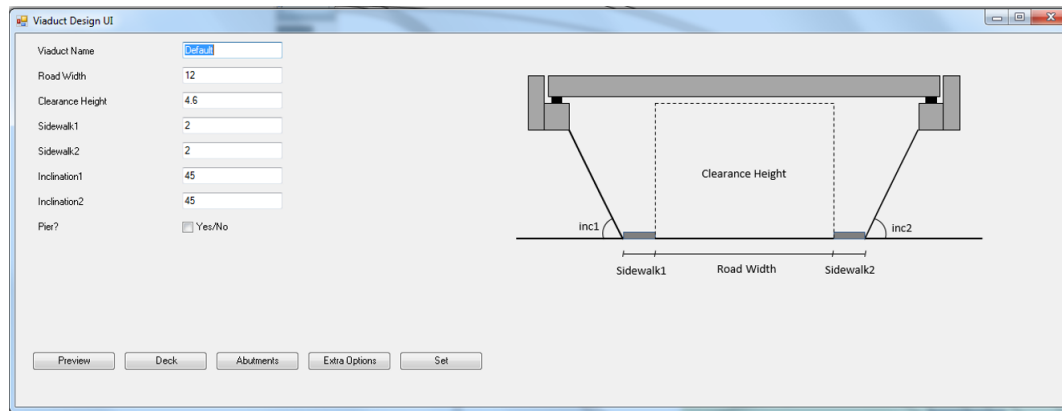


Figure 3.26: Python-Based User Interface

In Figure 3.27, the Dynamo Geometry is illustrated, for a set a parameters

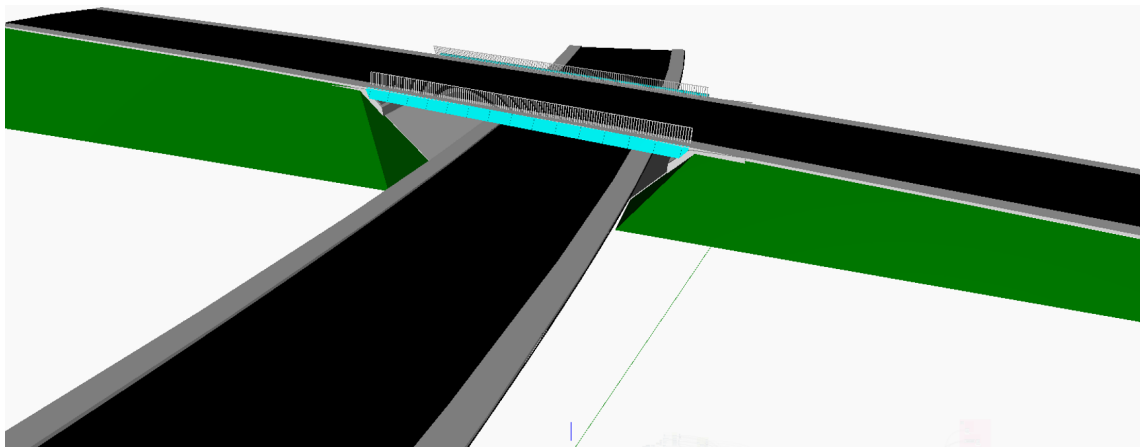


Figure 3.27: Geometry in Dynamo

3.7 Design Restrictions

An important step in the development of this algorithm is the definition of its area of application. A number of restrictions regarding the use of the model are denoted below:

- The knowledge model concerns only common prefabricated, concrete viaducts.
- The viaducts that can be designed using this model have maximum 2 spans.
- The width of the deck is considered constant.
- High abutments are only considered, since they are the most common solution, used in the Netherlands.
- Structural analysis is performed only for the cases of a straight or skewed slab geometry.
- The angle of skewness should be less than 20 degrees, since correction factors need to be applied for higher values. Skewed geometry is considered in the model, however the effect of an increased angle of skewness is not investigated.

- The minimum horizontal radius considered in the model is 295m (as specified for Distributor Roads).

3.7.1 Limitations of Input Values

The parameters specified in the previous sections have restrictions in terms of input values. The values entered as input fall into 3 categories, as defined in Table 4. The colours indicate the status of a value. It is important to denote that red values indicate that a value is either incorrect (e.g negative value for width) or lie out of the scope of this analysis.

Table 4: Input Limitations

	The values lie within the scope of the algorithm
	The values lie marginally out of scope - Specific parameters should be reconsidered
	The values are incorrect or out of scope

Table 5: Input Limitations

Alignment Curvature	$R < 295$	The curvature is too small
	$R \geq 295$	The alignment lays within the limits
Slopes	0-29 degrees	The slope is too small
	30-45 degrees	Unreinforced earth can be considered.
	46-70 degrees	Reinforced earth should be considered
	71-90 degrees	Other types of abutments should be considered (e.g Low abutments)
Clearance Height	Indicated by road type	4.6m + offset height (optional)
Viaduct's span	$8m < L \leq 21m$	Prefabricated SJP-FLEX concrete beams by Spanbeton can be employed
	$22 < L < 60$	SJP-FLEX beams cannot be used. Consider other sections (SKK or ZIP)
	$L > 60$	Prefabricated beams cannot be used. Consider In situ, Prestressed concrete or steel.
Skewed angle	$0 < \theta < 20$ degrees	The skewed angle of the deck lies with the limits
	$\theta > 21$ degrees	The effects should be investigated
Structural Analysis	$8m < L \leq 21m$	Structural Analysis is possible for the SJP-FLEX beams
	$L > 21m$	Structural Analysis is not possible for SJP-FLEX beams

3.8 Design Parameters

In this section, the design parameters are summarized and divided into three distinct categories: user-defined parameters, default and immutable.

- **User-Defined parameters:** User-defined parameters reflect the level of design freedom in the model. The values for these parameters are provided by the user, within the specified limitations of the model. Those parameters are defined through the user-interface.
- **Default parameters:** The default parameters are not essential to the design. The values of those parameters can be predefined, since they are not among the primary design choices or are highly standardised (e.g approach slabs). It is important to note that the values for these parameters can still be changed by the user, as they can be found on the Dynamo canvas, but they are not on the user-interface. The ability to change those values is important, since codes and regulations may change in the future it is not advised to build a parametric model around specific values.
- **Immutable parameters:** This category is closely related to the limitations of the platform. The logic behind this parameters was defined during the creation of the model and cannot be changed by the user. For instance, the type of the abutment (bankseat) is an immutable parameter which was decided early in this study and the logic of the algorithm revolves around it. Therefore, in order to change this parameter the whole model needs to be reconsidered.

The design parameters can be seen in Table 6. The default values are denoted with light gray and the set parameters are denoted with dark gray. The parameters which are important for the structural analysis are defined in Section 3.9.

Table 6: List of Parameters

Element Name	Number of Instances	Parameters	Values
Viaduct	1	Alignment	
		Slope (side 1)	
		Slope (side 2)	
		Road width underneath the viaduct	
		Pier	
Deck	1	Width	
		Slab Thickness	Section 3.5.2
		Crossfall	2.5%
		Tolerances	Section 3.1.1.1
		Asphalt Layer	t = 140mm
		Clearance Height	
Railings	2	Curved/Straight Edges	
		Position on Curb	
		Inclination	
		Shape of Vertical and Horizontal Bars	
		Distance between Vertical Bars	
Edge Elements	2	Number of Horizontal Bars	
		Shape	
		Size	
		Length of each element	
		Tolerance	
		Position	Section 3.1.2.5
Abutments	2	Cutting at Wing Walls	Section 3.1.2.5
		Type	Bankseat
		Shape (6 parameters)	
		Vertical Translation	0m
		Location	Depends on alignment
		Angle of Skewness	Depends on alignment
		Cut for Approach Slabs	Section 3.1.1.1
Bearings	n	Dimensions (3 parameters)	Section 3.1.1.6
		Position	Section 3.1.1.6
		Number	Number of beams
Approach Slabs	2 arrays	Dimensions (3 parameters)	Section 3.1.1.4
		Position	Depends on abutment
Wing Wall	4	Shape	Section 3.1.1.3
		Dimensions (3 parameters)	
		Position	Depends on abutment
Pier	0 or 1	Position	
		Number of Columns	
		Diameter of Columns	
		Dimensions of Pier Beam (2 parameters)	
		Pier Beam Cut to Skewed Angle	Section 3.1.3
Surroundings	-	Embankment angle	

The total number of parameters in the model, multiplied by the instances of the components arises to:

82 parameters

However, the parameters which the user needs to specify are less, since some components of the viaduct are usually standardised (default parameters - denoted with gray color) and some components are designed symmetrically, which implies that the relevant parameters need to be defined only once for all components of one group. An example is given below for the abutments:

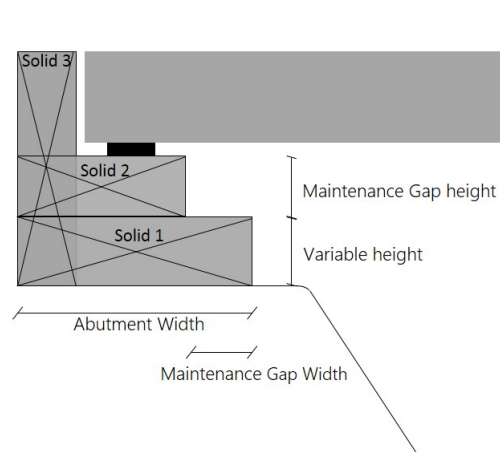


Figure 3.28: User-defined abutment parameters

Initially, for the design of the bearings the dimensions of the 3 solids that compose the abutment should be defined. However, The height of Solid 3 depends on the height of Solid 1, the height of Solid 2 (maintenance gap), the height of the slab, as well as the the height of the bearing. The width of Solid 3 is also depending on the total width of the abutment, as well as the width of the bearing and the tolerances around it. Thus, the shape parameters can be reduced from 6 to 4.

Moreover, the location of the abutment and the angle of skewness depend on the alignment, therefore they cannot be changed by the user. The type is also predefined, since the abutments are considered bankseats in the model. The cut for the placement of the approach slabs and the vertical translation are considered default.

In total, the user-defined parameters or the abutments are 4, as shown in Table 7, considering that the same abutment is used for both sides.

Table 7: Abutment parameters

Parameters	Number	User-defined
Shape	6	4
Total	11	4

The option for a symmetrical design of the abutments is given in the User Interface, as shown in Figure 3.29.

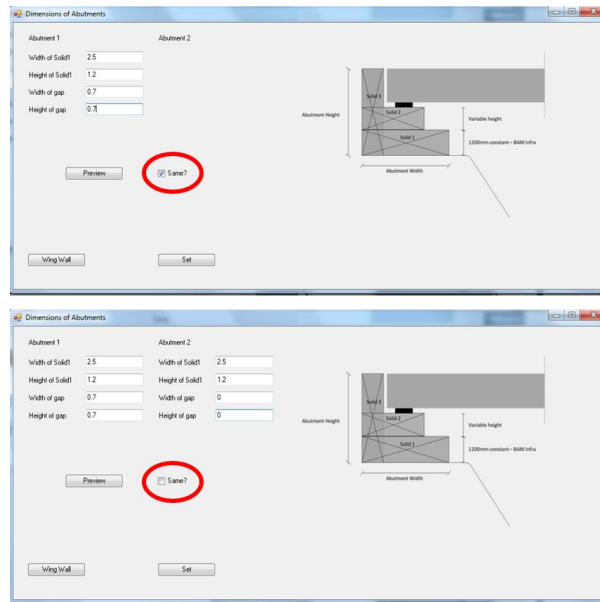


Figure 3.29: Option for symmetrical design of the abutments in the UI

By distinguishing the parameters in user-defined, default and set, it is concluded that the total number of parameters that the user has to define are 42, considering a non-symmetrical design and 30 considering a symmetrical design. In Table 8, the percentage of its parameter type in the overall parameters can be shown. In the case of a symmetrical design, only 36.6% of the parameters needs the attention of the engineer/architect, which implies that the design time can be drastically reduced by employing such a tool in the design practice.

Table 8: Design Parameters

Parameter Category	Number	Percentage of Total Parameters
User-Defined (non-symmetrical)	42	51.2%
User-Defined (symmetrical)	30	36.6%
Default	30	36.6%
Immutable	10	12.2%

3.9 Structural Analysis of the Design

3.9.1 Model Scope

The structural model is developed in the context of a conceptual study, which implies that further refinement is needed to derive final, detailed results. The aspiration is to prove that basic structural analysis considerations can be seamlessly linked to the design phase, by eliminating the need to develop individual models on multiple softwares. All parameters are defined through Dynamo and the structural engineer uses the Robot environment simply to assess the results of the analysis. The generation of the FE model and the execution of a linear analysis are also controlled by Dynamo.

The output of the structural analysis provides an overview of the resulting forces and the behaviour of the slab. Moreover, panels cuts along the longitudinal direction can be employed to get the results on the prefabricated beams.

The actual geometry of the deck slab is transferred to Robot for the structural analysis, therefore the angle of skewness is also considered in the model. However, for an angle of skewness up to 20 degrees, the effect on the results is not expected to be significant.

In this study the effect of this angle is not investigated. However, the direct transfer of the slab geometry in Robot increases the value of this study, since the model can be further extended and incorporate the appropriate considerations regarding slabs with an increased angle of skewness.

In this section, both an analytical approach and a numerical approach are presented, as well as the assumptions regarding the materials and the loading.

From this model the following can be derived:

- Effect of Prestressing on the slab
- Reaction at the supports for the design of the substructure and shear reinforcement in the beams

The structural system of the viaduct is considered statically determinate to avoid hogging moments at the supports. This is generally preferred, since differential settlements, temperature effects, shrinkage and creep can cause large hogging moments in statically indeterminate systems.

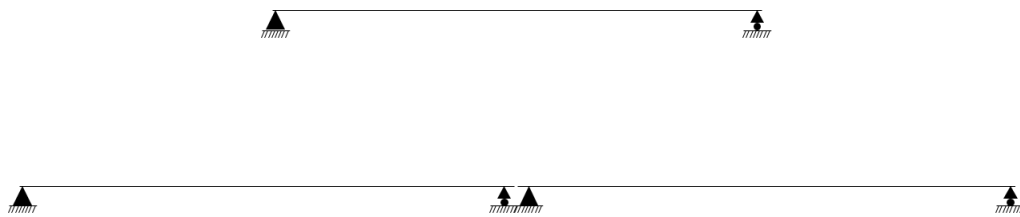


Figure 3.30: One span and two span statically determinate model

Structural analysis is conducted considering only SJP-FLEX beams and for spans up to 21m (due to the limitations of the SJP-FLEX length). This type of beam is very common in the Netherlands for the design of relatively short and straight viaducts. The Finite Element Model is developed on Robot, a structural analysis software by Autodesk [Autodesk, 2017c]. One of the main advantages that Robot has in relation to Dynamo is that extensive Robot API can be employed, using Python, to establish a direct link between the two platforms. This is the reason why Robot is chosen for the analyses, as the process of exporting IFC files is not desired in this research project.

All the structural parameters are defined in the Dynamo environment, where the user has the option to conduct a structural analysis of the viaduct's deck on Robot. In case there is a pier, and therefore, two statically determinate slabs, one of the slabs is modelled in Robot. The engineer can choose which slab should be modelled by selecting its index on the Dynamo canvas (1 or 2).

3.9.1.1 Connection to Robot

In order to establish a sound connection between Dynamo and Robot, a Python node is developed, as the available plugins for this connection were deemed inadequate. This node establishes a basic communication between the two platforms by accessing the Robot API and defining the structural analysis parameters through Dynamo. The goal of this Python script is to ensure that the users stay within Dynamo and do not need to input data in multiple platforms. When the Dynamo script is executed, the user needs to define whether a structural analysis should be conducted or not. In the former case, the python node which connects Dynamo and Robot is executed, while in the latter case it is not. The only interaction of the user with Robot is limited to simply opening the plate template of Robot, all other parameters are specified through Dynamo. In Figure 3.31, the data sets which are transferred to Robot through the node are shown. The Dynamo script pertaining to Robot can be found in Appendix E.

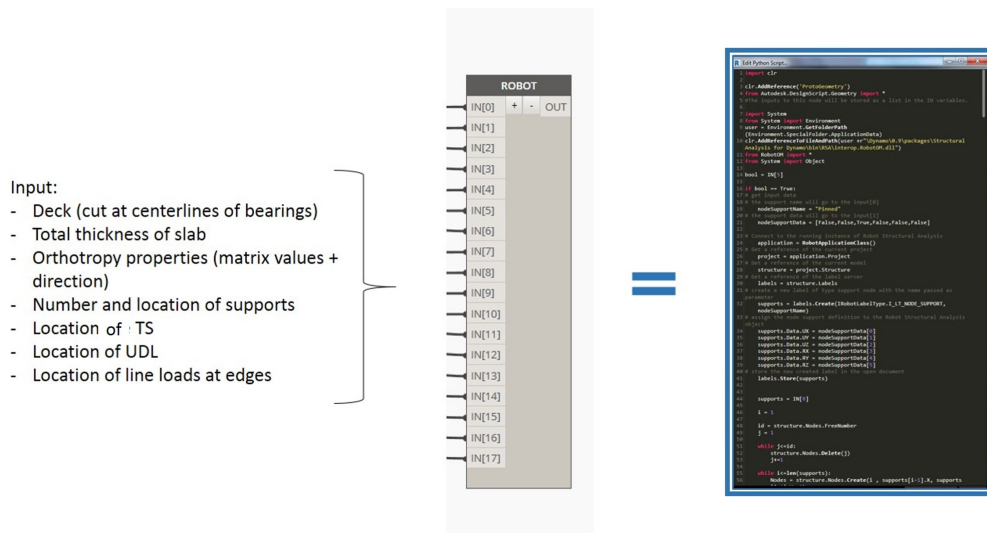


Figure 3.31: Python Script for the Connection to Robot

Important Notes:

- **Orthotropy:** A crucial dataset needed for the finite element simulation of the deck is the values of the orthotropy matrix, as indicated in section 2.5.3. The membrane stiffness of the plate element is ignored. The rest of the values correspond to the flexural and shear stiffness matrices. Defining the direction of the orthotropy axes is of crucial importance, since the local coordinate system of the slab may not be aligned with the global coordinate system of Robot, especially if there is an angle of skewness. To account for this divergence, the orthotropy is set along with a vector parallel to the longitudinal sides of the deck, which defines the main orthotropy axis.
- **Thickness of orthotropic slab:** The thickness of the slab is defined through the graphs provided by Spanbeton [Spanbeton, 2018] including the thickness of the pressure layer (120mm) and it is automatically transferred to Robot.
- **Material Definition:** The material is also defined through the Python node and it is C60/75, therefore the material of the prefab beams.
- **Notional Lanes:** The division of the carriageway into notional lanes and the assignment of the respective loads is automatically done in Dynamo. One arrangement of the notional lanes is considered. Notional Lane 1 is placed only at the edge of the carriageway, to induce maximum bending moments at the outer beams which are expected to be governing for the design. In order to have a complete structural analysis, multiple arrangements of the notional lanes should be considered along with multiple locations for the Tandem Systems. However, the scope of this conceptual study is to prove the benefits of establishing a connection between the design part and the structural analysis part, therefore limited structural analysis considerations are made.

An example of the panel properties which are set in Robot can be seen in Figure 3.32.

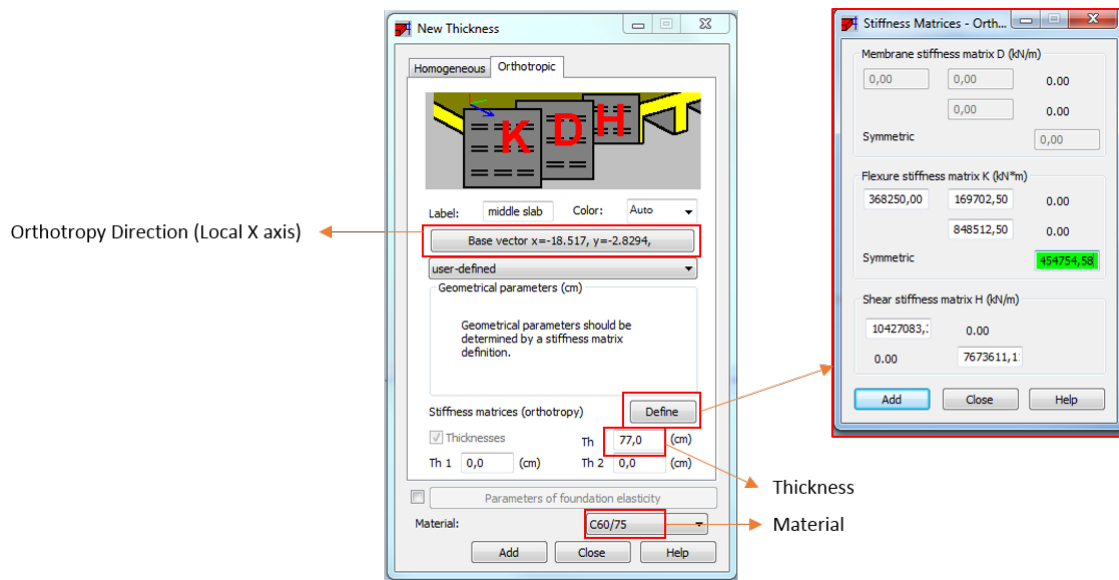


Figure 3.32: Properties of Orthotropic Panels in Robot

3.9.2 Finite Element Simulation

A number of design simplifications are considered in this study for a less time consuming and cost effective analysis.

