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Algorithms-Aided Design utilized in Structural Design

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Master of Science in Engineering Structures and Material
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PREFACE

This thesis is submitted in fulfillment of the requirements set for the Master's degree in Structures and Materials, specialized in Civil Engineering structures, at University of Stavanger, Faculty of Science and Technology, Norway. The research presented has been carried out in collaboration with Norwegian consultancy Multiconsult.

My motivation for studying Algorithms-Aided Design stems from a deep interest in technology driven and efficient workflows. In 2019 I was made aware of Parametric Design and was quickly convinced of its potential. Furthermore, as I dove deeper into the rabbit hole that is algorithmic design, it became apparent that other innovative technologies could be enabled by having parametrically defined structures. As many of these technologies have not seen noticeable adoption in the structural engineering community it became apparent that the topic could be suitable for my thesis. In addition, I was also fortunate to be able to apply said technology within projects at Multiconsult during the period December 2019 – June 2021, providing me with hands on experience.

I would like to thank my advisor at the University of Stavanger, Associate Professor Samindi Samarakoon for her guidance, feedback and critique during this work. In addition, I would also like to thank my external advisors at Multiconsult, Asle Moland Seim and Guillem Rojas Orts, you have been instrumental in shaping this thesis. Lastly, I would like to thank my family and friends for their support throughout the pursuit of this Master's degree, without you this would not have been possible.

ABSTRACT

For long, productivity within the construction industry has comparatively fallen in contrast to its sister engineering fields(Teicholz 2004). Structural engineers, which are tasked with producing precise and reliable reference for the builders at the building site can directly influence the productivity by delivering high quality and error free deliverables as well as being able to quickly reiterate on designs if necessary. To accommodate the need to increase productivity, structural engineers are looking at technologies like Algorithms-Aided Design(AAD) when producing their deliverables. AAD methods like Parametric Design has already seen noticeable adoption(Lee, J. et al 2014) and has provided possibilities to generate precise and highly customizable BIM-Models. Furthermore, as part of the structural design is to analyze structures, Analysis Models for Finite Element Analysis(FEA) is needed. in similar fashion to BIM-Models, Analysis Models can be produced parametrically. By doing so, additional innovative technologies are enabled. Generative Design which is one of them, provide optimization routines which can aid in the pursuit of optimal solutions given a set of criteria. In collaboration with Multiconsult, this thesis explores 9 cases where such AAD methods has been applied. The learnings from these cases together with feedback from industry professionals has served as foundation to define proposed workflows within three areas, parametric BIM-Models, parametric Analysis Models and finally, Generative Design of structures. These workflows inherit characteristics that when followed yielded consistent and reliable results.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

- FEM – Finite Element Method
- FEA – Finite Element Analysis
- BIM – Building Information Modelling
- AEC – Architecture, Engineering and Construction
- AAD – Algorithms-Aided Design
- AD – Algorithmic Design
- PD – Parametric Design
- GD – Generative Design
- A-BIM – Algorithmic BIM

1 INTRODUCTION

1.1 BACKGROUND

With the advent of new and more powerful technologies, designers and architects are facing lower thresholds when trying to realize increasingly complex structures (Banfi, F. et al. 2017). Structural engineers are often tasked with taking such concepts from an idea to a product which is buildable and structurally sound, while adhering to the initial design. As structural engineers, the final delivery will often be in the form of a highly detailed and information rich 3D-model (Model based delivery), traditional 2D-drawings, or a combination of the two. The purpose of such deliverables is to serve as the reference for the builders at the building site. Naturally, these references need to be of high quality and free of errors while precisely mimicking the physical and functional characteristics of the building. To achieve this, all the aforementioned deliveries are regularly generated in some form of BIM software such as Tekla or Revit (Kovacic, I., & Filzmoser, M. 2014, July). These software' offer easy collaboration between project team members and enables thorough quality control procedures. Consequently, proficiency in such tools is fast becoming a necessity to keep up in an environment where the bar is raised continuously (Russell, D. et al. 2014). As a result, efficient modelling methodologies such as parametric design has seen increasing presence in the typical structural engineering workflow. Furthermore, as this methodology is seeing more use, new and inventive workflows are proving to alter the ways structural engineers work on daily basis. Furthermore, structural engineers regularly use FEA tools to evaluate the structural integrity of structures. To be able to do so, analytical models must be generated. In much the same manner as with BIM-models, such analytical models can be made parametrically. In addition, by having an algorithmically defined structure, additional benefits are enabled. Seeing that the position of all elements are governed by the logic described by a script, optimization algorithms can be deployed which in turn can manipulate the geometry to achieve certain objectives. Subsequently, this enables the structural engineer to make use of Generative Design capabilities to achieve a higher degree of automation in their design work.