- Structural analysis is conducted at full service stage ($t = \infty$).
- The prefab beams and the in situ concrete layer are assumed to work together as one composite section. For the definition of the parameters of orthotropy the properties of the composite section are considered.
- The deck of the bridge is modelled as orthotropic plate elements (ignoring the membrane stiffness), which has a thickness equal to the height of the deck, h_t as can be seen in Figure 3.25.
- The edge elements are assumed to function as one composite section with the outer main beams, therefore they have a different flexural stiffness in the longitudinal direction compared to the rest of the beams, as well as a different width (1.5m). For this reason, two types of plate elements are considered in Robot, the "middle slab" element and the "edge slab". The orthotropy matrix values are the same for those two plates, apart from D11 (Section 2.5.3).

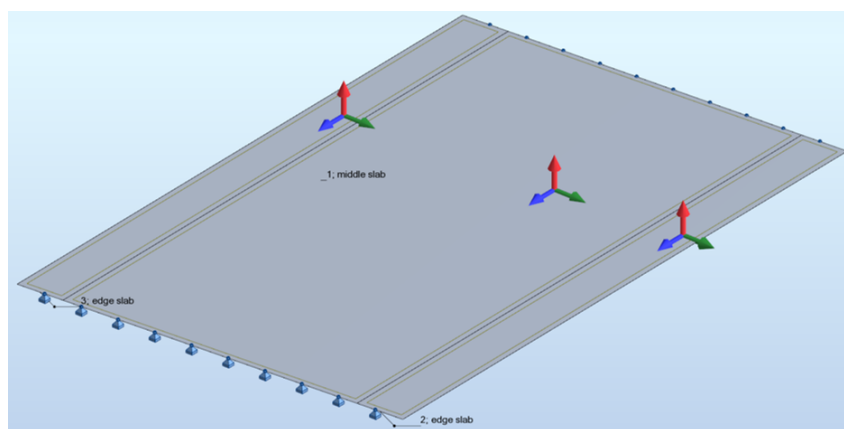


Figure 3.33: Plate Elements (Robot Model)

3.9.2.1 Supports

The number of supports depends on the number of beams that fit into the specified width. Supports are only placed underneath the main beams of the deck, since the edge beams are attached on the main beams during construction and do not have their own supports. The supports restrict only the vertical movement, simulating the function of the bearings (Figure 3.35). The location of the support points is defined in Dynamo, at the centerline of the bearings as shown in Figure 3.34. In this figure, the larger surface without an outline is the actual surface of the deck, while the surface with the outline defines the one that is considered in Robot.

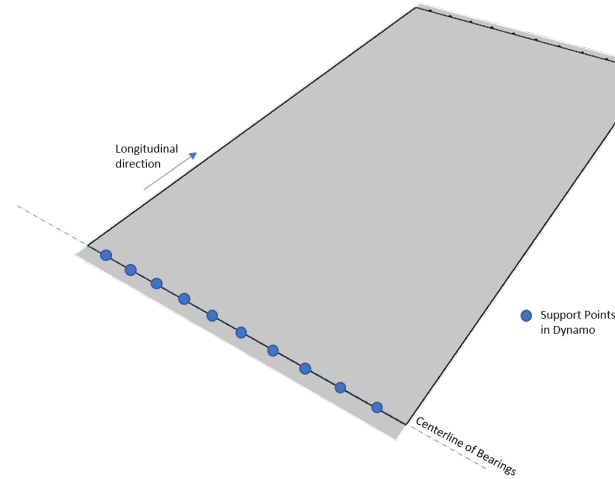


Figure 3.34: Support Points in Dynamo

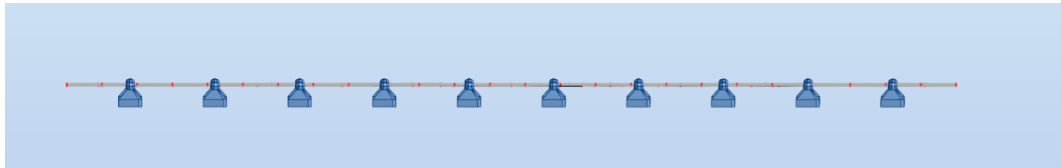


Figure 3.35: Supports (Robot Model)

3.9.2.2 Loads and Load Combinations

The loads are automatically placed on the deck, according to its geometry and distribution of notional lanes. The following loadcases are considered:

- **Dead Load:** The dead load is considered for the whole model, according to the properties of the materials involved (reinforced concrete: $\gamma_c = 25kN/m^2$) and the slab thickness.
- **Asphalt Load:** The asphalt load is applied on the carriageway as a uniformly distributed load, as shown in Figure 3.36.

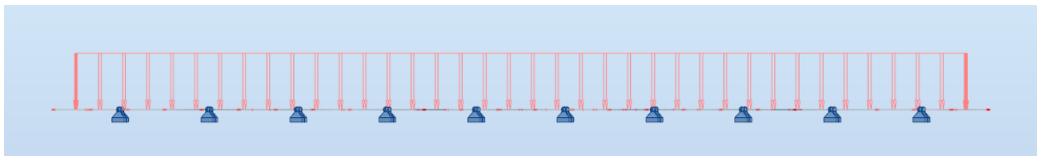


Figure 3.36: Asphalt Layer Load (Robot Model)

- **Edge Load:** A line load is applied at the edges of the viaduct to include the loads of the curb, the edge elements, the parapet and the railings. The magnitude of that load is 3.5kN/m (railing: 1kN/m + kerb: 2.5kN/m). (Figure 3.37)



Figure 3.37: Edge Line Load (Robot Model)

- **Traffic Loads:**

- **UDL on Notional Lane 1:** The load on Notional Lane 1 is equal to 9 KN/m^2

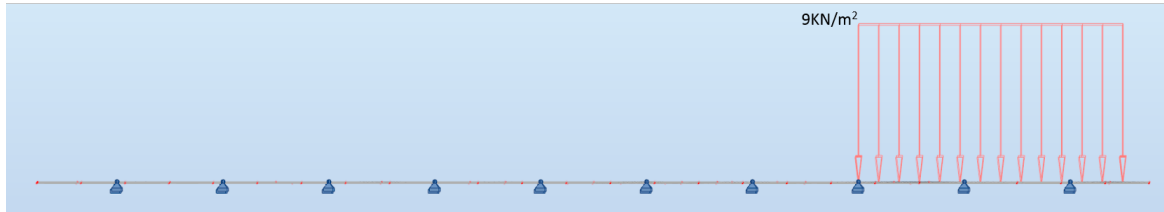


Figure 3.38: Load on Notional Lane 1 (Robot Model)

- **UDL on the rest of the Notional Lanes** The load on the rest of the lanes is equal to 2.5 KN/m^2

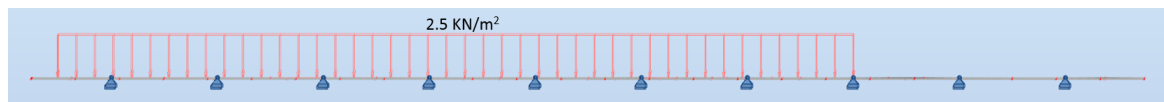


Figure 3.39: Load on the rest of the Notional Lanes (Robot Model)

- **Tandem System - one vehicle on each Notional Lane:**

The location and magnitude of the loads of the Tandem System are defined in Dynamo. Each vehicle is positioned in the middle of the span for each notional lane, as illustrated in Figure 3.40, where the rectangles correspond to the wheels of the vehicles. The angle of skewness is taken into account in the position of the loads. Indeed, in Figure 3.40, the wheels of the three vehicles are not completely aligned in the transverse direction, since a small angle of skewness is considered in this example (3.7 degrees).

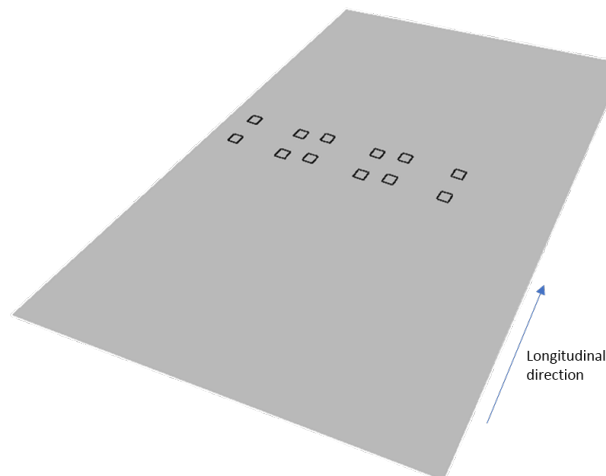


Figure 3.40: Location of TS in Dynamo (Perspective View - Dynamo Model)

The transverse arrangement of the TS loads in Robot is shown in Figure 3.41, while Figure 3.42, shows the location of the TS loads in the middle of the span for the maximum bending moment.

The structural engineer has the option to place the tandem system at the ends of the viaduct (Figure 3.43) to get the maximum shear.
The load values derive as following:

- TS1: $Q_1 = 300\text{KN}$ per axis
Contact area of wheel: $0.40 \times 0.40 = 0.16\text{m}^2$.
Load on contact area: $\frac{Q_1/2}{0.16} = 937.5\text{KN/m}^2$

- TS2: $Q_2 = 200\text{KN}$ per axis
Contact area of wheel: $0.40 \times 0.40 = 0.16\text{m}^2$.
Load on contact area: $\frac{Q_2/2}{0.16} = 625\text{KN/m}^2$

- TS3: $Q_3 = 100\text{KN}$ per axis
Contact area of wheel: $0.40 \times 0.40 = 0.16\text{m}^2$.
Load on contact area: $\frac{Q_3/2}{0.16} = 312.5\text{KN/m}^2$

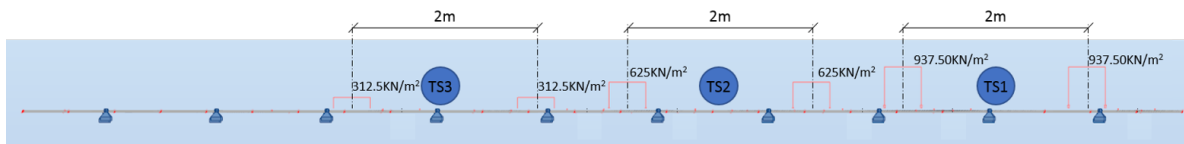


Figure 3.41: TS Loads (Transverse View) (Robot Model)

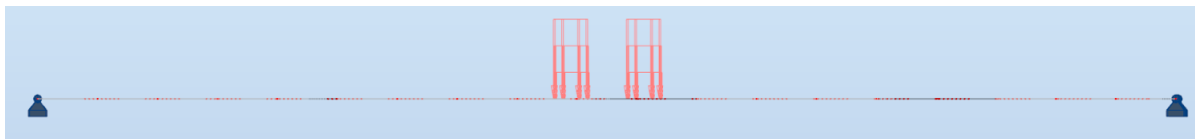


Figure 3.42: TS Loads for Maximum Bending Moment (Longitudinal View) (Robot Model)



Figure 3.43: TS Loads for Maximum Shear (Longitudinal View) (Robot Model)

- **Prestressing:** The SJP-FLEX beams have horizontal tendons as they are produced on prestressing beds (Figure 3.44). The effect of the prestressing can be implemented in the FEA model as a moment at the supports (Figure 3.44).

$$M_P = F_{P\infty} * e_P$$



Figure 3.44: Prestressing Bed

The prestressing moment is applied at the slab as shown in Figure 3.45. Through logic checks based on the direction of the local coordinate system, it is ensured that the moment is applied around the transverse direction of the deck and with the right direction (Figure 3.44).

Magnitude: The magnitude of the prestress force at $t = 0$, is the input needed by the engineer. Therefore, the prestressing force is defined in Dynamo, and then translated into a moment in Robot. The structural analysis is conducted for $t = \infty$, therefore the moment in the Robot model is reduced by 20% to account for the prestressing losses (Section 3.10.3.4).

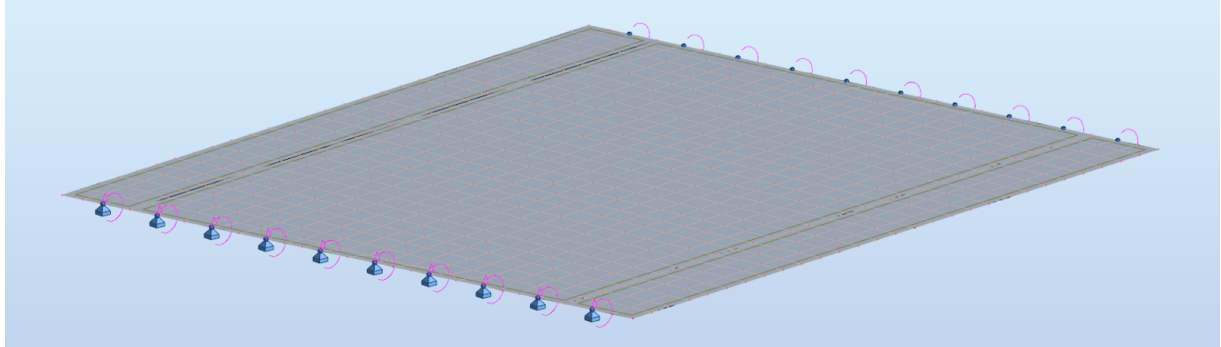


Figure 3.45: Prestressing Moment on slab

3.10 Model Validation

As was mentioned in Section 1.3.2.3, an important hindrance to new technologies and automation is the lack of trust from the engineers. This aspect is considered in this study although, due to the fact that this research is conceptual, extensive validation cannot be easily achieved.

Nevertheless, an effort is made in this section, to validate the output of the model. Two types of validation can be attempted:

- **Geometry Validation in Dynamo:**

The geometry produced by the model, can be checked by deriving dimensions through the model and comparing them with the set parameters. This type of validation can be achieved immediately by investigating the exported model, where dimensions can be checked. On the Dynamo canvas, one can validate the results by looking at the "Validation" group (3.46). Some of the values which are measured are the inclination of the slopes, the width of the viaduct, the clearance height and the angle between the longitudinal and transverse edges of the deck. The divergence between the user-defined values and the values measured in Dynamo is deemed insignificant, if the provided alignment is within the prescribed limits (Section 3.1.2.2).

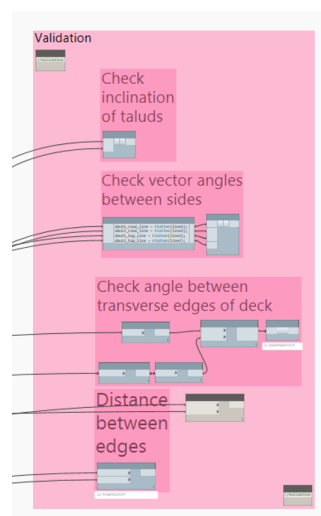


Figure 3.46: Dynamo Validation Group

- **Geometry Validation in Robot:**

The geometry which is modelled in Robot can be easily validated, using the dimension tool. In Figure 3.47, the distances between the supports are measured, along with the total width of the viaduct. The width of the SJP-FLEX beam is 1.2m, therefore the distance between the supports is correct. The specified width of the viaduct is 12.6m, which is transferred with a negligible divergence (0.001%) in Robot.

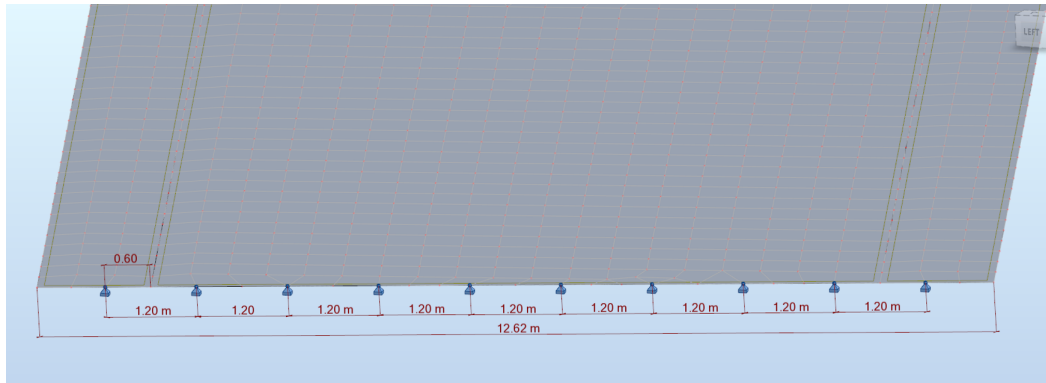


Figure 3.47: Dimensions of Robot model

- **Structural Analysis Validation:**

The validation of the structural analysis can be achieved through the following:

- **Visual Verification:**

Visual verification of the expected behaviour of the structure. This simple approach lead to the realisation of an important issue in the connection between the softwares. Initially, the moment due to prestressing was not correctly applied in the model, since at some of the supports instead of finding a bending moment close to the one prescribed, the bending moment in Robot was close to 0kNm. This indicated a problem in the definition of this loadcase. The moment was initially applied at Dynamo points, which were transferred to Robot and possibly due to divergences in the definition of the point coordinates between the softwares, some points were not placed at the right locations (edge of the panels), therefore the moment was not correctly applied on the panels. The issue was resolved by retrieving the respective points (support points) from the Robot database, to ensure that the location of the points was clearly defined.

- **Sum of reactions:**

One way to partially validate the model is to ensure that the sum of the applied forces is equal to the sum of the reactions. For the slabs investigated, the sum of reactions in Robot was always equal to the total applied loads for each loadcase.

- **Comparison with analytical solutions:**

The results of the structural analysis can be validated through the analytical solution of the orthotropic slab. The bending moments on the beams due to the uniform loads (Dead Load) are very close to the ones derived from simple hand calculations. However, for the point loads a more sophisticated approach should be employed. The Guyon-Massonnet method is an efficient way to define the load distribution on the beams and it is employed to verify the results of the Robot model in Section 3.10.1.1.

3.10.1 Analytical results for the TS

An example is solved to validate the model:

The dimensions of the deck are the following:

- specified width: 12m (12.6m in the Robot model for SJP-FLEX beams)
- Length: 18.73m
- beams: SJP-FLEX650

3.10.1.1 Guyon - Massonnet Method

In bridge design, there are a number of ways to consider the behaviour of the bridge's deck and the way the loads of the traffic are transferred from the deck, to the superstructure and then to the substructure. One of the methods used to assess the fraction of the load which is carried by the longitudinal girders is the Guyon - Massonnet method. The aforementioned method is based on an orthotropic plate analysis, meaning that the equivalent plate possesses the same longitudinal and transverse stiffness as that of the actual deck. The load distribution factors are developed by correlating the actual deflection of a bridge section under the loads and the deflection of the same bridge section with the same loading system uniformly distributed across the bridge [Xanthakos, 1994].

The composite slab is considered for the calculations with uncracked concrete. The edge beam is attached on the outer main beam, therefore they are considered to function as one element in the model, as shown in Figure 3.48.

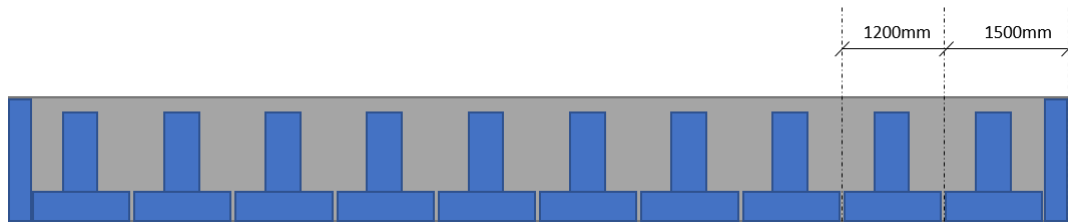


Figure 3.48: Edge beam

The properties of the section are given in Table 9. Calculations in Appendix

Table 9: SJP-FLEX650 Properties

Property	Value
I_{comp}	$42.1 \cdot 10^9 \text{mm}^4$
E_1	39000 MPa
E_2	34000 MPa
D_{11}	1313520 kNm
D_{22}	848512.5 kNm

The load distribution on the orthotropic slab is governed by the two dimensionless parameters: θ and α . For solid slabs the parameter α can be considered equal to 1 [Blaauwendraad, 2012] and θ is calculated as shown in Equation 10.

$$\theta = \frac{b}{2a} \sqrt[4]{\frac{D_{11}}{D_{22}}} = \frac{6.3}{18.73} \sqrt[4]{\frac{1313520}{848512.5}} = 0.3752 \quad (10)$$

where:

$$b = \frac{\text{width}}{2} = 6.3\text{m}$$

$$2a = L = 18.73\text{m}$$

D_{11}, D_{22} are specified in Table 9

The respective Guyon-Massonnet table is employed for $\theta = 0.3752$ and $\alpha = 1$, through linear interpolation of the values calculated in "Compléments à la méthode de calcul des ponts à poutres multiples" [Massonnet, 1962]. The tables are available in Appendix D. The longitudinal bending moments are calculated for the TS in order to validate the results of the FE analysis in Robot. The outer beams (b1 and b2 in Figure 3.49) are checked, since the highest longitudinal moments are expected near the edges.

Tandem System Loadcase:

The Guyon-Massonnet method uses reference points on the transverse section of the deck to derive the load distribution factors. Therefore, the respective positions of the beams under investigation and the load positions are denoted as shown in Figure 3.49.

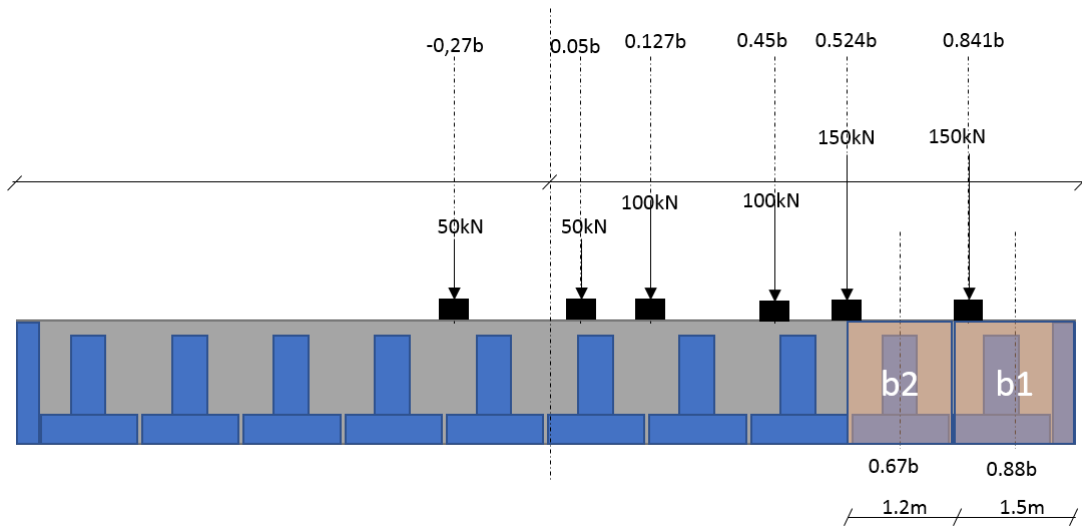


Figure 3.49: Tandem System on the deck with load locations

Determination of Mean Load (P_{mean})

The total loads on the deck are spread uniformly over the width of the slab:

$$P_{mean} = \frac{4 * 150 + 4 * 100 + 4 * 50}{12.6} = 95.23 \text{ kN/m}$$

Determination of Mean Load Distribution Parameters for b1 (K_{mean})

$$K_{0.841b} = \frac{1.449 + 1.253 + 1.208 + 1.023 + 0.982 + 0.893}{6} = 1.135$$

$$P_{0.841b} = K_{0.841b} * q_{mean} * b_{eff} = 1.135 * 95.23 * 1.5 = 162.129 \text{ kN}$$

$$M_{0.841b} = \frac{P_{0.841b}}{2} * \left(\frac{18.73}{2} - 0.6 \right) = 710.5 \text{ kNm}$$

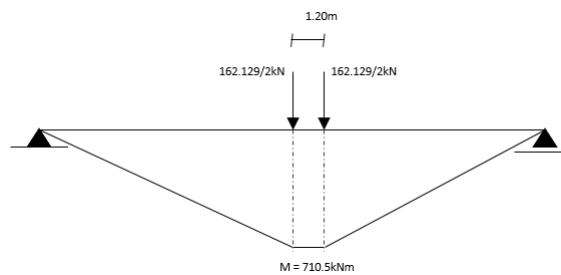


Figure 3.50: Longitudinal bending moment ($M_{0.841b}$) due to TS

Determination of Mean Load Distribution Parameters for b2 (K_{mean})

$$K_{0.67b} = \frac{1.344 + 1.217 + 1.184 + 1.036 + 1.001 + 0.891}{6} = 1.112$$

$$P_{0.67b} = K_{0.67b} * q_{mean} * b_{eff} = 1.112 * 95.23 * 1.2 = 127.075 \text{ kN}$$

$$M_{0.67b} = \frac{P_{0.67b}}{2} * \left(\frac{18.73}{2} - 0.6 \right) = 556.91 \text{ kNm}$$

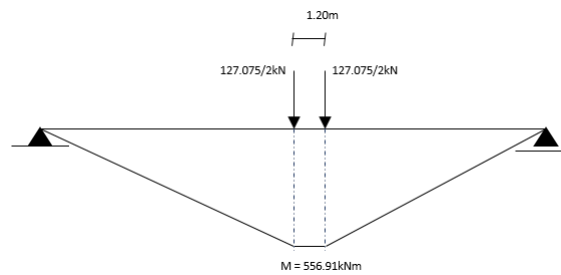


Figure 3.51: Longitudinal bending moment ($M_{0.67b}$) due to TS

3.10.1.2 Comparison with Robot results

The analytical and the numerical results are compared for the Tandem System Loadcase, in order to ensure that the FEA model functions as expected. The peaks at the supports are due to the use of point supports. In a further step of development, the simulation of the supports should be further investigated to account for those inaccuracies. Panel cuts are used to find the longitudinal bending moment on the beams. The results at the panel cuts are in kNm/m, therefore they need to be multiplied with the effective width of the beam.

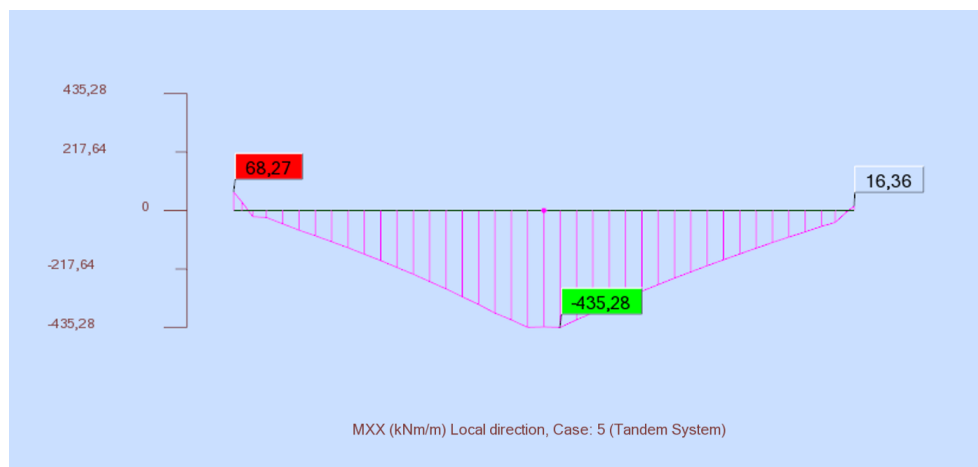


Figure 3.52: Longitudinal bending moment on beam 1

The maximum bending moment in Robot is calculated per meter, therefore it needs to be multiplied with the actual effective width of the beam (1.5m).

$$M_{max} = 435.28 \text{ kNm/m} \text{ (Figure 3.52)}$$

$$M_{beam1} = 435.28 * 1.5 = 653 \text{ kNm}$$

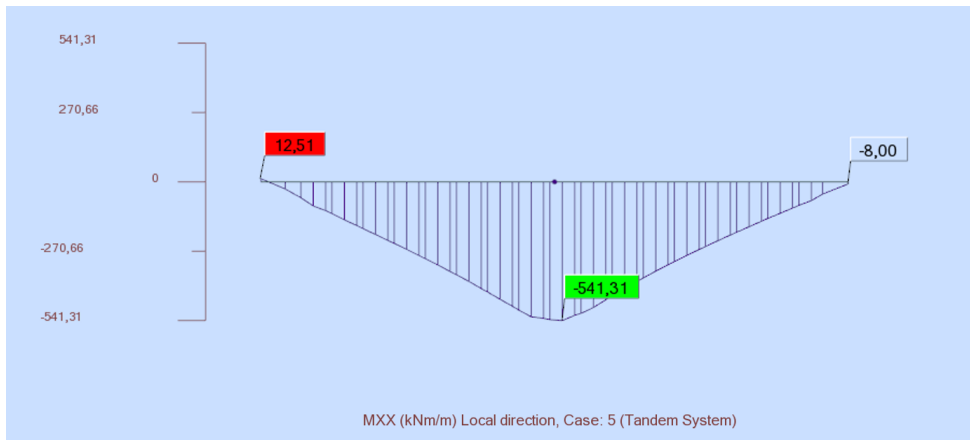


Figure 3.53: Longitudinal bending moment on beam 2

The maximum bending moment in Robot is calculated per meter, therefore it needs to be multiplied with the actual effective width of the beam (1.2m).

$$M_{max} = 541.31 \text{ kNm/m (Figure 3.53)}$$

$$M_{beam2} = 541.31 * 1.2 = 649.6 \text{ kNm}$$

Table 10: Comparison of Analytical and Numerical Results for the Tandem System

Beam ID	Calculation method	Value of $M_{bending}$ (kNm)	Convergence
Beam 1	Robot	653	0.92
	Guyon - Massonnet	710	
Beam 2	Robot	649.6	0.86
	Guyon - Massonnet	556	

The convergence between the results of the FE model and the Guyon - Massonnet method is deemed satisfactory. The divergence between the analytical moments and the ones derived from the numerical moment is justified, considering that the last beam (b1) has a different stiffness and effective width from the rest. The Guyon-Massonnet method spreads the orthotropy properties uniformly on the slab and does not take into account such irregularities.

3.10.2 Predimensioning of Prefabricated Beams

The relation between the height of the prefab beam (SJP-FLEX) and the span of the viaduct is given by the graph shown in Figure 3.54, as is indicated by Spanbeton.

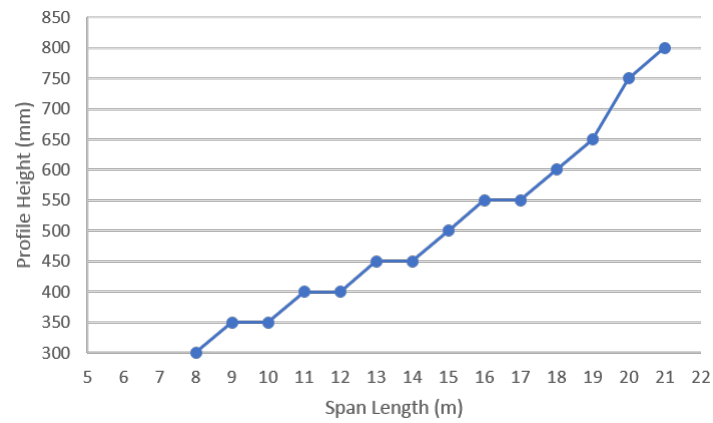


Figure 3.54: Profile Height - Span relation

3.10.3 Prestressing Calculation

In the structural analysis, the height of the prefab elements can be directly derived from the graph in Figure 3.54. In this section, the prestressing is manually calculated. The required prestressing force is calculated based on the “Cross section” method at the representative cross-section in the middle of the span. In this study, limited tensile stresses are allowed in the concrete. The following states are considered:

3.10.3.1 $T = 0$ - Construction stage

The loads considered at this stage are the prestressing force: F_{P0} and the self weight of the beam: M_g . This stage is governing for limiting the stresses at the top fibre of the cross section.

$$\sigma_{ct} = \frac{F_{P0}e_p}{W_{ct}} - \frac{F_{P0}}{A_c} - \frac{M_g}{W_{ct}} \leq \bar{\sigma}_t, \text{ stress at the top fibre} \quad (11)$$

$$\sigma_{cb} = \frac{-F_{Pi}e_p}{W_{cb}} - \frac{F_{Pi}}{A_c} + \frac{M_g}{W_{cb}} \geq \bar{\sigma}_d, \text{ stress at the bottom fibre} \quad (12)$$

where:

$\bar{\sigma}_t$ is the maximum tensile stress

$\bar{\sigma}_d = 0.6f_{ck}$ is the limited allowable compressive stress [EN1992-1-1(2004), 1992]

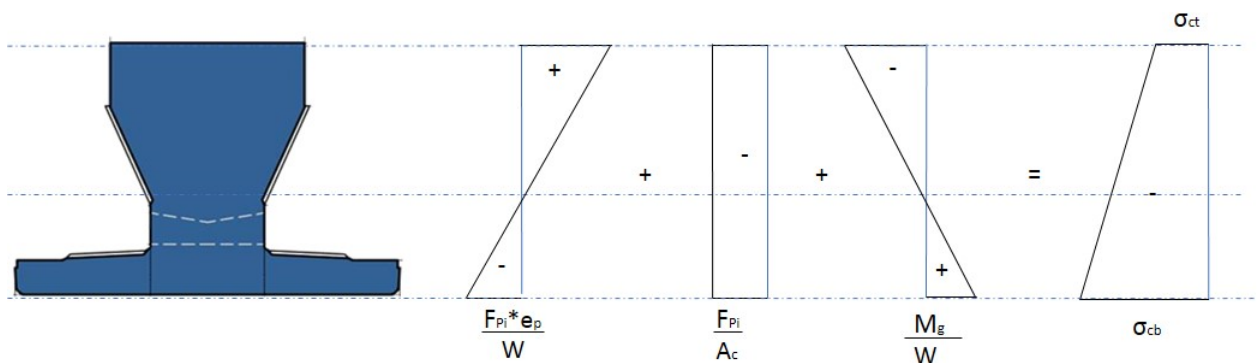


Figure 3.55: Stresses due to loads at $t = 0$

3.10.3.2 $0 < T < \infty$ - Casting the pressure layer

When the pressure layer is cast, its self weight is carried by the prefab beams. Partial losses are considered for the prestressing force. This stage is not governing for the stress checks, since the equations in this stage are taken as part of the full service stage.

$$\sigma_{ct} = \frac{F_{Pp}e_p}{W_{ct}} - \frac{F_{Pp}}{A_c} - \frac{M_g}{W_{ct}} - \frac{M_{pl}}{W_{ct}} \geq \bar{\sigma}_d \quad (13)$$

$$\sigma_{cb} = \frac{-F_{Pp}e_p}{W_{cb}} - \frac{F_{Pp}}{A_c} + \frac{M_g}{W_{cb}} + \frac{M_{pl}}{W_{cb}} \leq \bar{\sigma}_t \quad (14)$$

where:

$\bar{\sigma}_t$ is the maximum tensile stress

$\bar{\sigma}_d = 0.6f_{ck}$ is the limited allowable compressive stress [EN1992-1-1(2004), 1992]

F_{Pp} is the prestressing force with partial losses for $t < \infty$

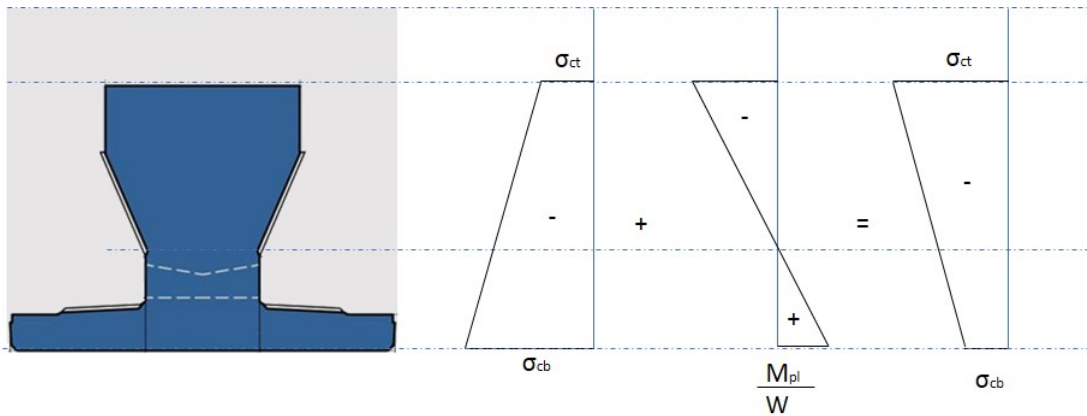


Figure 3.56: Stresses due to loads at $0 < t < \infty$

3.10.3.3 $T = \infty$ - Full service stage

The pressure layer and the prefab beam have now a composite function. The discontinuity which appears at the final stress distribution along the height of the cross section is due to the different concrete qualities of the pressure layer and the prefab beams.

$$\sigma_{ct} = \left(\frac{F_{P\infty}e_p}{W_{ct}} - \frac{F_{P\infty}}{A_c} - \frac{M_g + M_{pl}}{W_{ct}} \right) - \frac{M_l + M_s}{W_{ct,s}} \geq \bar{\sigma}_d \quad (15)$$

$$\sigma_{cb} = \left(\frac{-F_{P\infty}e_p}{W_{cb}} - \frac{F_{P\infty}}{A_c} + \frac{M_g + M_{pl}}{W_{cb}} \right) + \frac{M_l + M_s}{W_{cb,s}} \leq \bar{\sigma}_t \quad (16)$$

$$\sigma_{ct,slab} = \frac{M_l + M_s}{W_{cb,s}} \geq \bar{\sigma}_d \quad (17)$$

where:

$\bar{\sigma}_t$ is the maximum tensile stress

$\bar{\sigma}_d = 0.6f_{ck}$ is the limited allowable compressive stress [EN1992-1-1(2004), 1992]

$F_{P\infty}$ is the prestressing force with total losses for $t = \infty$

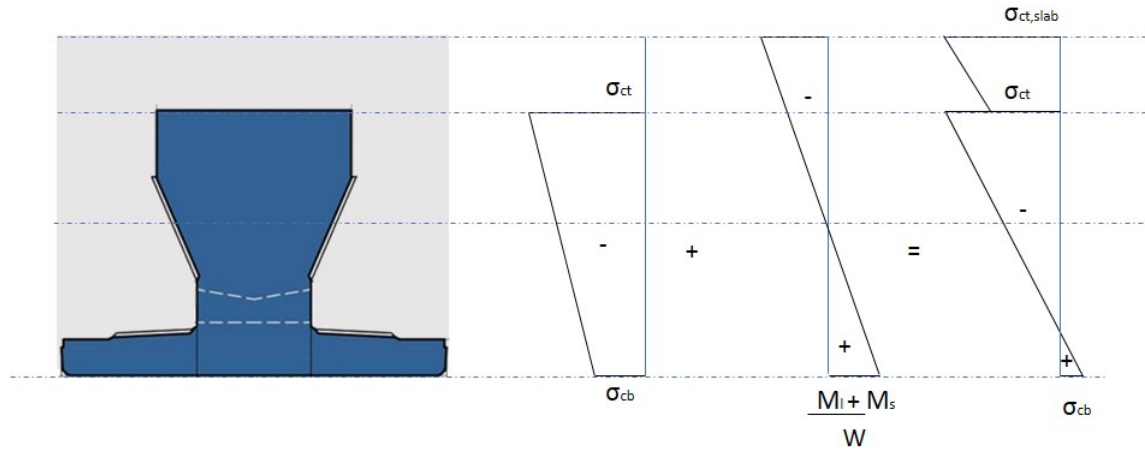


Figure 3.57: Stresses due to loads at $t = \infty$

Through the definition of the maximum allowable stresses at each stage the required prestressing force can be derived.

3.10.3.4 Time Dependent Losses

Initially the time dependent prestressing losses because of creep and shrinkage, relaxation of the prestressing steel and tendon friction are considered to be 20%. This estimation is deemed adequate for predimensioning, however for the next stages of the design it needs to be calculated precisely. For this research it is considered 20 %.

3.10.3.5 Calculation of Prestressing for SJP-FLEX650:

The necessary prestressing in the beams derives from the equations specified in Section 3.10.3 considering the Frequent Load Combination. The strands are considered uniformly spread in the flange of the beam, therefore e_p is a constant in the calculations and equal to 225mm for the SJP-FLEX650. Since, the Robot model is validated, the additional dead loads and variable loads at the full service stage are taken directly from Robot.