1.2 PROBLEM STATEMENT

Through a multitude of cases, this thesis aims to study to which degree Algorithms-Aided Design can be adopted into the daily workflow of a structural engineer. Furthermore, the experience gained when studying these cases together with feedback from industry professionals will serve as foundation for a proposed workflow of best practice within three areas, parametric BIM-models, Parametric analysis models and finally, Generative Design of structures.

2 METHOD

To answer the question posed by the problem statement a rigid research methodology must be in place, the following chapter will describe the procedure this thesis used.

2.1 QUANTITATIVE AND QUALITATIVE RESEARCH

As this thesis mainly conducts research through case studies, the qualitative research method will be the overarching method, this also falls in line with use of surveys to obtain feedback from industry professionals on the different topics. However, to evaluate the accuracy of some case studies, quantitative methods are needed to compare the numerical results from various different sources. In other words, the quantitative research method will be used to validate the outcome of certain cases to be able to evaluate the cases as a whole qualitatively.

2.2 INFORMATION GATHERING

2.2.1 Case study

As this thesis explores Algorithms-Aided Design as a whole, and although the different areas which are being studied are interrelated, the procedure to explore them will be slightly different. However, the through the experiences gained when studying the different cases each chapter aims to propose a common workflow that yielded the best and most reliable results.

2.2.2 Literature review

To understand the potential of AAD a thorough review of the current methods available. This included studying relevant papers as well as gaining knowledge within commonly used AAD software. A more in-depth description can be viewed in the next chapter.

2.2.3 Survey

To understand the perception of industry professionals regarding the use of AAD surveying was used in the form of questionnaires.

2.2.4 Observations

The author’s observations as a participant in the cases was used to gather information.

2.2.5 Webinar and online courses

Although the author had some knowledge about AAD beforehand, extensive studies through webinars and online courses was needed to reach an acceptable competency within the relevant tools to properly evaluate the potential of the technology, the research that was done can be viewed in Table 1.

Table 1 Webinars and online courses

	Extent and format	Description
NTNU – Parametric boot camp 2021	5 consecutive full days of lectures and workshop.	NTNU holds a yearly parametric design boot camp covering everything from basic Grasshopper scripting to more advanced Generative Design procedures.
Harvard GSD - Introduction to Computational Design	31 online lectures.	Harvard GSD has made their Computational Design class GSD-6338 publicly available on YouTube. This series of lectures gives a fundamental insight to the typical tools and methods used in AAD.
Multiconsult - Parametric Design internkurs	5 consecutive full days of lectures and workshop.	Multiconsult held a weeklong course regarding Parametric Design, this included everything from coaching in Grasshopper to workshops and examples from the projects where Parametric Design had been applied.
StruSoft - FEM-Design	5 Webinars.	StruSoft regularly arranges webinars to promote the capabilities of FEM-Design. The author participated in several of these.
Various sources – Karamba3D, Grasshopper and FEM-Design	Online lectures.	Tutorials for all the different grasshopper plug-ins was found mainly on YouTube.

3 LITERATURE REVIEW

3.1 ALGORITHMS-AIDED DESIGN

Algorithms-Aided Design or AAD for short refers to the process of deploying algorithms to aid in the design of objects, building and products. Furthermore, there exist some ambiguity in the scientific community regarding the terminology describing such actions(Humppi, H., & Österlund, T. 2016). Computational Design, Parametric Design and Generative Design could also fall under this description, but for the sake of this thesis has been understood lie within the realm of AAD. In other words, AAD will be regarded as an umbrella term used to describe a multitude of different design methodologies. Furthermore, this thesis will mainly focus on two principles which are increasingly relevant in the daily life of a structural engineer, these are Computational Design and Generative Design.

3.1.1 Computational Design

At first glance Computational Design might be mistaken for Computer Aided Design(CAD), this is however not the case(Menges, A., & Ahlquist, S. 2011). Although computational design is often executed on a computer (not always), it mainly refers to the fact that the design is done computationally, i.e. Design generated based on numbers manipulated through equations and scripts. One common application of Computational Design is to generate BIM-Models which can also be referred to as Parametric Design(Boeykens, S. 2012), this application will be further studied in this thesis.