Table 11: Properties of SJP-FLEX650 [Spanbeton, 2018]

Property	Beam	Composite Section
I	$16.7 * 10^9 \text{ mm}^4$	$42.1 * 10^9 \text{ mm}^4$
z_p (from bottom fiber)	287mm	380mm
Area	$358 * 10^3 \text{ mm}^2$	$924 * 10^3 \text{ mm}^2$
Self load	9.1 kN/m	23.5 kN/m

For the beam under investigation, the following stress checks are governing:

- **T = 0 - Construction stage:**

The loads considered at this stage are the prestressing force: F_{P0} and the self weight of the beam: M_g .

$$\sigma_{ct} = \frac{F_{P0}e_p}{W_{ct}} - \frac{F_{P0}}{A_c} - \frac{M_g}{W_{ct}} \leq \bar{\sigma}_t \rightarrow F_{P0} \leq 6233 \text{ kN} \quad (18)$$

$$\sigma_{cb} = \frac{-F_{P0}e_p}{W_{cb}} - \frac{F_{P0}}{A_c} + \frac{M_g}{W_{cb}} \geq \bar{\sigma}_d \rightarrow F_{P0} \leq 6435 \text{ kN} \quad (19)$$

where:

$$\bar{\sigma}_t = 4.4MPa$$

$$\bar{\sigma}_d = -36MPa \text{ [EN1992-1-1(2004), 1992]}$$

$$e_p = 225mm$$

$$M_g = 9.1 * \frac{18.73^2}{8} = 399.05kNm$$

• **T = ∞ - Full service stage:**

The pressure layer and the prefab beam have now a composite function. The discontinuity which appears at the final stress distribution along the height of the cross section is due to the different concrete qualities of the pressure layer and the prefab beams.

$$\sigma_{ct} = \left(\frac{F_{P\infty}e_p}{W_{ct}} - \frac{F_{P\infty}}{A_c} - \frac{M_g + M_{pl}}{W_{ct}} \right) - \frac{M_l + M_s}{W_{ct,s}} \geq \bar{\sigma}_d \rightarrow F_{P0} \geq -4619kN \quad (20)$$

$$\sigma_{cb} = \left(\frac{-F_{P\infty}e_p}{W_{cb}} - \frac{F_{P\infty}}{A_c} + \frac{M_g + M_{pl}}{W_{cb}} \right) + \frac{M_l + M_s}{W_{cb,s}} \leq \bar{\sigma}_t \rightarrow F_{P0} \geq 4043kN \quad (21)$$

$$\sigma_{cpl} = \frac{M_l + M_s}{W_{cb,s}} \leq \bar{\sigma}_t \rightarrow -6MPa \leq -21MPa \quad (22)$$

$$\bar{\sigma}_t = 4.4MPa$$

$$\bar{\sigma}_d = -36MPa \text{ [EN1992-1-1(2004), 1992]}$$

$$e_p = 225mm$$

$$M_{g+pl} = 23.5 * \frac{18.73^2}{8} = 1030.5kNm$$

$$M_{l+s} = 912kNm$$

The value of M_{l+s} is taken from the Robot model, for a load combination based on the Frequent load combination. This combination is the following: $G_{asphalt+line+loads} + 0.8Q_{traffic}$.

By considering this combination, the moment M_{l+s} can be derived directly from the model, accounting for the distribution of the Tandem System on the beams.

It is interesting to note that the stress at the top of the in situ layer (Equation 22) is much lower than the stresses in the beams which explains why a lower quality of concrete is used.

From the Equations 18-21 , derives that:

$$4043kN \leq F_{P0} \leq 6233kN$$

Definition of Strands:

The total amount of prestressing steel in the beam is found, considering the data in Table 12.

Table 12: Data for Calculation of Strands

F_{Pmin}	4043kN
Y1860 - σ_{pm0}	1395MPa
A_{strand}	150mm ²

$$A_{p-req} = \frac{F_P}{\sigma_{pm0}} = \frac{4043 * 10^3}{1395} = 2898mm^2$$

$$n = \frac{A_{p-req}}{A_{strand}} = \frac{2898}{150} = 19.3 \rightarrow 20strands$$

$$A_p = 3000mm^2$$

$$F_{P0} = \sigma_{pm0} * A_p = 4185kN$$

Therefore, the prestressing force, required in the beam is:

$$F_{P0} = \sigma_{pm0} * A_p = 4185kN$$

3.10.4 Shear

Prestressing has a positive impact on the shear resistance of the elements as it prevents the formation of tensile cracks. The general design guidelines for shear ([EN1992-1-1(2004), 1992]) indicate that the shear capacity of the element must be calculated and compared to the design shear force. There is no need for shear reinforcement (minimum reinforcement applies), in the following case:

$$V_{Ed} \leq V_{Rd,c} \quad (23)$$

where:

V_{Ed} : is the design shear force

$V_{Rd,c}$: is the characteristic shear force capacity

If $V_{Ed} \geq V_{Rd,c}$, shear reinforcement needs to be calculated, ignoring the contribution of the shear capacity of the unreinforced element.

The structure under investigation is checked for the composite section under the full service loads ($t = \infty$). In the case of the SJP-Flex beams, no longitudinal reinforcement is considered, apart from the prestressing.

Load Combination for Shear:

The Shear is checked in the ULS, for the 6.10b Load Combination (Section 2.5.6.2). For the shear check, the Loads of the Tandem System are placed closest to the supports, as shown in Figure 3.43, to maximise the reaction forces at the bearings. The maximum reaction force is the V_{Ed} , considered in the calculation. This approach is conservative, since usually the V_{Ed} is calculated at a distance d from the supports. However, the objective of this conceptual study is to include the main principles of the structural analysis, therefore a detailed consideration of the parameters is not deemed significant in this step of the process.

Table 13: Data for Shear Calculation

Property	Value	
α (Angle of Shear Reinforcement)	90 degrees (vertical)	
Shear Reinforcement	$\varnothing 10mm$	$A_{sw} = 157.1mm^2$
	2 legs	
Self load	9.1 kN/m	23.5 kN/m

The shear capacity of prestressed elements without shear reinforcement in regions cracked under bending is calculated according to cl. 6.2.2 [EN1992-1-1(2004), 1992]:

$$V_{Rd,c} = \left[C_{Rd,c} k (100 \rho_l * f_{ck})^{1/3} + k_1 \sigma_{cp} \right] b_w d \quad (24)$$

$$V_{Rd,c} \geq \left[\nu_{min} + k_1 \sigma_{cp} \right] b_w d \quad (25)$$

where:

$V_{Rd,c}$: is the design value of the shear capacity

$C_{Rd,c}$: coefficient derived from tests (recommended 0,12) [EN1992-1-1(2004), 1992]

k : size-effect coefficient $1 + \sqrt{\frac{200}{d}} \leq 2$

ρ_l : $\frac{A_{sl}}{b_w d} \leq 2$, d in mm

A_{sl} : Area of longitudinal reinforcement and prestressing: $3000mm^2$

$k_1 = 0.15$ [EN1992-1-1(2004), 1992]

σ_p : is the axial stress caused by prestressing, $\sigma_p = \frac{N_{Ed}}{A_c}$

$$\nu_{min} = 0.035k^{3/2}f_{ck}^{1/2}$$

In regions uncracked in bending, the shear resistance should be limited by the tensile strength of the concrete. When the design shear force exceeds the $V_{Rd,c}$ (Equation 26), tensile splitting shear failure is possible, which usually leads to failure. This check is only allowed if the stress at the outer fibre of the concrete is less than $\frac{f_{ctk,0.05}}{\gamma_c}$ [EN1992-1-1(2004), 1992]. The shear resistance in this case is calculated as follows:

$$V_{Rd,c} = \frac{Ib_w}{S} \sqrt{f_{ctd}^2 + a_1\sigma_{cp}f_{ctd}} \quad (26)$$

where:

$V_{Rd,c}$: is the design shear force capacity

I : Moment of Inertia of section

S : Resistance moment of section

f_{ctd} : Design tensile stress of concrete

The necessary values for the calculation of the shear capacity are given in Table 14.

Table 14: Data for Shear Calculation at $T = \infty$

Property	Value
$C_{Rd,c}$	0.12
d	708mm
b_w	456mm (equivalent width, excluding flange)
k	1.583
ρ_l	0.00929
f_{ck}	60
k_1	0.15
σ_p	10.37
ν_{min}	0.54
I	$13.486 * 10^9 mm^4$
S	$5.745 * 10^7 mm^3$
f_{ctd}	2.06MPa

In regions cracked in bending (Equations 24, 25):

$$V_{Rd,c} = 786.7kN$$

$$V_{Rd,cmin} = 676.53kN$$

In regions uncracked in bending (Equations 26):

$$V_{Rd,c} = 541.5kN$$

$V_{Ed} = 1062kN$, from the ULS combination in Robot.

$V_{Ed} = 1062kN \geq V_{Rd,c}$, therefore shear reinforcement needs to be calculated.

Calculation of Shear Reinforcement

According to EN1992-1-1 ([EN1992-1-1(2004), 1992]), since V_{Ed} exceeds $V_{Rd,c}$, the shear capacity of the section is ignored and the shear reinforcement is designed to withstand the full design shear force.

$$V_{Rd,s} = \frac{A_{sw}}{s} * z * f_{ywd} * \cot \theta$$

$$1062 = \frac{157.1}{s} * 0.9 * 708 * 434.8 * 2.5 \rightarrow s = 102mm$$

According to this conservative calculation, 2-legged stirrups $\varnothing 10$ should be placed every 10cm.

3.10.5 Structural Analysis Conclusions

The structural analysis part of the project focuses on automating the creation of the structural model, taking the most important parameters into account. An important part of this study is addressing the connection issues that occur, in the process of creating a computational link between different platforms. The latter appears to be the most challenging part, since ensuring the validity of the assumptions and the results is of crucial importance in structural engineering. To that aim, Guyon-Massonnet method is employed to check the load distribution on the beams.

The slab geometry is modelled directly in Robot, without requiring from the engineer to create the computational model. The only needed action by the engineer is to evaluate the results. Prestressing and Shear are taken into account, by considering the appropriate load combinations and allowing the user to add the prestress as a moment in the structural analysis. This option is available on the Dynamo canvas.

It can be easily deduced, that further refinement of the model (supports, meshing etc.) can lead to a really high level of automation for the structural analysis part. This model acts as a proof of concept for the aforementioned statement, since also the calculations that were done manually in this study can be integrated in the model and further increase its value. The current model can facilitate the work of the structural engineer, since the resulting forces of the combinations, which were considered can be directly used in the calculations.

3.11 Applications Overview

The computational part of this project requires the cooperation and coordination of a number of applications. An overview of those applications is given in Figure 3.58 and the information flow between them is illustrated in Figure 3.59






Application	Dynamo	Python	Robot Structural Analysis Professional 2017	Revit 2017	Lumion
Logo					
Vendor/Developer	Open-Source	Python Software Foundation	Autodesk	Autodesk	Act-3D
Version	1.3.2	2.7	30.0.0.5913	17.0.416.0 20160225_1515	7.5
Short description	Parametric Platform	High-level, textual programming language	Structural analysis software	BIM environment	3D render development
Why was it chosen?	Link between parametric design and BIM (Revit connection)	Python currently extends Dynamo possibilities and provides access to the API of other applications.	Direct link between Dynamo and Robot API	Direct translation of the parametric model into an object-oriented model	Direct model import from Revit
Role in the Project	Dynamo provided the visual programming environment to develop the parametric model of the viaduct and was the connecting platform for the other applications	Python was employed to surpass the limitations of the parametric platform, ensure a stable connection between the applications and create the user interface	The structural analysis of the deck is conducted on Robot. All conditions are defined in Dynamo and then communicated to Robot through a Python node	Import of alignments in Revit, communication with Dynamo, export of object-oriented model (output of parametric model)	Fast 3D visualisation of the design

Figure 3.58: Overview of Applications used in the Project

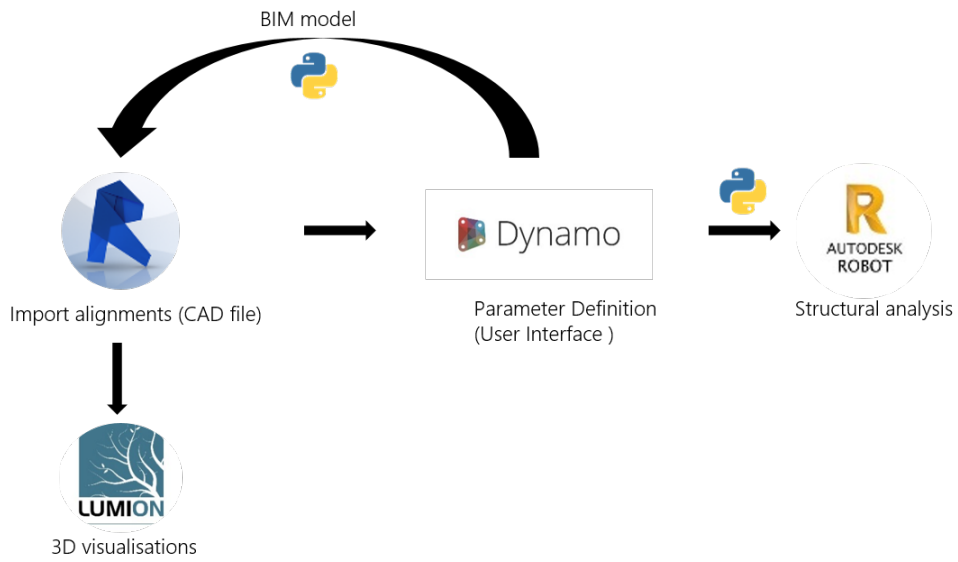


Figure 3.59: Information flow in the Parametric Platform

4 Case Study

The Hoevelaken project, executed by BAM, includes the construction of new viaducts in the area of Hoevelaken, as well as the expansion of existing ones. The model, developed in this study, will be assessed, using the Hoevelaken Quality Team requirements which provide guidelines about the conceptual design of the viaducts.

4.1 Introduction

The A28/A1 Hoevelaken junction is the infrastructure system which facilitates the traffic distribution using the A1 between Bunschoten and Barneveld and /or the A28 between Maarn and Nijkerk, including the connections with the connecting roads (reference [relatics.bam](#)). This concerns the settlement of all types of traffic that are admitted to the public highway on the basis of the Road Traffic Act (Wegenverkeerswet). More specifically It concerns:

- Supra-regional traffic (national and international traffic with both origin and destination outside the Utrecht region.
- Regional traffic (traffic with origin or destination within the region of Utrecht)
- Local traffic (traffic with origin and destination within the region of Utrecht)

The design requirements used to assess the output of the study refer to the new viaducts and not to the extension of the existing ones. It is important to note that the assessment of this conceptual study is based on the freedom which is provided to the user to explore different options. A requirement is considered to be met by the model, if it is tied to specific components, for which the required parameters exist in the model. For instance, in the requirements an inclination of 15 degrees is required for the railings. This requirement is considered to be met, since the component railing exists in the model, as well as the parameter inclination, within this component.



Figure 4.1: Location of Hoevelaken project

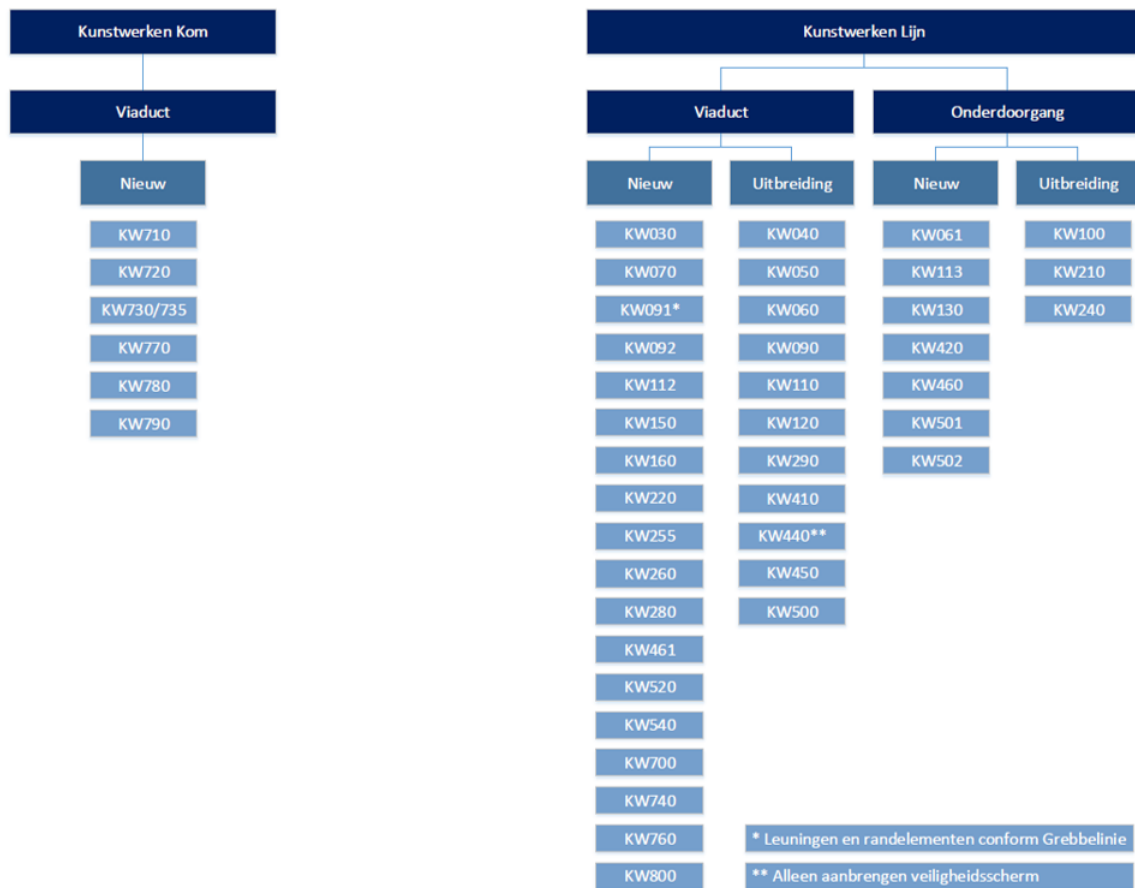


Figure 4.2: Types of viaducts in the Hoewelaken project

4.2 Hoewelaken Requirements

A number of viaducts, which are located in the interchange (kom), are considered sculptural. This term implies that they have a complex geometry and therefore are not in the scope of this research.

The viaduct which is chosen to test the platform is KW700. The reason for this choice is the fact that this viaduct is new and it does not have complex design needs. The requirements from the quality team are used to assess the value of the outcome of this research. Those requirements are divided in 11 categories, of which 2 are in the scope of the research:

1. General Requirements:

This category sets the guidelines for the design of the viaducts, in terms of their quality. The viaducts should be integrated in the surroundings, thus creating a continuous and quiet addition to the landscape.

2. Hoewelaken Interchange (Environment - Viaducts):

In this category, special instructions and references are given for the sculptural viaducts at the interchange. This category is not investigated in this research.

3. Viaducts: (24/56 requirements met)

This category lies within the scope of this research. In this category, more specific requirements are given regarding the design of the viaducts. It is composed of guidelines about the function of the viaducts, the visual impact of the design, the relation to the surroundings and the experience of the user, as well as ensuring that the design is cohesive.

The requirements which could be met within this category, refer to the following parts:

- **Span, Clearance height:**

The clearance height of all spans of the viaduct should be the same or have a gradual transition.

• **Deck Curvature:**

In the case of a curved road alignment, curved, prefab beams should be employed to ensure that the underside of the viaduct is composed of smooth lines. In the parametric model, there are two options for the creation of the deck. The first one is to use straight lines to connect the abutments and the second one is to create a curved deck which follows the alignment. However, for the structural analysis SJP-FLEX beams are considered, which are straight, therefore the structural model is created only for the first option. Nevertheless, this requirement is considered to be met by the model on the level of conceptual design.

The two options for the deck creation are shown in Figure 4.3, where a top view of a curved deck (a) and a straight deck (b) for the same alignment are illustrated.

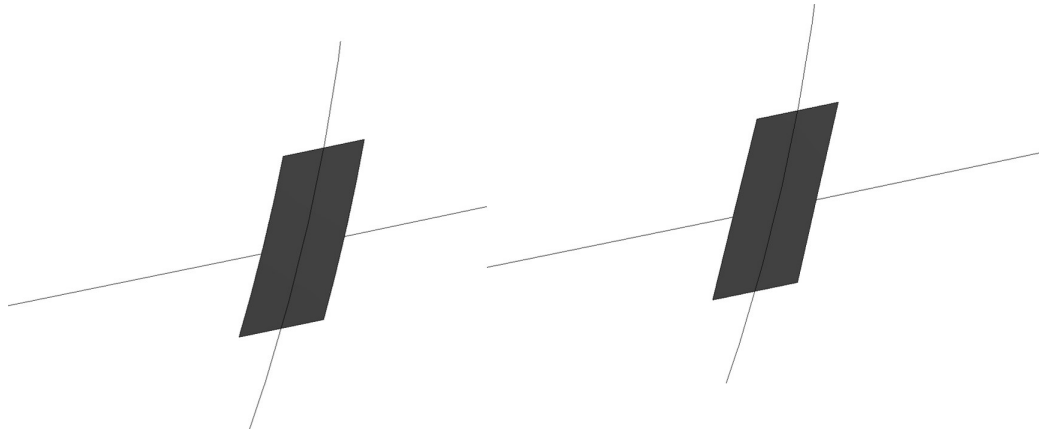


Figure 4.3: (a) Curved deck (b) Straight deck (Revit Model)

• **Viaduct - Environment relation and Abutment Type:**

An example of an achieved requirement can be seen in Figure 4.4. This figure refers to requirement 3.12 of the Quality Team report. This requirement dictates that the border between the viaduct and the environment should lie on the abutment. In this Figure, it is also shown that a high abutment is designed in Dynamo, therefore requirement 3.50, which specifies that only high abutments (bankseats) should be placed, is also met.



Figure 4.4: (a) Desired abutment design (b) Unwanted abutment design (c) Abutment modelled in Dynamo

• **Detailing of edges:**

In Figure 4.5, on the left, the desired design for the edge elements is illustrated. The edge elements should have an angle of 30 degrees to the vertical and have a concrete finish. Both requirements can be achieved by the parametric model. On Figure 4.5(b), the edge element described by the requirements is shown in the parametric model. Another requirement dictates that the edges of the viaduct should not be segmented. In this study, the edge elements are segmented and placed along the edges of the viaduct. The edge elements are curved which allows for a smooth and fluent design. However, this option may increase the cost of the component significantly, as suppliers will need to manufacture a custom element. Usually, the edge elements are straight and segmented, which renders placing them along curved edges challenging.

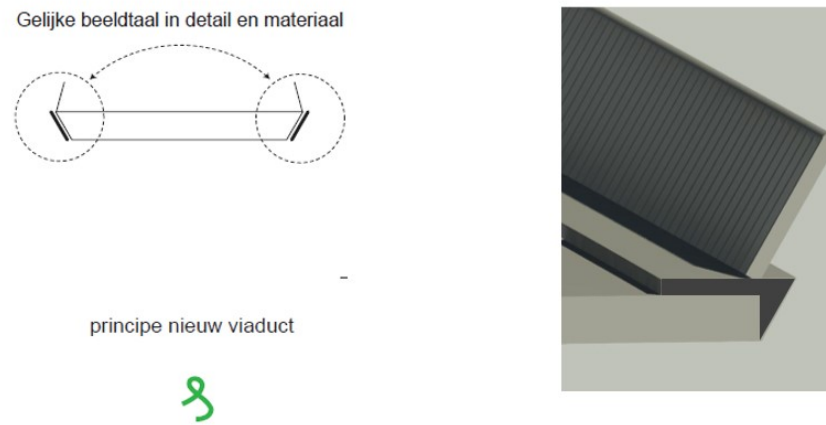


Figure 4.5: (a) Edge Element in Requirements (b) Edge Element in Parametric Model (Revit Model)

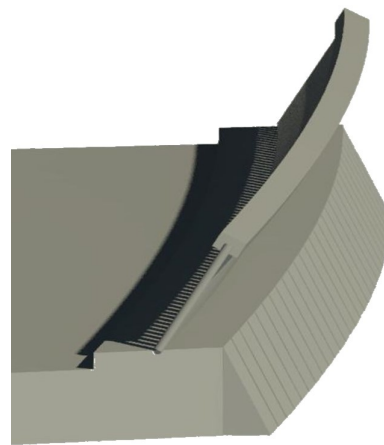


Figure 4.6: Curved Deck and Curved Edge Elements (Revit Model)

- **Pier Location and Design:**

The requirements dictate that the spans should be as large as possible and that piers should be used for spans larger than 20m. In this study, the use of a pier is optional, which enables the user to investigate a single span or a 2-span solution. Moreover, the location of the pier is parametric, therefore the most suitable location for the pier can be found.

- **Slopes:**

As mentioned in the requirements, the slopes at the abutments should have an angle of at least 45 degrees to the vertical axis. This inclination is one of the parameters in this study, therefore this requirement is met by the model.

Table 15: List of Requirements

Category	Number of Requirements
Cohesive Design	3
Span and Clearance Height	2
Deck Curvature	2
Viaduct - Environment relation and Abutment Type	2
Detailings of Edges	7
Pier Location and Design	4
Slopes	4
Total	24

The requirements which could **not** be met within this category, refer to the following parts:

- Architectural requirements not tied to specific objects: sightlines, light considerations etc.(12 requirements)
- Requirements referring to extensions of existing viaducts (8 requirements)
- Detailed requirements: Drainage, cables etc. (8 requirements)
- Specific Pier Design (2 requirements)
- Retainment Walls (2 requirements)

The aforementioned requirements could not be met for the following reasons:

- Some architectural requirements were deemed too vague to be addressed with the platform.
- They refer to components which were not considered in the study.
- They require a complex pier design which is not currently available in the model
- They refer to a later stage of the design. For instance, drainage considerations require a much more detailed model, as they are not part of the general design considerations that this model investigates.

4. Road Furniture:

Road furniture are not extensively considered in the model. The railing is the only component in this category that is considered, since it has a high design importance, as well as a safety function.

5. Lighting:

This category is not considered in this study.

6. Handrails and Shields: 5/20 requirements met

The railings are considered in the model, but safety screens are not considered. From the requirements pertaining to the railings 5/8 can be met. For instance, the inclination of the railings should be 15 degrees, which is a user-defined parameter for the railings. The result in Revit is shown in Figure 4.7.

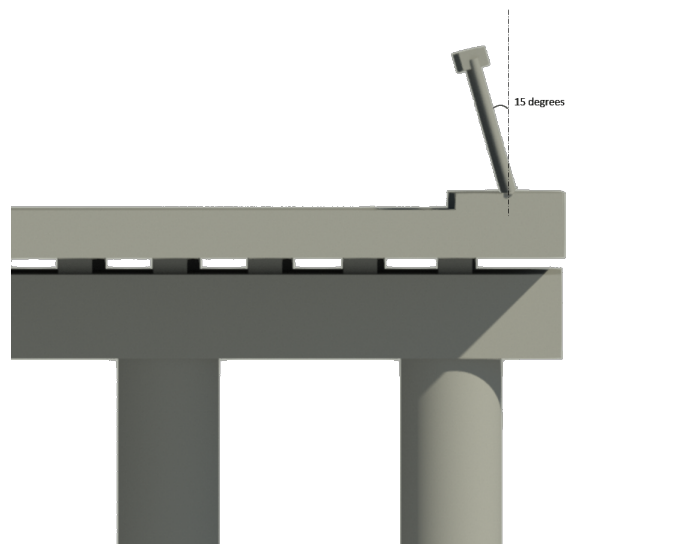


Figure 4.7: Inclined Railing (Revit Model)

7. Sound Barriers:

This category is not considered in this study.

8. Ground Retaining Structures:

This category is not considered in this study.

9. Edges and connections

In this requirement category, emphasis is given on the architectural connection between the viaducts and the environment. Specific directions are given for a number of viaducts, insisting on the extensive use of green areas. This category lies outside the scope of the model.

10. Environmental Link:

The surroundings of the viaducts are modelled geometrically in the model with the angle to the horizontal as a parameter. However, the ground retaining walls are not included in the model as specific components.

11. Materials/ Colors/ Finishings:

This requirement category can be partially met through the platform, since the model designed on Dynamo can be exported to Revit, where the proper materials can be applied directly on the bridge components. This constitutes an important advantage of the platform, since different materials, colors and finishes can be immediately tested and compared.

4.3 Case Study Conclusions

In the Hoewelaken project, a recurrent requirement is the development of a coherent design, where all viaducts share common features, such as the cornices. The aforementioned requirement can be met through the output of this research, since it emphasizes on creating a standardised viaduct, which can be adapted to the specific needs of the project. The model can be used to facilitate the design of the viaducts for 24 out of 56 requirements regarding conceptual design, which can be an important asset during the design phase, since the interpretation of the requirements by the designers can be visualised easily, discussed and agreed upon. Moreover, in case there is a change, the new parameters can simply be redefined in the platform and develop a new design. Suggestions about improving the area of application for the model can be found in Section 7.

5 Observations and Discussion

The aim of this research project is the development of a knowledge model around common concrete viaducts, in an attempt to establish the level of detail to which they can be standardised. The aforementioned aspiration lays on the principles of BIM and parametric design, while the requirements of both the architect and the structural engineer are considered. The output of this project is illustrated in Figure 5.1, where three distinct processes within any AEC project can be distinguished. These processes are: the list of requirements, the design and the structural analysis and they are considered linked in this project. The project was developed under the guidance of a multidisciplinary group of practitioners from BAM A&E and BAM Infra. This interaction with architects, structural engineers, system engineers and BIM modellers revealed interesting and even contradicting views about this structure type and the design process overall.

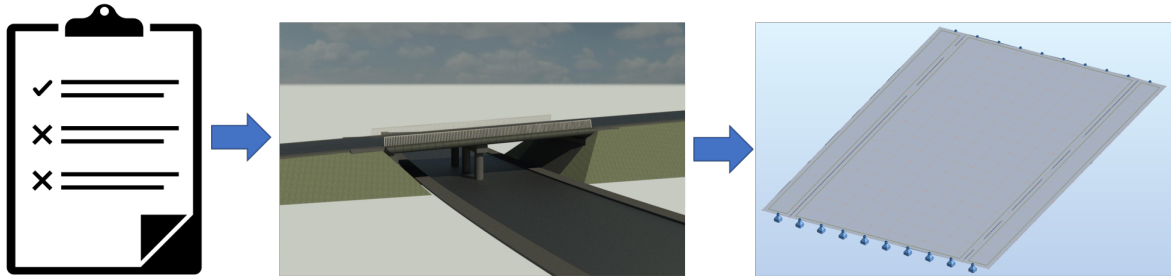


Figure 5.1: Data Flow between List of Requirements, Design Output and Structural Analysis

In this section, a reflection on the research project is presented and the limitations of this project are considered.

- This fragmentation of the AEC industry and the continuous interpretation of requirements renders the standardisation of the knowledge around viaducts challenging. However, there is consensus among practitioners about the main driving forces of the design which are aesthetics and cost efficiency. A successful design should maintain a balance between those two factors.
- In the process of developing a standard viaduct, one simple question should be asked: How standard is standard? Even though common concrete viaducts are considered a very standardised structure with limited design freedom, there is not a unanimous agreement on the design steps and choices, which implies that the final outcome will highly depend on the people involved in the project. For instance, it was argued that the maintenance gap at the bearings can be omitted, since the bearings can still be reached without it. This underlines the importance of knowledge databases, where all design choices are explicitly, and as objectively as possible, justified. With views, requirements and codes that are ever-changing, a solution can be provided through parametric design by establishing the main parameters which influence the whole design. For instance, in this study to address the issue of the abutment design, the maintenance gap is optional, and its size is parametric.
- Nowadays, the goal of automation and knowledge-based engineering is shared by many practitioners and researchers. One of the main challenges which they have to face is gaining the trust of engineers with a traditional mindset, who do not easily trust new tools and methods. Those concerns can only be addressed through extensive validation of results. Indeed, the quality and therefore the success of such methods, depends highly on clearly defining their area of application and justifying all automated design choices. In this study, validation is considered to a limited degree, due to the fact that it is a conceptual study and the first iteration of a complex process.
- An interesting observation which underlines the limitations of the current BIM practices is that each discipline develops its own Revit model and often disregards the models produced by the other disciplines. As can be understood, this may lead to loss of valuable information and the reassessment of requirements which had already been dealt with during a previous step. This emphasizes the importance of a common platform, so that the different disciplines will not need to develop new models.

In this study, the model is developed only once in Dynamo and the relevant information is transferred automatically to Robot. This ensures that no information is lost in the process as there is only one central file.

- An important hindrance to the efficient cooperation between the practitioners is the use of different platforms, which are not yet fully connected. Crucial information can be lost, during the exchange of BIM models through IFC files. This underlines the importance of developing an integrated platform, where the connection between the applications is seamless and information is protected. Moreover, information at most companies is primarily exchanged through Revit files, which means that when practitioners want to retrieve the data, pertaining to their discipline, they are burdened with a lot of irrelevant information. Therefore, it is significant to determine which information is relevant for each discipline and provide the appropriate data type.
- Platforms which employ visual programming, such as Dynamo, are powerful tools, which enable the practitioners to seamlessly integrate parametric design in their work. However, those tools are still under development, which imposes limitations to what can be achieved through them. A dense visual programming environment, associated with handling complex logic, can become very slow, which can lead to a harder and more time-consuming evaluation of the script. In addition to this, another important issue is the single-direction logic flow in the model, which does not allow for an iterative process in the script. Any attempt to create a loop within Dynamo leads to a “cyclic dependence” issue. Nevertheless, those limitations can be surpassed by employing textual coding, which is deemed currently necessary for a more efficient work flow. Indeed, the combination of Dynamo with high-level, object-oriented coding languages, like Python can vastly increase the possibilities within the parametric platforms. In this research, Python was employed to address those limitations and decrease the execution time of the script, as well as create the user interface and establish a connection between Dynamo and Robot. Although employing textual programming to overcome the limitations is effective, it opposes the aspiration of visual programming, which is to facilitate computational design by non-programmers. Therefore, the further development of parametric platforms, to allow e.g a nonlinear propagation of data through the script, is highly needed to firmly establish parametric design in the AEC industry.
- An interesting observation is that developing an academic project in an industrial setting instilled a product-development approach in the process. The interaction with practitioners, provided a basic understanding of the practical issues they have to address and facilitated the integration of those issues in the project. In addition to this, it is noticed that different levels of information are needed from each practitioner. For instance, the architect will not be involved in the definition of the approach slabs, which is the responsibility of the structural engineer. This underlined the importance of considering the end user of the model and creating a user-friendly interface where parameters are presented gradually and with respect to the design levels.
- As an extension of the aforementioned point, it can be argued that the design process itself should be more product-oriented, rather than project-oriented. The latter implies that instead of considering each project a unique design case, similar projects (e.g concrete viaducts) should be considered customisable versions of one product. That would be an extensive case of standardisation which would enforce a highly productive collaboration between the different disciplines, in order to address the possible design issues, optimise them and reach unanimous decisions. This approach facilitates knowledge reuse and instils more intelligence in the design process.

6 Conclusions

In this section, the most important conclusions of this study are presented and the research questions are answered in the different subsections. The limitations of the project and the solutions to them are discussed and the outcome of the research is assessed.

6.1 General Conclusions

The main research question, defined in the beginning of the project is the following:

To what extent can the design of concrete viaducts be explicitly described in a knowledge model and how can this knowledge model be translated into a parametric tool, facilitating the design process for the architect and serve as a communication tool between the architect and the structural engineer?

In this research project, standard, prefabricated viaducts are considered with only their main components, in order to reduce the complexity of the design. The need to reduce the scope of the research derives from the large amount of information associated even with standard, concrete viaducts, when an object-oriented approach is adopted. This approach dictates that the viaduct needs to be designed as a system of interlinked components, whose properties and interrelationships are explicitly defined. As a result, the object under investigation is seen as a product, whose attributes are defined in detail and can be extended. Indeed, the level of detail depends on the amount of time that the designer/engineer dedicates to the model and the limitations that are imposed by the current parametric platforms. Another limitation is the general consensus around the definition of the components, since a clearly defined logic is needed for the development of the model.

The conclusions of this study are presented by answering the following questions. Research questions Q1-Q3 are answered here, while Q4 is answered in Section 6.5:

- **What is the outcome of this study? (answer to Q1 and Q2)**

The outcome is a flexible platform for the design of concrete viaducts, which incorporates basic design parameters, while providing a certain level of design freedom. The viaduct components that are considered, are the deck, the pier and the abutments, which are also divided in subcomponents. The final design is connected to a structural analysis software (Robot), from which the results can be directly assessed by the structural engineer. This model can be used as a basis of conceptual design and discussion among the considered disciplines (architect and structural engineer) during the tender phase of a project.

- **Top-down or bottom-up approach?**

The approach of this research is primarily top-down. A UML class diagram is employed to control the logic and to separate the components into main systems and subsystems. The aforementioned approach facilitates the development of an organised, structured system which can be easily controlled and maintained. This structure is partly maintained in the parametric model, where the components are separated in groups, thus encapsulating the logic behind their creation and facilitating the access to them. The parametric model induces also bottom-up considerations in the development of the model, since it forces the designer to consider the details of each object and how the components interact in a local level. For instance, tolerances played an important role in the way the deck slab was created.

- **How many parameters are considered in this study and in which categories they are separated? (answer to Q3)**

In the study a number of 82 parameters are coordinated to produce the final design. Three categories are considered regarding the use of the parameters in the project. Those categories are the following: user-defined, default and immutable. The first category is directly accessible by the user through the UI and is refers to components that change regularly during the design process, such as the cornices, the railings etc. The default parameters are linked to the specific type of design (prefab viaduct) and are important to reduce the work load/decisions of the designer (e.g tolerances). A default value is given to those parameters, but the option to change them is still available. The immutable parameters cannot be changed, since they derive from fundamental decisions made in the beginning of the project.

For instance, the type of the abutments (bankseat) cannot be changed without reconsidering the whole model.

- **What is the value of automation in this study?**

In a symmetrical design, the number of parameters that need the attention of the user (user-defined) are 30 out of 82 (36.5%). This indicates that the design time can be drastically reduced, since 63.5% of the design issues considered in this study are automatically addressed by the platform. These percentages serve as indications of the potential of this conceptual study. A more automated design process allows the designer to spend time on more creative and challenging parts of the design process and not on the mundane parts of it.

- **What is the relationship between the Knowledge Model and the Parametric Model?**

The Knowledge Model in this study, evolved from a class diagram to the Parametric Platform. All knowledge and logic regarding the structure under investigation are induced into the parametric model through iterations and logic checks. Therefore, the Knowledge Model and the Parametric Model can be considered merged.

- **What are the advantages of the output of this study?**

The knowledge/parametric model developed in this research, constitutes the first iteration in the development of a design platform for architects and structural engineers, which has the following advantages:

- The design choices are translated into a Revit model, which can be used for any BIM process. For instance, materials can be defined and the volumes of the components can be extracted and linked to cost analysis.
- 3D conflicts can be identified more easily, since a 3D model becomes the basis of discussion between the disciplines, instead of 2D drawings or hand sketches. Agreements can be more easily reached through an integrated process like this and misunderstandings can be avoided.
- Design time can be significantly reduced by having default and immutable parameters which minimise the input.
- Direct link to structural analysis for SJP-FLEX beams with the main parameters considered (material, loading, supports, orthotropy matrices).

- **What are the disadvantages and possible solutions?**

- As the complexity of the task at hand increases, the volume of the script also increases, which is one of the main disadvantages of the current parametric platforms. An efficient solution to address this issue, is the use of textual programming, as is done in this study with Python.
- A complex parametric script is accompanied by an increased difficulty in its navigation. To address this issue and to make the platform more usable an UI is developed.

6.2 Dynamo Conclusions

In this section, the way Dynamo was used in this research is assessed. In a very complicated model with a lot of intersecting wires, it is important to create groups of nodes which form specific bridge components. This approach helps protect the logic on which they are built. A very efficient way to validate the logic behind the component, is to copy the nodes and use them to create the same component at the other side of the viaduct e.g abutments, approach slabs etc. If the logic is autonomous and well defined the component will be created properly with the new input as well. That underlines the high level of design modularity. It can be argued that introducing coding could facilitate this process, since each component could be described by a node of textual programming. Dynamo could be then used as a canvas to connect those components. That would significantly decrease the computational time needed to execute the script, as Python nodes run faster in Dynamo than the visual programming components. Another advantage of Python derives from the way that Dynamo functions. In Dynamo geometry nodes are drawn, whether they are needed as components or are just auxiliary. That indicates that the memory resources needed for a large script with a lot of temporary geometry can be quite significant leading to increased computational time. With Python, auxiliary geometry can be generated to develop the final volumes without burdening the script. That can lead to a faster execution of the script, as was established in this study. However, this can be

deemed a short-term solution, since resorting to textual programming confines the logic in “black boxes” and opposes the vision of visual programming, namely the possibility to create models with transparent logic, understandable by non-programmers.

6.3 Case Study Conclusions

The number of parameters that can be expressed through the platform that is developed is 24/56 for the “Viaducts” category. This outcome indicates the potential of this research, since for 43% of these requirements the output of this case study can be of use. The requirements that can be achieved were tied to specific components that were considered in this case study, while the ones that could not be met were considered too abstract or referring to components which were not part of this model.

6.4 Parametric Model Conclusions

The conclusions about the parametric model are drawn by assessing the parametric model in a number of categories:

- **Usability:**

The platform developed for this research aims at facilitating the work of architects and engineers, therefore, the usability of the final outcome is of high importance to its overall value. While the merits of parametric design are becoming more and more praised within the AEC industry, getting familiar with the parametric platforms and becoming able to produce useful algorithms can be a time-consuming process for professionals who cannot invest time on learning this tool. This observation led to the decision of integrating a friendly user interface in the parametric platform, so that it is easy to use. That way, one of the main disadvantages of parametrics, which is the inevitable “spaghetti problem”, associated with increased complexity of the algorithm can be surpassed.

- **Extensibility:**

The extensibility of the model can be assessed in two levels. First, the level of the knowledge model, hence the conceptual relations between the components and the reassessment of the relation among them by doing more iterations. The other level is the level of the parametric model, where the conceptual logic needs to be transformed into accurate logic checks and be tested. The extensibility of the platform is considered high, since the components themselves and the relationships among them can gradually become more detailed.

- **Interoperability:**

To assess the interoperability of this study, the development process is tracked. The knowledge model (top-down class diagram UML) is translated into a parametric model in Dynamo. Then, it is connected to a structural analysis software (Robot) and it can be exported to Revit. From Revit the connection with multiple platforms is possible. For instance, it can be directly sent to Lumion and create realistic renders of the design. The interoperability of the model is deemed to be high, and only restricted by the current connections between the different commercial packages. Moreover, it can be used on multiple computers, as long as the proper folder is transferred and the licenses for Revit and Robot are available.

The research questions which arise within the parametric tool development are the following:

- *Q5. What parametric plugins can facilitate the integration of the structural analysis in the parametric model?*

The available plugins were deemed inadequate to create the desired connection between the applications. Therefore, a Python script was developed, using the explicit documentation of Robot API to create the desired connection.

- *Q6. How can terrain considerations be implemented into the design?*

The surroundings are not explicitly designed in this study, as they are not directly related to the viaduct structure. A basic depiction of the surroundings is available to the designer, with the parameter of specifying the angle to the horizontal axis.