3.1.2 Generative Design

Generative Design refers to the process of deploying optimization algorithms that aids in the search for optimal solutions given a set of inputs and constraints (Krish, S. 2011). Then, the optimization algorithms explores the possible solution space through iteration of generational genome populations. A common method used in Generative Design are Evolutionary solvers. A typical approach of using Generative Design can be viewed in Figure 1.

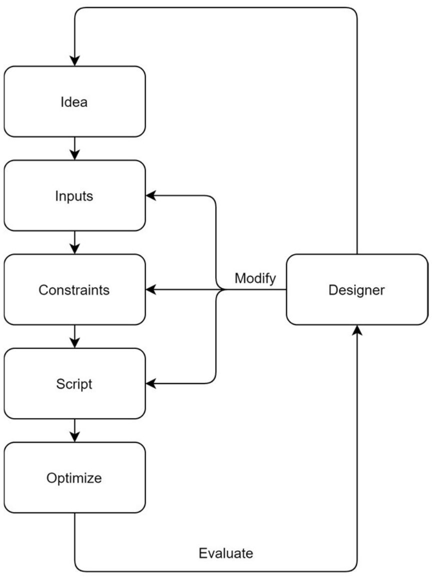


Figure 1 Generative Design approach

3.1.2.1 Evolutionary solver

Evolutionary solvers or genetic algorithms which they are also called are not a new phenomenon. Evolutionary computing was mentioned as early as 1964 by Lawrence J. Fogel in his Ph.D. Thesis "On the Organization of Intellect", it was however not before 1984 with Richard Dawkins's book "The blind watchmaker" which included a seemingly endless stream of what he called "bio-morphs" that the idea gained notable recognition. This sparked a new wave of interest within the area, and with the ever increasing power of the personal computers, the potential was further solidified. To describe the inner workings of an evolutionary solver, David Rutten's paper "Evolutionary Principles applied in problem solving" (2010) will serve as foundation.

Function

The way an evolutionary solver optimize a function is by slowly, by steadily exploring a so-called fitness landscape. The fitness landscape firstly depend on the amount of input parameters which is called genes, and secondly on how the functions responds to alterations of said genes. The response to a given value of a set of genes is called fitness and can be represented by a geometric entity with one higher order than the number of genes, i.e. if you have two genes the fitness landscape will be a surface in 3D space. Figure 2 illustrate a fitness landscape with three peaks which shows the fitness response to two genes, Gene A and Gene B.

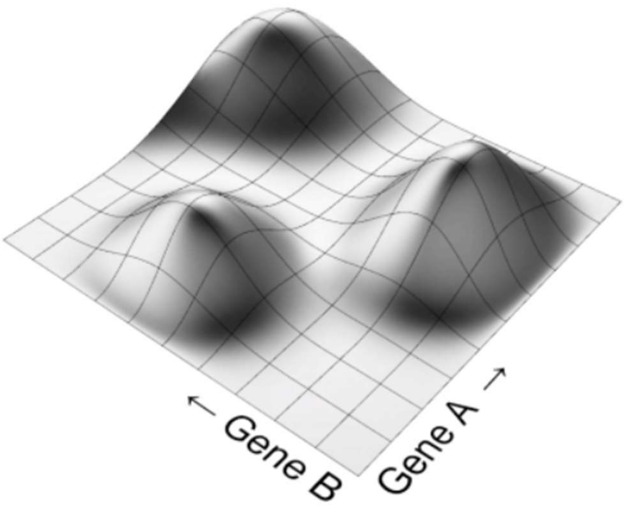


Figure 2 Fitness landscape (Rutten, D. 2010)

The fitness landscape is not known, otherwise it would be trivial to find the solution. It is explored through a multitude of iterations with evaluating so-called genomes. A genome is a particular value from the fitness function given genes with a static value e.g. Gene A is set to 3 and Gene B is set to 4 yields a fitness of 200.

Populate fitness landscape

The initial step in a evolutionary solver is to randomly populate the fitness landscape(Figure 3) given the domain of the genes e.g. Gene A and B can only have integer values in the span of 0 to 10. This random distribution of genomes is referred to as generation 0 and will serve as foundation for further optimization through selections.