- *Q7. How can a user-friendly interface be developed?*

An effective way to build a user-friendly interface, is to employ a top-down approach, so that parameters

are gradually exposed to the user. Therefore, the structure of the UML model is employed to develop the UI. Moreover, "Preview" buttons ensure that the designer has an understanding of what each design choice means, through the visualisation of the respective values.

6.5 Structural Analysis Conclusions

The structural analysis in this study is highly automated and conducted only for the deck slab, considering SJP-FLEX beams. The main principles of structural analysis are considered in order to show the value of an integrated model, with a direct link between design choices and structural consequences. The input needed by the structural engineer is the prestress force (F_{P0} at $t = 0$) and the rest of the parameters are defined automatically. A linear analysis is conducted for the load cases considered and 3 load combinations. The research questions regarding the structural part of the project are answered below:

- *Q8. What loads should be considered?*
Load Model 1 is deemed adequate for the purpose of this conceptual study (Section 2.5.5).
- *Q9. What are the structural considerations that influence the design?*
The main factors for the structural analysis are the span of the deck and the skewed angle, which are automatically transferred to Robot. Due to the fact that precast beams are considered in this study, the height of the slab is given by the Spanbeton graphs according to the span, and the tolerances are predefined according to the type.
- *Q10. What structural considerations/checks are too detailed and can therefore be omitted?*
The calculation of the loading on bridges can be a very complicated process considering various characteristic and accidental loads, for instance loads due to wind, differential settlements due to earthquakes, dynamic loads, impact loads, as well as fatigue considerations. The structural analysis in this study, includes simple concepts which serve as a proof of concept, as the main aim is to integrate the structural considerations early in the design process and prove that they do not confine the design, but aim at providing the bridge designer with a broader perspective.
- *Q11. How can the structural analysis be integrated in the model, without restricting the design spaces?* (also answer to Q4)
The structural analysis in this model is a separate step from the design process, acknowledging the fact that the two disciplines considered require different types of information. The direct link established between those two steps is not restrictive, since the intent is to translate the design choices, namely the geometry of the slab to a structural model.

7 Recommendations

A number of recommendations can be formulated based on the outcome of this research. Two categories of recommendations can be distinguished, one referring to changes and improvements of the current algorithm and one referring to a vision about the future of such endeavours. The suggestions therefore are separated in “Algorithm Improvements” and “Future Vision”.

Algorithm Improvements

- As was suggested by many practitioners, linking the model to cost analysis would be a very significant next step (5D model). The cost estimation of every design change would be a very strong asset for the design team, as it would enable them to realise the exact cost of their design choices, manage their expectations and have more fruitful discussions with the clients.
- Another suggestion is to increase the level of detail, with the aspiration to retrieve final documentation (2D drawings). The inclusion of more components would also increase the architectural value of the model, since more options would be available to the designer. The model can be extended by considering the following:
 - Road furniture (sound barriers, lighting poles etc.)
 - Attachment methods, since they determine the feasibility of different options
 - Direct link to the suppliers (e.g 3D printing of cornices)
 - Multi-criteria optimisation
 - Further development of User Interface to include design advice based on the selected parameter values
- Considering the fact that the parametric model has a primarily top down structure, break points could be introduced at parts of the script, to take into account construction steps (4D model).
- The foundations are not in the scope of this tool. However, they are an important part of the design, as they compose a significant part of the final cost. Incorporating the foundation piles in the platform and assessing the ground quality would increase the value of the platform, as changes that are made in the superstructure have a direct impact on the substructure.
- The structural analysis can become further detailed, by adding all the necessary loadcases and load combinations, so as to be able to get a complete structural analysis. Moreover, the loads of the road furniture and other elements can be translated directly into loadcases in Robot, as was done in this research for the asphalt layer.
- The research area of this study was limited to a specific type of bridge, however expanding this research to other types of bridges, attempting to standardise the knowledge and find similarities between the design procedures is deemed of high value. A bottom-up approach would be important for this study, in order to detect emerging patterns among the different bridge types.

Future Vision

- The construction field can benefit highly from the advent of AI technologies and machine learning by training the computers to make choices instead of manually programming every decision. A cognitive algorithm can take more consistent and well-informed decisions than a human in less time, since it can take into account a large amount of information with a negligible error margin. Therefore, there is significant value in establishing a connection between this parametric approach and machine learning by teaching the computers to resolve all common design-related issues and leave the most creative work and crucial decisions to the designer.

In addition to the latter, the cognitive algorithm can be trained through its interaction with the designer, to memorise design choices and evolve according to the taste of the designer. This interaction will also benefit the designer, who will be trained alongside the algorithm, by reconsidering design choices and gaining knowledge. Moreover, as the model is extended using machine learning principles, potential problems and risks can be predicted and mitigated leading to the adoption of proactive instead of reactive strategies.

- The success of the aforementioned connection depends highly on the quality and the amount of data that is fed to the model. A large data set is the basis of a more intelligent system and can lead to more accurate decisions and predictions. As can be understood, the computational capacity needed to execute such a model would exceed the capacity of a typical computer, therefore it would be crucial for this platform to be cloud-based. Another reason to consider a cloud-based platform, is interoperability. The output of this study is a model tied to specific applications, which requires a limited file exchange between the practitioners. In order, for the designers to grasp the full benefits of such models, an online model should be used by everyone involved in the project, without needing to exchange files at all and without needing to consider specific software needs or version compatibility.
- A direction to which this research can be extended is the development of independent, intelligent components. This approach would include investigating each component in depth and creating separate algorithms which can adapt to different input and to the other components. Dynamo could then be employed as a canvas to connect them and create a BIM model. This idea could be further enhanced following the machine learning principles and creating a system of interlinked cognitive algorithms.
- Visual programming offers a unique possibility to all designers to use parametric design in their daily work without requiring extensive programming knowledge. Moreover, it helps maintain a level of transparency of the parametric model's logic. Transparency can be the key to a more efficient validation of the output of the parametric systems, which is crucial to gain the trust of the practitioners. However, the limitations of the current parametric platforms, which were presented in this research force the designers to use textual programming, as it addresses those limitations. This contradicts the vision of visual programming, as through coding the logic is usually confined in "black boxes". A suggestion based on the findings of this research is to further invest in visual programming, by considering the aforementioned technologies (machine learning, cloud-based technologies), as the AEC industry can benefit highly in terms of transparency, extensibility and modularity.

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Appendices

A Introduction to (UML) - Class Diagrams

Class diagrams give an overview of a system by illustrating its subsystems and the relationships among them. A main characteristic of the class diagrams is that they are static. The latter implies that they display which classes interact but not what happens when they do interact [Miller, 2003]. The UML tool which was employed for the realisation of the UML model was Visual Paradigm [Visual Paradigm, 2017].

As can be seen in Figure A.1, a UML class notation is a rectangle, divided in three parts:

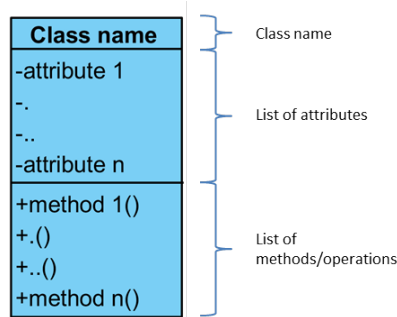


Figure A.1: UML class entity (Visual Paradigm)

- **Class name:** A class name denotes the general concept of the elements that belong to that class.
- **Attributes:** A significant piece of data, containing values that describe each instance of that class.
- **Methods or operations:** Methods or operations allow the user to specify the behavioural features of a class by defining how the classes can interact with each other.

A.1 Attribute Properties

Static attributes: If an attribute is declared as static then its value is shared with all the instances of this type. The user can denote a static attribute by underlining it.

Multiplicity is an important concept of UML, which declares that an attribute represents a group of objects. Also known as cardinality, multiplicity specifies the number of elements of a collection of elements. The different types of multiplicity are presented in Table 16.

UML multiplicities can be **ordered** and/or **unique**. The specification “ordered” denotes that all values within the specific collection of elements are sequentially ordered and “unique” denotes that each value is found only one time in the collection of elements. UML multiplicities are by default unique and not ordered. Those options are preserved in this research project.

Table 16: UML multiplicities [Miller, 2003]

UML multiplicities	
Multiplicities	Meaning
0..1	zero or one instance. The indication n..m denotes n to m instances
0..* or *	no limit on the number of instances
1	exactly one instance
1..*	at least one instance

Encapsulation is an important concept of UML models which is associated with data protection. Attributes should always be private or protected, so that it is ensured that the correct type of data is passed to the parameters. For instance, if among the attributes of a class lies a field “name”, where a string value is expected, then due to encapsulation considerations, the methods which allow the objects within the class to receive a name should be written:

```
+setName (newName:string):void
```

In that way, the type of the parameter is protected by ensuring it is a string.

Access to attributes and methods by other classes is defined by the symbol which precedes the name of the feature. The most common cases are shown in Table 17.

Table 17: UML access specifiers

Access specifiers	
Symbol	Access
+	public: members are visible to all
-	private: only visible to members within the class
#	protected: only visible to subclasses of the class

A.2 Types of Classes

A.2.1 Abstract classes

Abstract classes usually contain abstract methods, which are specified in other subclasses. Abstract methods can be considered as “placeholders”, for methods which are defined in a subclass of the current class. In general, they denote a generic behavior and also delegate behavior to subclasses. For instance, the `getArea()` method cannot be specified in a meaningful way for every geometric object, as it depends on its shape (Figure A.2). This signifies that the class `GeometricObject` is semantically incomplete and cannot be instantiated, but only extended. The names of abstract classes and methods are denoted in *italics*.

A.2.2 Concrete classes

Concrete classes are the default class type considered by UML. A concrete class can be directly instantiated. The bottom level classes of a UML diagram should always be concrete, so that there are instances which exhibit the indicated behavior.

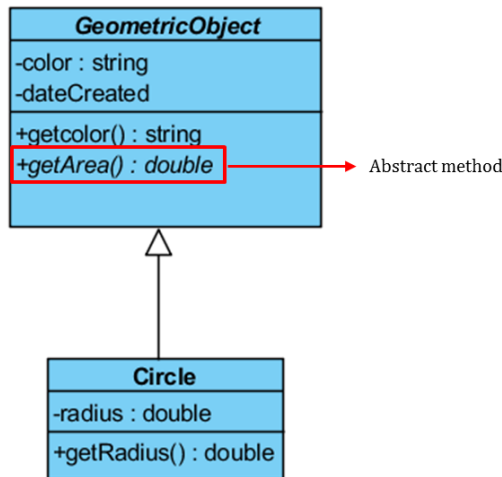


Figure A.2: UML abstract class (Visual Paradigm)

A.3 Relationships

Three important relationships within the UML class diagrams are aggregation and composition and inheritance.

Aggregation: This relationship denotes a is part of association between two classes and is symbolised by a clear white diamond at the end of the “whole” class. A typical example is illustrated in Figure A.3. It is important to note that in aggregation relationships, both classes exist independently of each other. For instance, the class wheel exists regardless of whether it belongs to a car assembly or not (Figure A.3).



Figure A.3: UML aggregation relationship (Visual Paradigm)

Composition: This relationship denotes a “is entirely made of” association between classes and is symbolised by a black diamond at the end of the “whole” class (Figure A.4). It is a stronger relationship than aggregation, since in the case that the “whole” class is removed, the parts are also removed. For instance in Figure A.4, the departments cannot exist before the company exists.

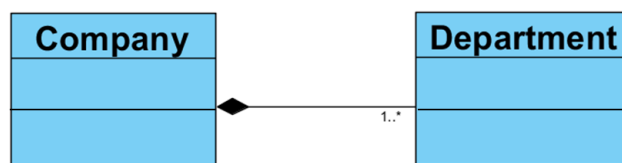


Figure A.4: UML composition relationship (Visual Paradigm)

Inheritance: This relationship refers to the ability of subclasses (child classes) to inherit the identical functions of another class and then add new features of its own. For instance, A savings account inherits the functionality of a bank account and it also has its own functionality (Figure A.5). Inheritance is also known as generalisation and is illustrated by an empty white triangle pointing to the superclass (Figure A.5).

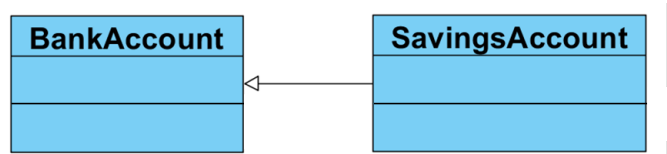


Figure A.5: UML inheritance relationship (Visual Paradigm)

Dependence: Dependency is a directed relationship, which shows that a class depends on another class for specification or implementation. The nature of the relationship is further described on the dashed arrow which connects the two classes (Figure A.6).



Figure A.6: UML dependence relationship (Visual Paradigm)

A.4 Methods

Getters & Setters: These methods allow the user to access and change the values of the attributes. A setter function is added to diagrams to create instances with different parameter values. If a specific attribute of a class does not have a setter function, then it cannot be changed after the model has been created. However, in some classes, where attribute values are predefined, there are no setter functions, so that the user cannot accidentally change the logic of the algorithm.

A.5 Class Diagram Development Tips

An important note regarding class diagrams is that tightly coupled classes should be avoided, since a system where a change in one class can cause all sorts of changes in other classes is not desired. It is therefore, preferred to design loosely coupled classes, where changes can be more easily monitored.

B UML Model

The UML model is presented in this section. The overview of the whole model is shown in Figure B.1, while the classes associated with the main components of the viaduct are shown in Figures B.2, B.3, B.4. The classes denoted with red colour are not considered in this study, the classes denoted in gray are standardised (have default values), while the classes denoted in blue are defined by the user. This distinction is explained in Section 3.8.

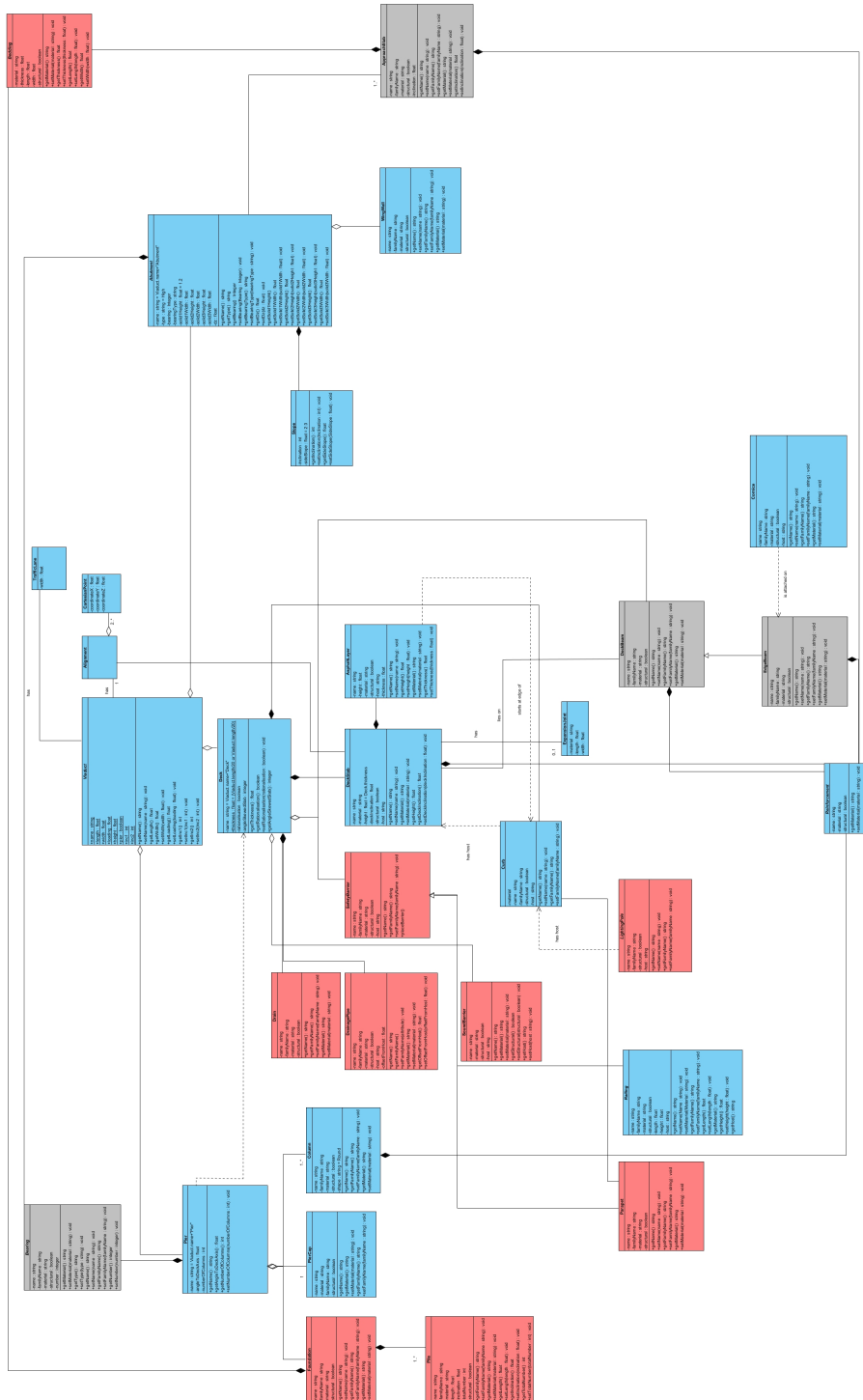


Figure B.1: UML Class Diagram

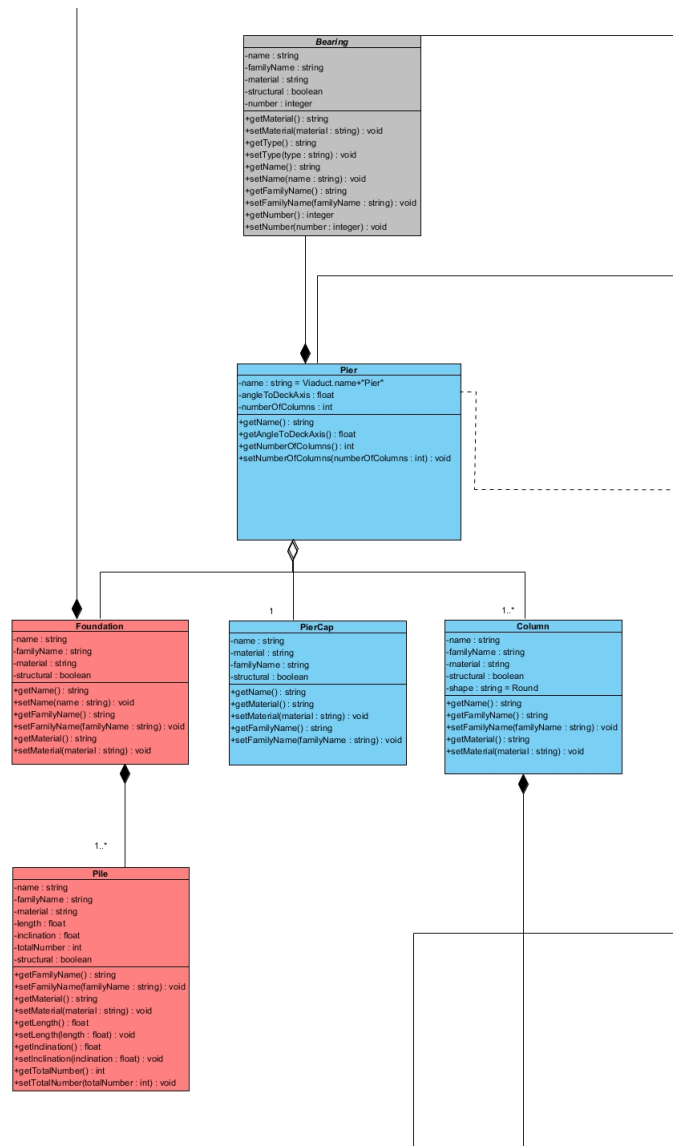


Figure B.3: UML Class Diagram - "Pier"

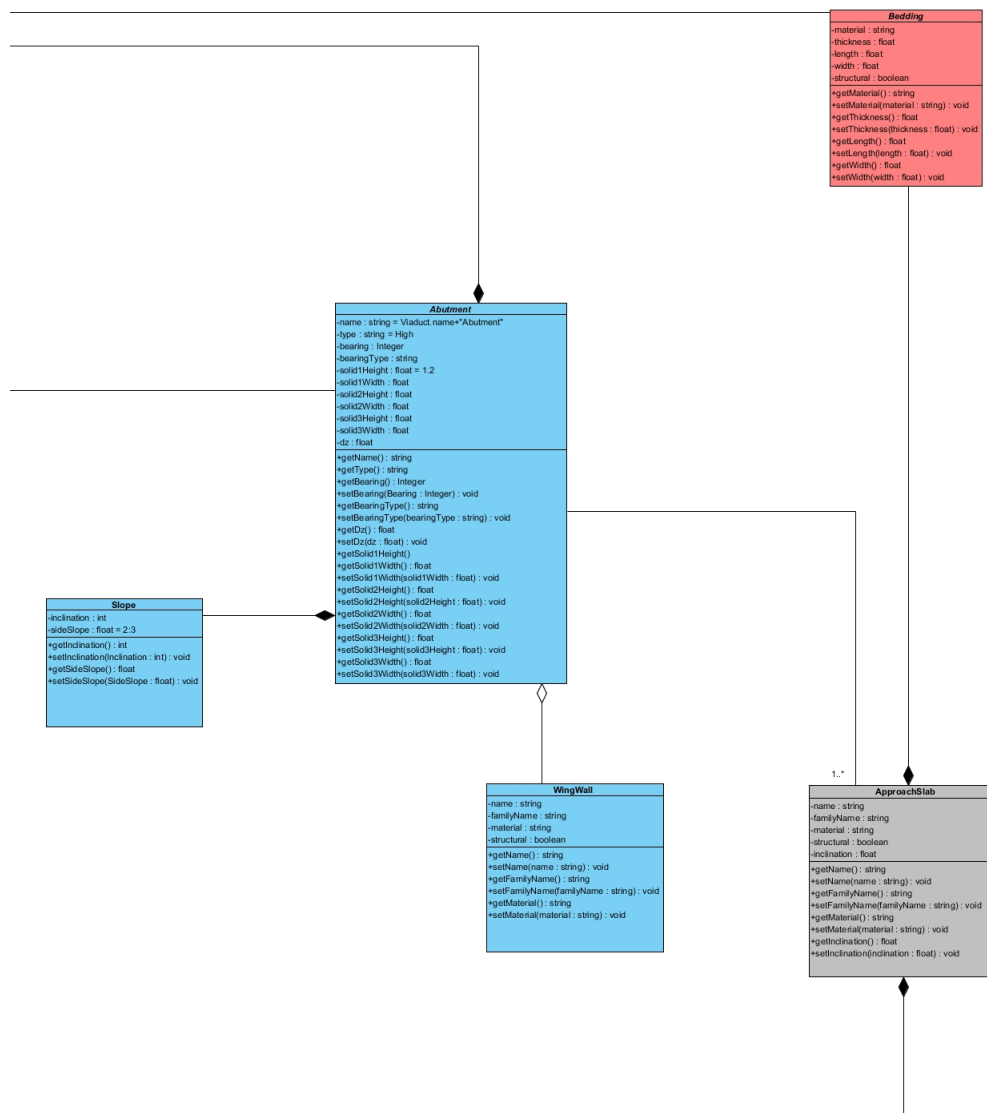


Figure B.4: UML Class Diagram - "Abutment"

C Dynamo Script

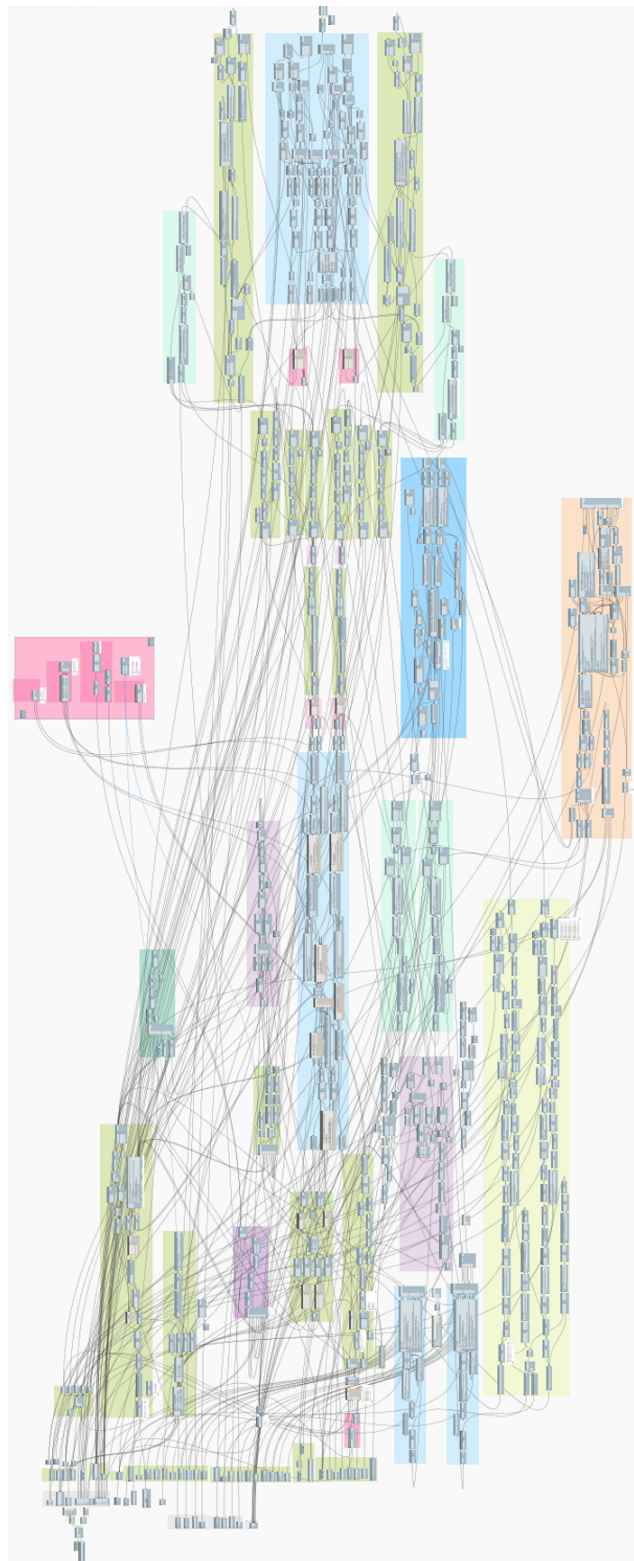


Figure C.1: Dynamo Script

C.1 User Interface

In this section, the user interface is presented. For the development of the user interface the UML model is used as a guideline, since the top down structure of the model facilitates the gradual exposure of parameters to the user, according to the design level to which they belong. The UI is developed using WinForms, namely a library for GUI applications, which is part of Microsoft's .NET Framework.

The first window of the interface corresponds to the first design level, which is the "Viaduct" class of the UML model (Figure C.2). The basic global parameters are defined through this window. The "Preview" button is employed in order to enable a schematic visualisation of the selected values (Figure C.3). The buttons "Back" and "Next" are linked to the design levels, allowing the user to go back and change the values he selected or to move forward and provide the algorithm with more input. The "Preview" button introduces a form of encapsulation in the consideration of the parameters, since if the user inserts a value of wrong type (e.g "string" instead of "float"), then a message appears on the "Preview" window to warn the user (C.4).

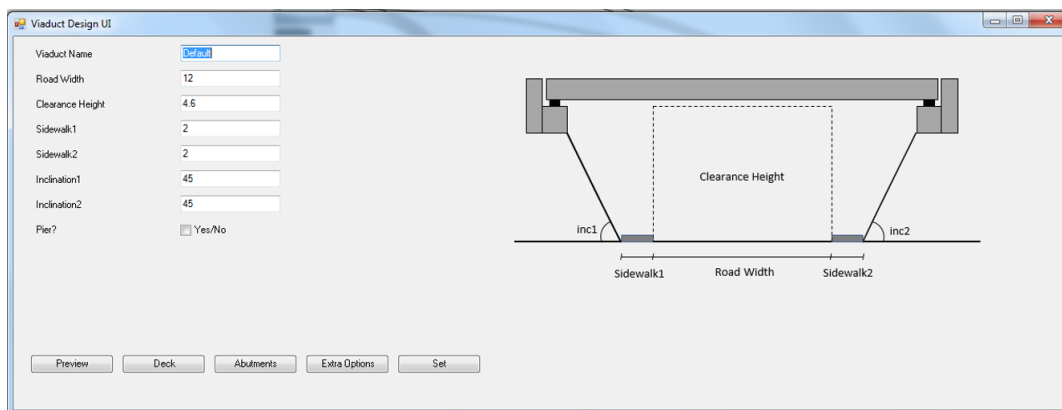


Figure C.2: Dynamo input - User Interface

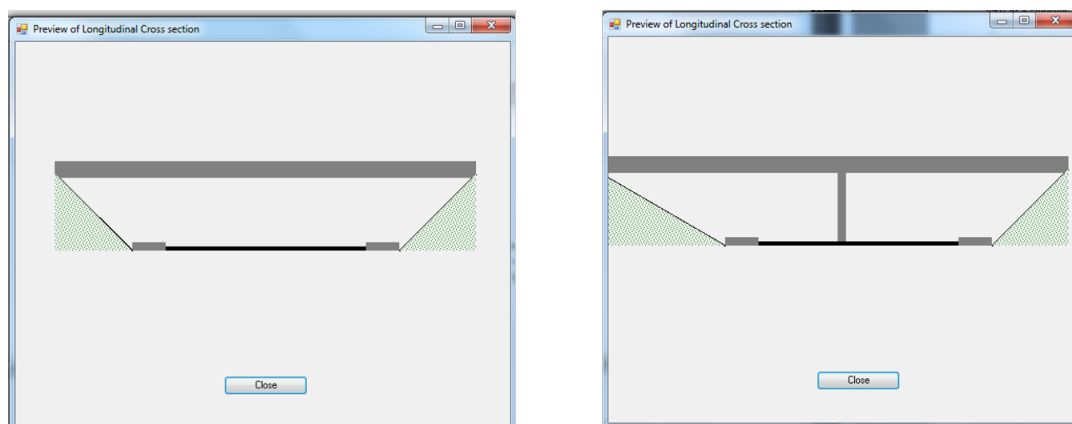


Figure C.3: Preview of Global Parameters (with Pier on the left - without Pier on the right)

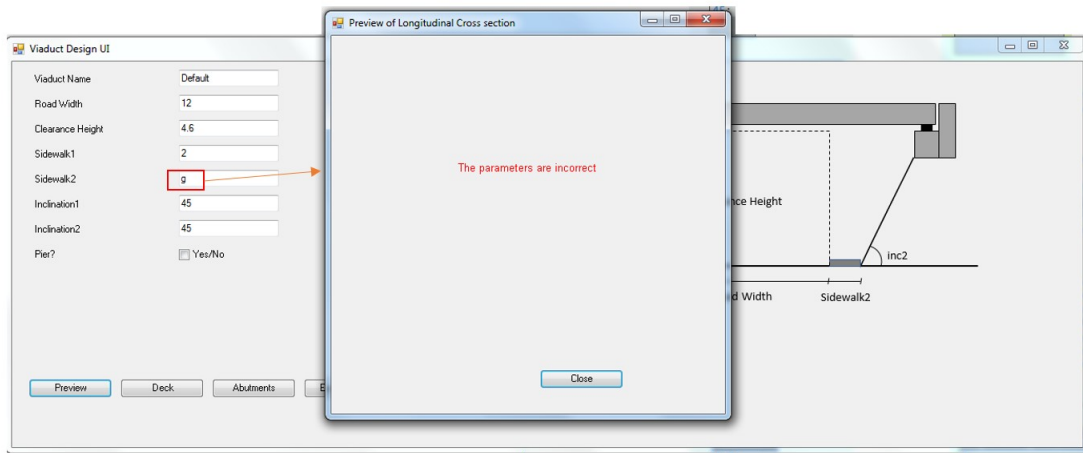


Figure C.4: Warning about Incorrect Parameter Values

By clicking the “Abutment” button a new window opens with the abutment design parameters. The option to choose the same parameters for both sides is available by ticking the ”same?” checkbox. In Figure C.5, a symmetrical design is chosen and a preview of the abutments is shown on the right window. In Figure C.6, an asymmetrical design is chosen, where the abutment on the right has no maintenance gap, as shown in the preview window.

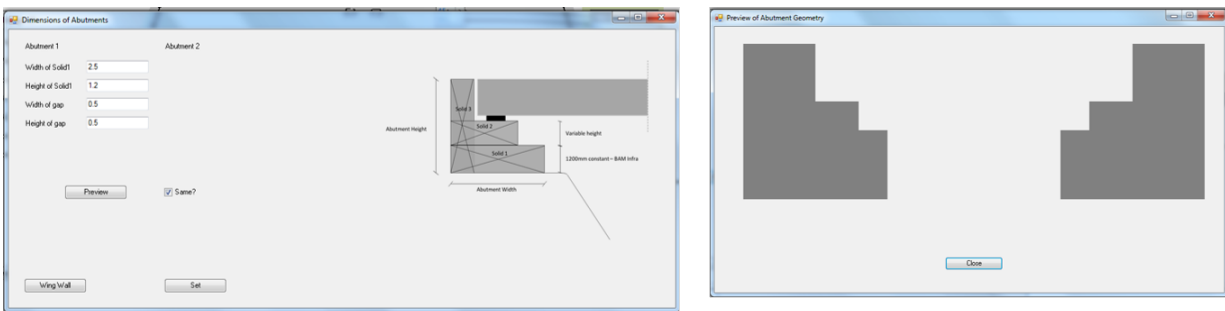


Figure C.5: Window for Abutment Design and Preview - Symmetrical Design

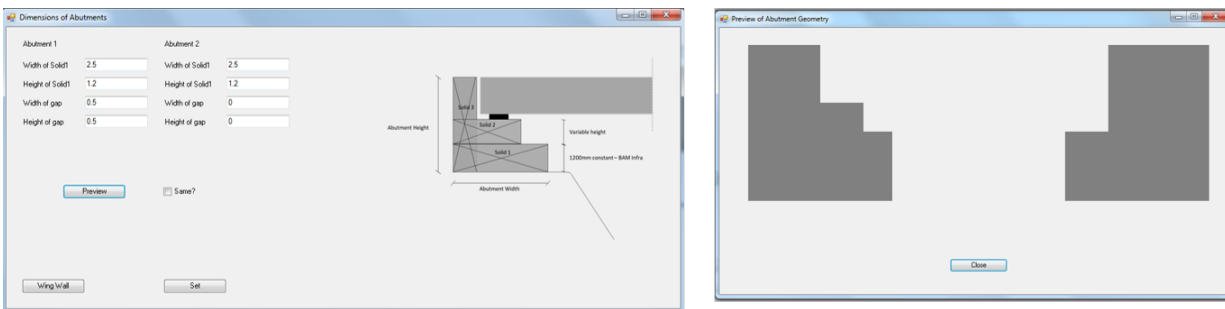


Figure C.6: Window for Abutment Design and Preview - Asymmetrical Design

By clicking the “Deck” button, the parameters related to the deck are shown to the user. For instance, the edge element options and the railing options are accessed through this window. In Figure C.7, the edge element options are shown.

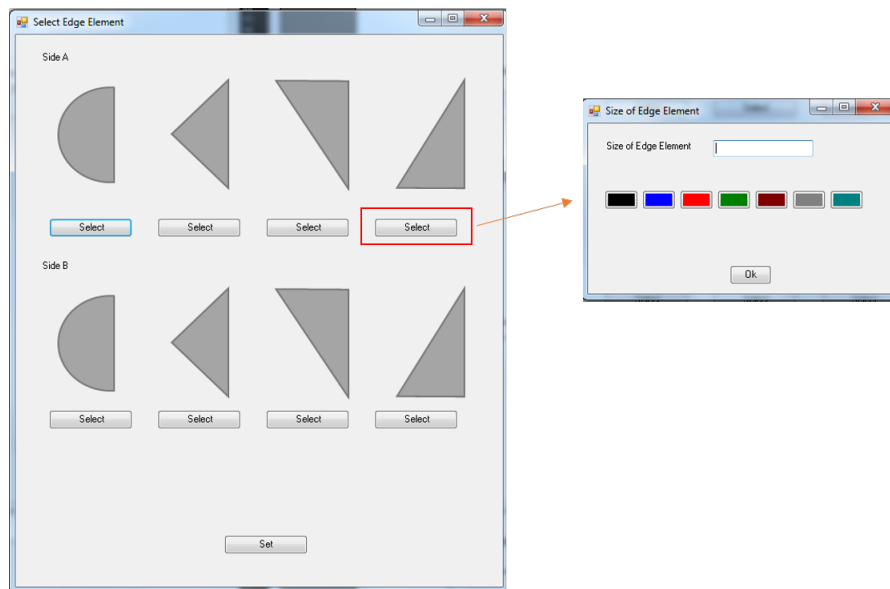


Figure C.7: Edge Element Options

C.2 Building the script

In this section, the initial steps of the Dynamo script are presented:

- Step 1: Import the alignments of the road and the viaduct. Note that the alignment of the road for this investigation should be planar, so as to define the horizontal plane. The alignment of the bridge is a 3D curve, incorporating the transverse and longitudinal curvature (Figure C.8).

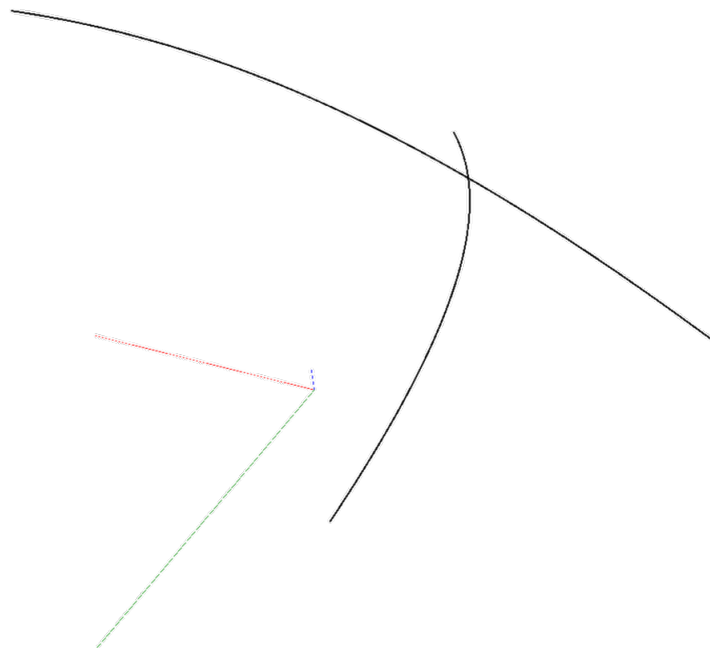


Figure C.8: Alignments

- Step 2: The two alignments are separated, based on their height difference (Viaduct height > Road height). The height difference is corrected based on the value that the user has denoted as clearance height (Figure C.9).

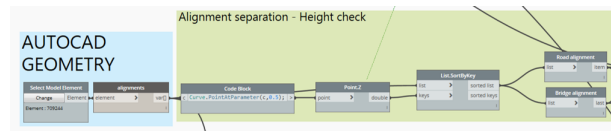


Figure C.9: Alignments

- Step 3: Create the geometry of the road underneath. Since the alignment of the road is planar, the sides of the road are created by offsetting the alignment (Figure C.10).

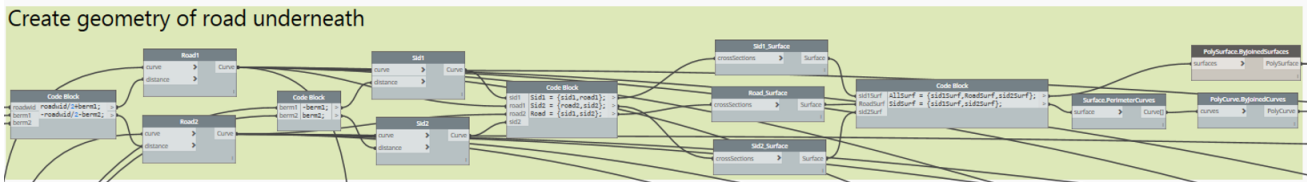


Figure C.10: Creating the geometry of the road

- Step 4: Create the two sides of the viaduct. The sides cannot be created through offsets, since the 3D curvature of the alignment does not allow the use of the normal vectors. Instead, the alignment is divided in points as shown in Figure C.11. The algorithm to specify the outer points of the deck is shown in Figure C.12.
 - a: The alignment of the viaduct is divided in 100 points.
 - b: The tangent of the alignment at those points is defined.
 - c: Due to the longitudinal alignment, the tangent at the points has also a Z component, however, the extrapolation of the division points of the alignment to the edges of the viaduct, should be on the XY plane, therefore a new vector is created with only the X,Y components of the tangents.
 - d: Circles are created around the division points, on XY plane, with a radius equal to the width of the viaduct (+ an offset is that is needed).
 - e: Circles are created around the division points using as normals, the vectors specified in c. The radius is equal to the width of the viaduct.
 - f: The intersection points between the two sets of circles define the edges of the viaduct.