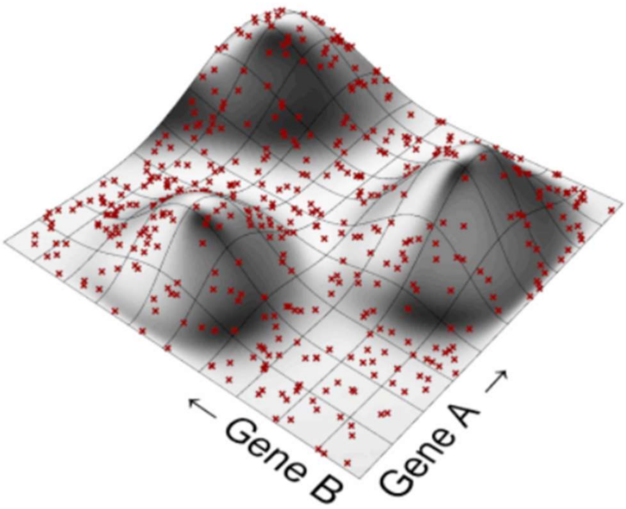


Figure 3 Populated Fitness Landscape (Rutten, D. 2010)

Optimization

Once the fitness of all the genomes from generation 0 has been evaluated, a hierarchy from best to worst can be established, in this case, the algorithm is trying to find the highest peak in the fitness landscape. The best performers are the ones closest to the peaks in the initial generation and they get to live while the remainder are killed off. Since it is quite unlikely that one of the randomly generated genomes from generation 0 by chance happened to be the most optimal solution, further optimization is needed. This is achieved by breeding the genomes that got to live after exterminating the low performers. Genomes need to breed with other genomes that are at a certain distance away to discourage inbreeding which would cause a lack of diversity in their offspring. However, since their offspring will be a sort of average of the two parents, it is important that breeding between genomes from different peaks is avoided, this would likely cause their offspring to end up in a valley between the two peaks. Furthermore, this process is repeated until a cluster is formed at the highest peak, this process is illustrated in Figure 4.

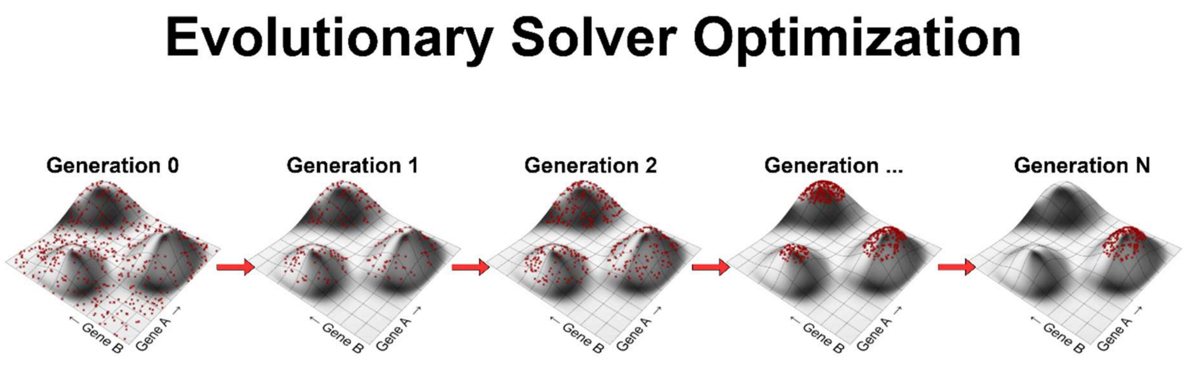


Figure 4 Generations of optimization (Modified from Rutten, D. 2010)

Fitness function

In Evolutionary computing, fitness is in its entirety defined by the user. Whether a genome is fit or not relies on what outcome the user wants to minimize or maximize. A trivial example could be a two gene function that controls dimensions of a rectangle. In this hypothetical example we want to maximize the total area, now the fitness for a genome will be the associated area given a set of gene values. A combination of genes that yields a large area will be comparably better fit than one that returns a lower value. In this case, this will eventually guide to algorithm to maximize both dimensions.

Selection mechanisms

Evolutionary solvers make use of selection mechanisms to decide which genomes gets to mate. Three methods which are commonly used are Isotropic Selection, Exclusive Selection and Biased Selection.

Figure 5 Isotropic Selection (Rutten, D. 2010)

Isotropic Selection(Figure 5) in a sense means the absence of selection, and everyone gets to mate. This might sound silly at first but it has shown to have potential upsides when looking for an optimum in a complicated fitness landscape. For instance, isotropic selection reduces the speed which colonization occurs at the initial optimums the algorithm encounters. These optimums might be local and there might exist a better, global optimum which will yield better fitness.