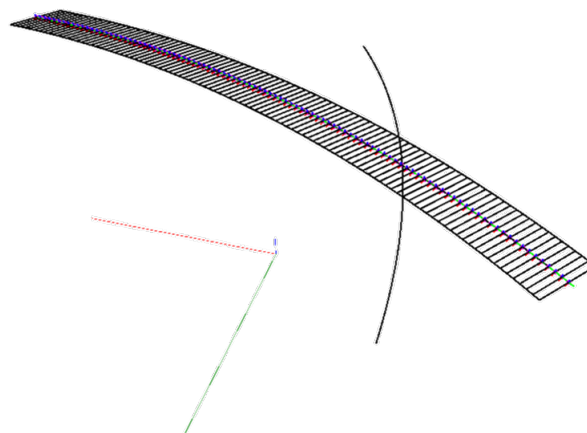


Figure C.11: Sides of the viaduct

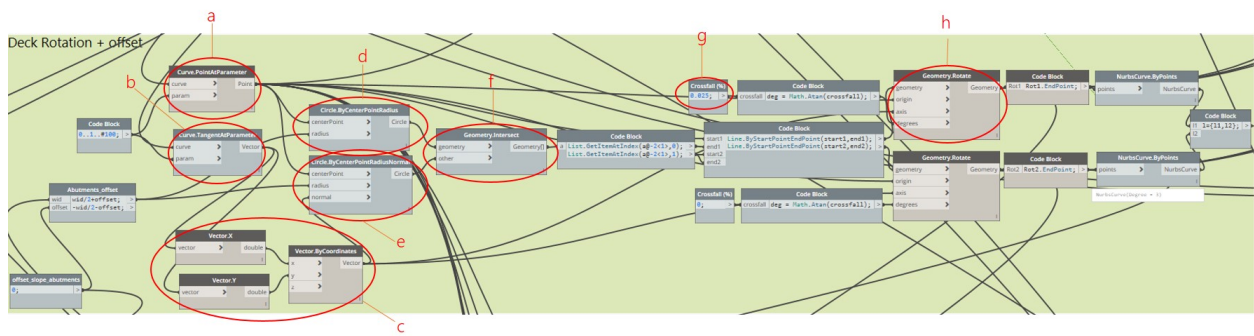


Figure C.12: Creating the sides of the viaduct - 1

- step 5: Create the slopes and the abutments. The slopes at the abutments of the viaducts need to maintain a specific inclination (e.g 45 degrees), which implies that they may not be aligned with the road edges. In order to specify the location of the slopes, the intersection points between the viaduct edges and the road edges are found (Figure C.13). In Figure C.14, auxiliary vertical lines are employed to create the slopes.

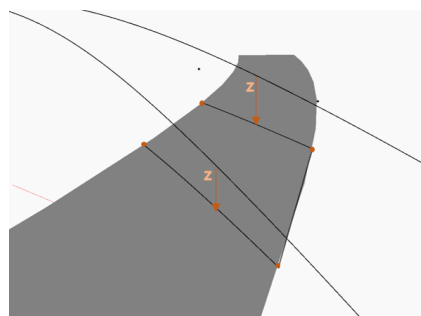


Figure C.13: Intersection Points - (Viaduct Edges - Road Edges)

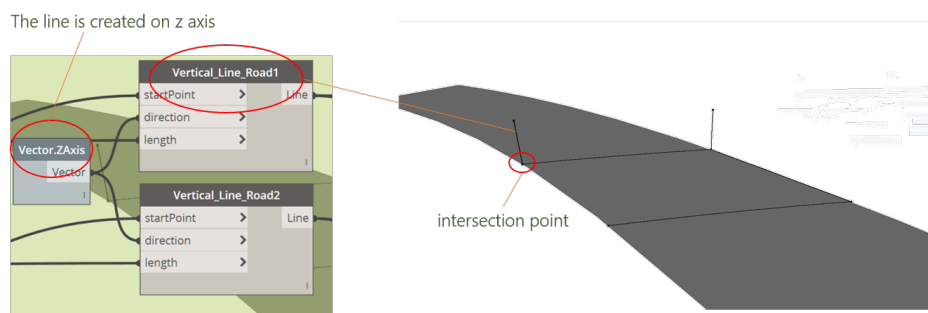


Figure C.14: Vertical Lines

In Figure C.15, the three possible rotation situations for the slopes are illustrated. The outcome is checked so that situation (a) is always maintained.

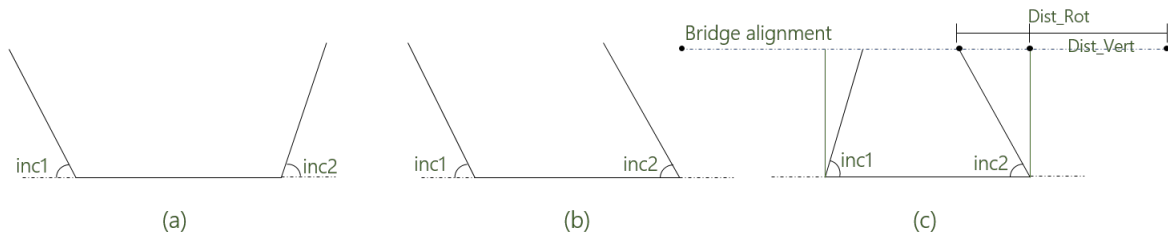


Figure C.15: Possible Rotation Outcomes of Slopes - Longitudinal View

For the definition of the slopes (Figure C.16), the lines between the intersection points at the edges of the road (c), are translated, using the rotated lines (Figure C.15), as vectors to the surface that signifies the top end of the slope (b - that surface is an offset of the deck surface in order to specify where the slope ends). If the deck surface (a) has an inclination, the line will not be parallel to surface b, therefore the line is also projected to it, to ensure that it lays on the plane of the surface. From this projected line a vertical surface is created and rotated at the indicated inclination to find where it intersects with the road surface (d). This process ensures that the abutments are aligned with the deck slab. Moreover, it ensures that the skew angle at both sides is almost identical regardless the inclination angle, which lead to a more economic design.

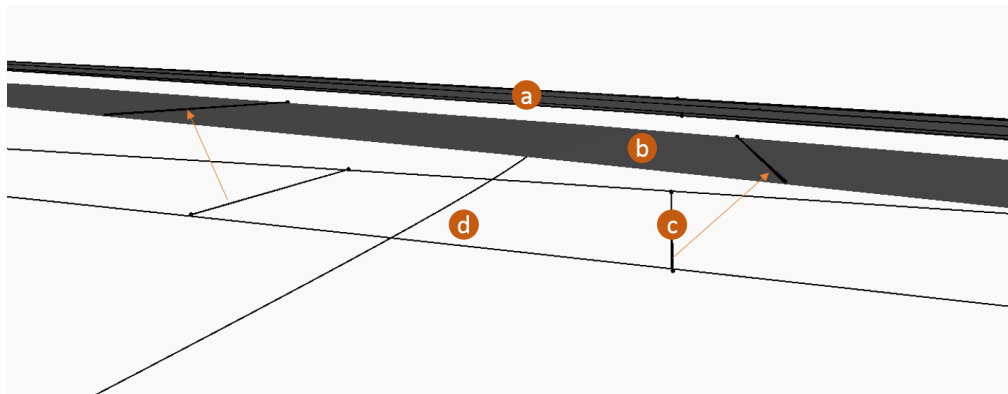


Figure C.16: Creation of Slopes - 1

The abutments are extruded as solids, at the direction of the tangents at the intersection points between the alignment and the slope (Figure C.17).



Figure C.17: Abutment Creation

D Guyon - Massonnet Method

The Guyon-Massonnet method is based on an idealised representation of the actual slab of the deck with an orthotropic slab, whose structural properties are uniformly spread in two orthogonal directions along their length. The goal of the method is to determine how a concentrated load is spread on the beams of an orthotropic slab. It was proposed by Guyon(1946) and Massonnet(1950), who also included the effect of shear. [Xanthakos, 1994]. The output of the method is load distribution factors, which allow for the definition of the load on each beam, based on the location of the beam and the load. In this study, the parameters of the method for the example that is solved are as follows:

- $\alpha = 1$
- $\theta = 0.3752$
- $b = \frac{\text{width}}{2} = 6.3$

The respective values of the load distribution factors are found through linear interpolation and are presented in Figure D.1. The load distribution factors for the two beams which are investigated (0.67b, 0.841b) are also included in the table, apart from the values at the reference stations.

$\theta = 0,3753$	$\alpha = 1$											
K1	-b	-0,75b	-0,5b	-0,25b	0	0,25b	0,5b	0,67b	0,75b	0,841b	b	
0	0,934202	0,967649	1,002802	1,034704	1,050081	1,020894	1,0028024	0,978897952	0,967649	0,955474	0,934202	
0,25b	0,809909	0,859906	0,915113	0,975482	1,034704	1,078752	1,0929976	1,091617472	1,090968	1,088826	1,085084	
0,5b	0,709048	0,769138	0,836791	0,915113	1,002802	1,092998	1,171524	1,207073312	1,223802	1,238183	1,26331	
0,75b	0,626062	0,693143	0,769138	0,859906	0,967649	1,090819	1,2238024	1,311711168	1,35308	1,394174	1,465976	
b	0,55097	0,626062	0,709048	0,809909	0,934202	1,085084	1,2633096	1,401122752	1,465976	1,545599	1,684722	

Figure D.1: Load Distribution Factor K_1

Through linear interpolation the K_1 factors are found for the specific locations of the loads of the tandem system (Figure D.2). Each value corresponds to the location of each wheel of the tandem system. The average of those factors at the location of the beams is multiplied with the equivalent load spread over the width of the viaduct to find the load.

K1	-b	-0,75b	-0,5b	-0,25b	0	0,25b	0,5b	0,67b	0,75b	0,841b	b
0,841b	0,598728	0,668725	0,747265	0,841707	0,955474	1,088732	1,238183021	1,344256985	1,394174	1,449293	1,545599
0,524b	0,701081	0,761843	0,830297	0,909813	0,999428	1,092788	1,176542726	1,217118546	1,236213	1,253158	1,282766
0,45b	0,72922	0,787292	0,852456	0,927187	1,009183	1,090148	1,15581872	1,183982144	1,197236	1,208312	1,227664
0,127b	0,871061	0,912915	0,958256	1,004619	1,042269	1,050286	1,048621562	1,036159468	1,030295	1,023217	1,01085
0,05b	0,909343	0,9461	0,985264	1,02286	1,047005	1,032466	1,02084144	1,001441856	0,992313	0,982144	0,964378
-0,27b	1,099342	1,101595	1,09928	1,079892	1,032152	0,970653	0,908847072	0,890862161	0,852644	0,892773	0,80184

Figure D.2: Load Distribution Factors K_1 - Tandem System

F Robot Results

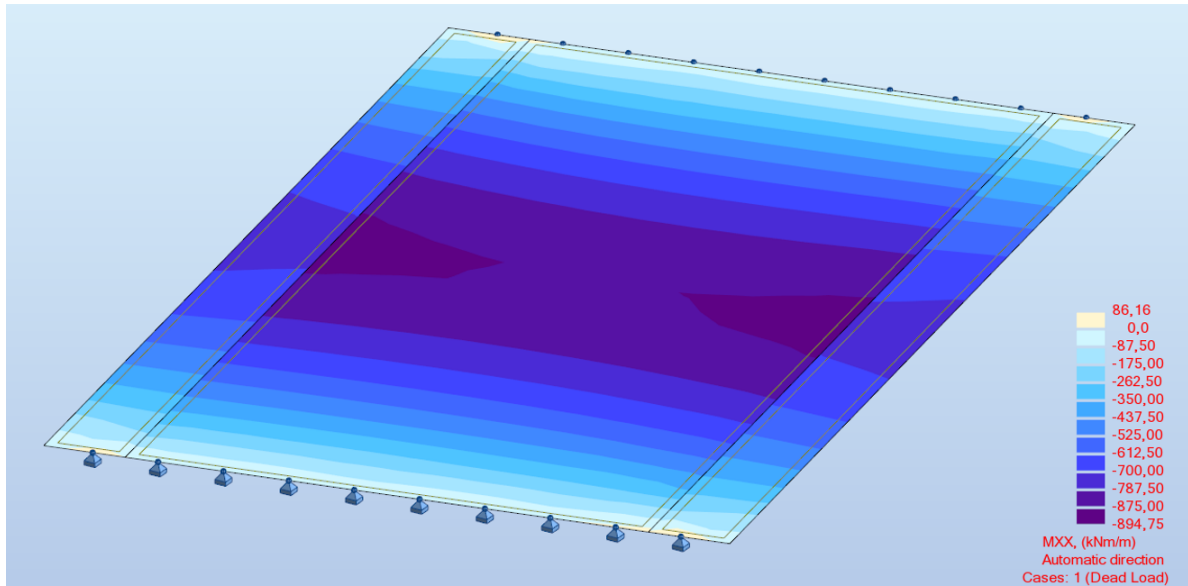


Figure F.1: Longitudinal Moments for LoadCase: Dead Load

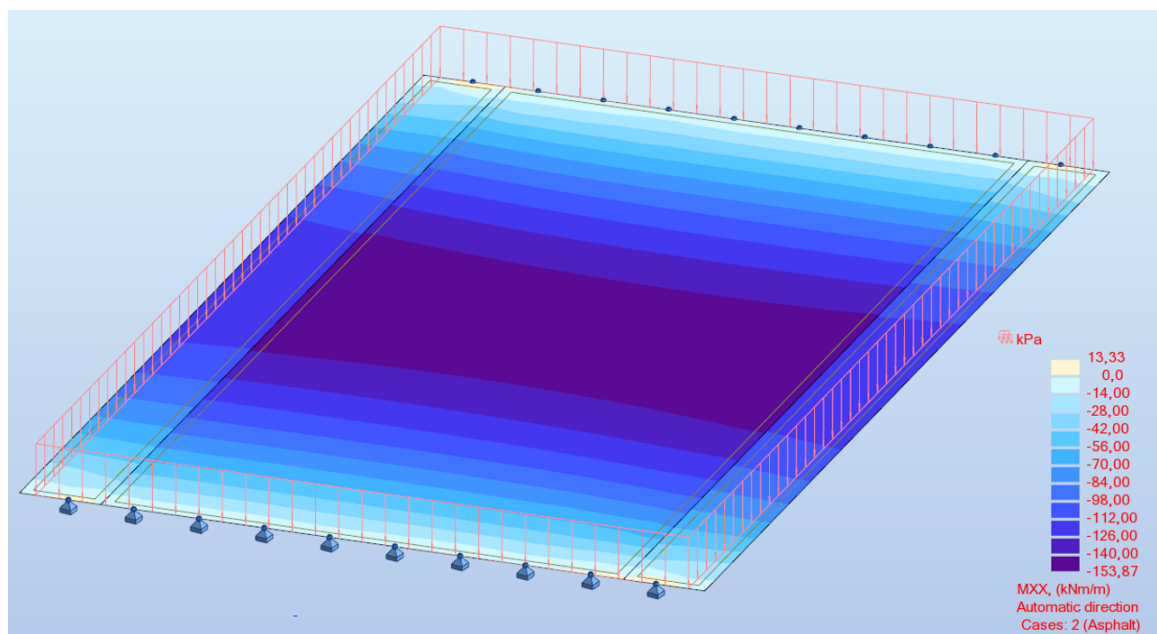


Figure F.2: Longitudinal Moments for LoadCase: Asphalt

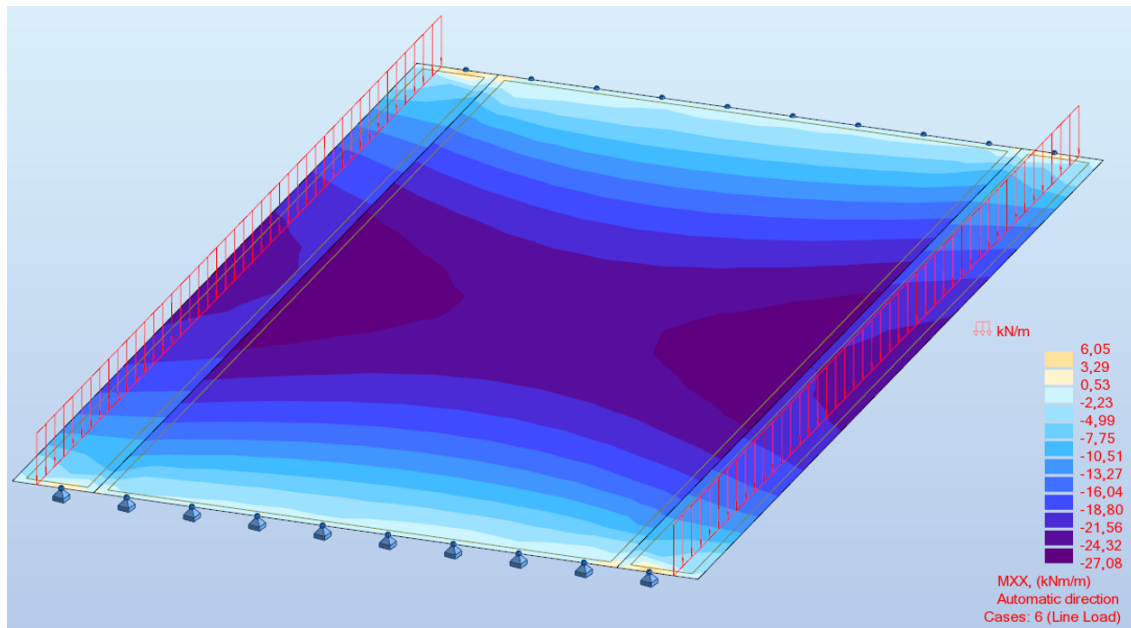


Figure F.3: Longitudinal Moments for LoadCase: Line Load

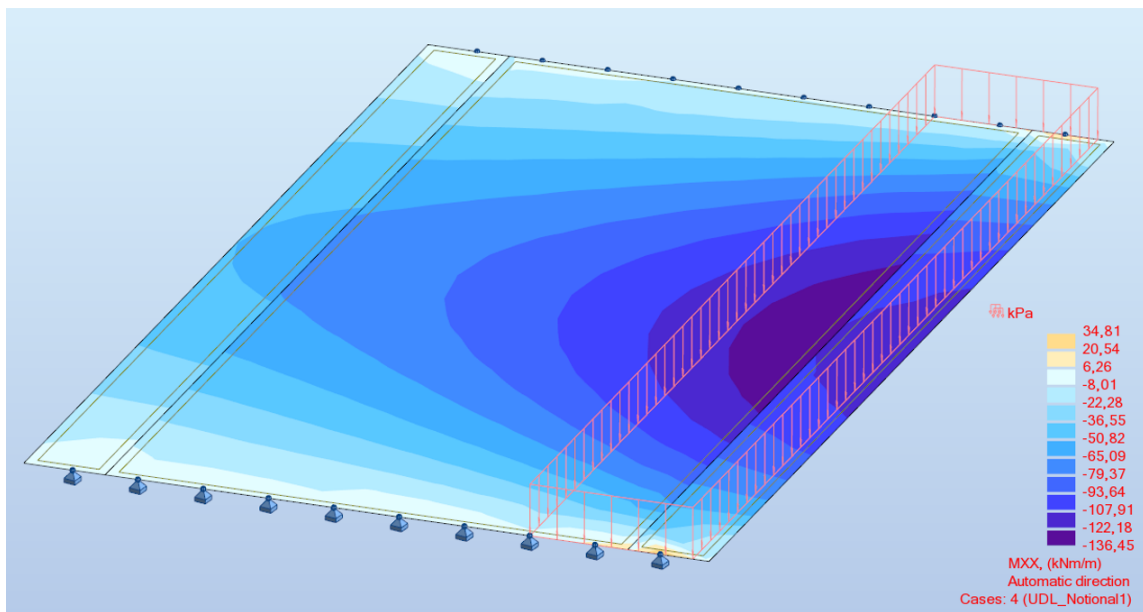


Figure F.4: Longitudinal Moments for LoadCase: Load on Notional Lane 1

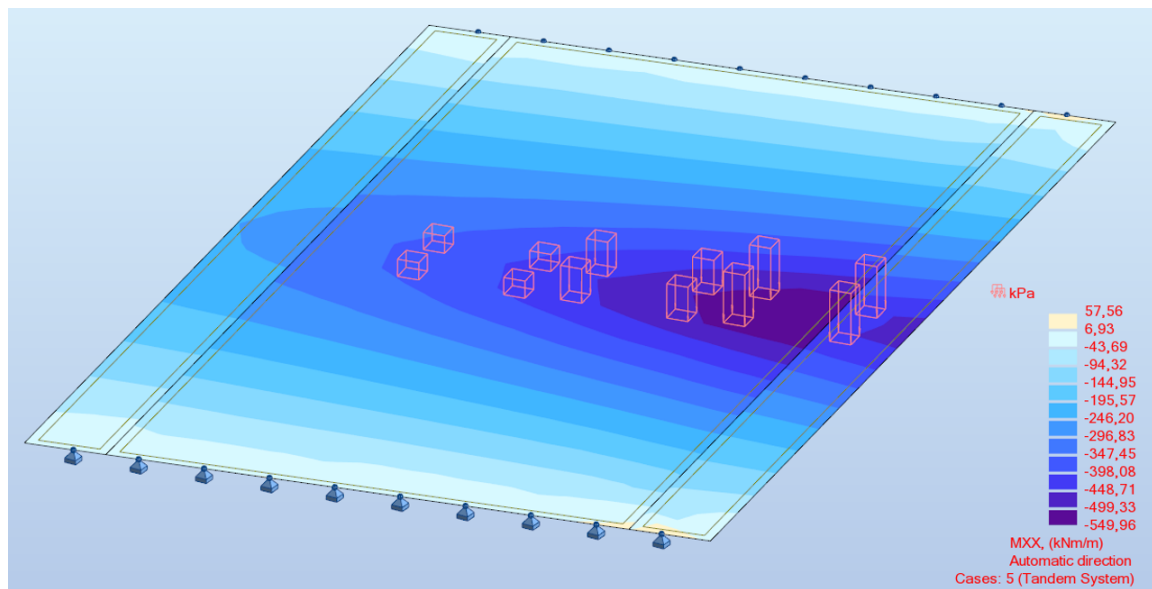


Figure F.5: Longitudinal Moments for LoadCase: Tandem System

G 3D Visualisations