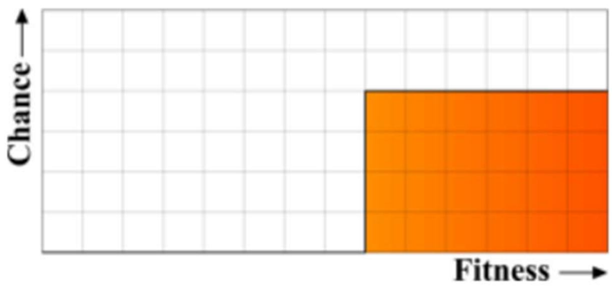


Figure 6 Exclusive Selection (Rutten, D. 2010)

A more common method is called Exclusive Selection(Figure 6), this will only let the top % fittest genomes to mate, this selection method will accelerate the colonization of optimums in the fitness landscape.

Figure 7 Biased Selection (Rutten, D. 2010)

The last commonly used method is called Biased Selection(Figure 7), this is in a way a combination of isotropic and exclusive selection, almost everyone gets to mate, but the fitter genomes get to mate more frequently, and as such, their characteristics will be further amplified in the population.

Coupling algorithms

According to David Rutten(2010), coupling is the process of finding mates. At the point when a genome has been selected to mate i.e. is has been deemed fit enough to survive, it needs to find a suitable mate. One common selection method is called selection by genomic distance. As mentioned earlier, picking a mate that is to closely related to the particular genome should be avoided, if not, you run the risk of rapid decline in the population diversity. On the other hand, you neither want to stray to far away, doing so could result in so-called zoophilic mating, by having two parents of different clusters mate and their offspring, which will inherit roughly equal traits from each parent, end up with an unwanted combination of characteristics and thereby low fitness.
In Figure 8 this is illustrated by a fit genome, marked in red, searching for a potential mate. Following selection by genomic distance, his optimal search area will be within the green region, all mates outside this region will either cause the offspring to gain inbreeding or zoophilic characteristics.

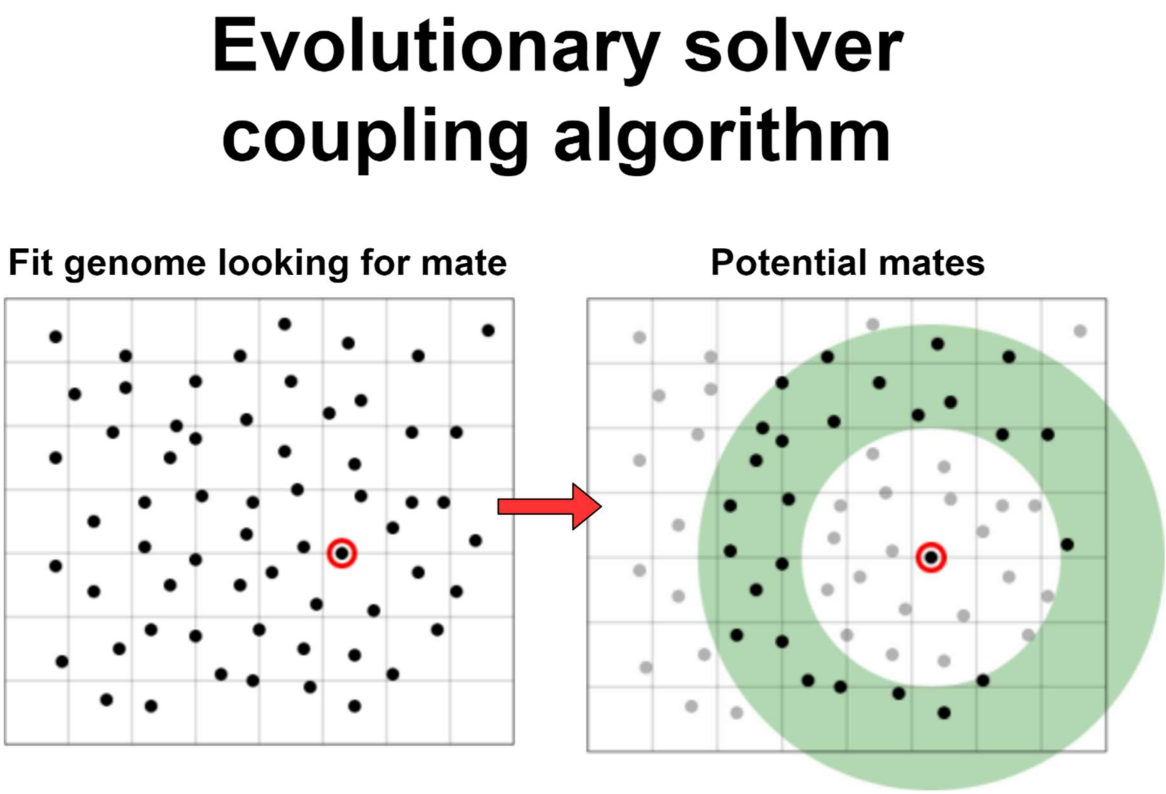


Figure 8 Fit genome looking for mate (Modified from Rutten, D. 2010)

Coalescence algorithm

Once a genome has found its mate, it time to generate an offspring. Which characteristics the offspring will inherit from each of the parents can be determined through a couple of different methods. Crossover mating, which is one of these methods, works by the offspring inheriting a random number of traits from "mom" and the remainder from "dad". Blend coalescence on the other hand, take the traits from both parents and average them, these averaged traits are the traits that the offspring will inherit.

Mutation

The aforementioned methods have all sought to improve the quality of the solution. However, even when taking precautionary steps, they all have a tendency to reduce the diversity of the population. To reintroduce some diversity, the evolutionary solver make use of mutations. One way it achieves this is by so-called point mutation. Point mutation takes the genome of an offspring and alters the value of one of its genes, this results in the offspring being slightly different from its parents. The degree to which the mutation can alter the value of a gene is limited and should not cause the genome to drastically alter its characteristics. Afterall, mutation is done to encourage more thorough exploration of the fitness landscape, which will result in a higher probability of finding the global optima compared to one of the local ones.

3.2 Building Information Modelling

Building Information Modelling (BIM) provides AEC professionals with the tools to generate virtual models that not only contains the geometry of the structure, but also any accompanying metadata that is relevant to support the design, procurement, fabrication and construction of said structure(Eastman et al. 2008). As the AEC industry is continuously looking to decrease cost, increase quality and productivity, and reduce project delivery time(Azhar, S. 2011), industry professionals has turned to BIM and seen promising results(Azhar, Nadeem et al. 2008). Benefits such as clash detection between interdisciplinary models, building life cycle analysis and precise quantity estimations are some that are available within the BIM environment. Furthermore, AEC professionals now primarily use BIM-models rather than traditional CAD tools like Autocad to generate their deliverables as they usually inherit a higher degree of interoperability between the multidisciplinary models in a given project. Lastly, in recent years it has become apparent that the use of Algorithmic Design together with BIM-Modelling (A-BIM) opens up vast possibilities in terms of efficiency, precision and customizability (Caetano, I., & Leitão, A. 2019).

3.3 INTEROPERABILITY

Interoperability refers to the ability to effortlessly exchange data cross-platform to encourage multidisciplinary collaborative environments. In the AEC industry this has proven to be especially important seeing the vast amount of different tools and software are involved in the completion of structures. As a result the industry has collaborated to agree upon a common data exchange known as Industry Foundation Class.

3.3.1 Industry Foundation Class IFC

IFC is standard for openBIM data exchange, it enables exchange of the geometry of a given structure together with a rich set of metadata which can be defined in the different modelling software's.

3.4 SOFTWARE

To evaluate the potential of AAD a set of software needed. These has been picked due to their prevalent use within Multiconsult. In addition, some software has been chosen based on the potential they might bring to the future use of AAD.

3.4.1 Rhinoceros 3D

Rhinoceros is a 3D-CAD software developed by McNeel. The geometry is defined by NURBS(Non-uniform rational basis spline) that the user can manipulate to freeform the wanted shape of the object being modelled. Rhinoceros is widely used in the industry, and has long been a favorite among designers. In later years, with the inclusion of visual programming capabilities provided by the imbedded application Grasshopper, Rhinoceros has seen noticeable adoption among architects and civil engineers who seek to enhance their efficiency in modelling BIM-models. In addition, FEA software providers has also seen the potential, and are now providing plug-ins that enable bi-directional interoperability between their respective software and the modelling capabilities that Rhinoceros bring.

3.4.1.1 Grasshopper

Grasshopper is a visual programming language developed by David Rutten that enables scripting of the geometry within Rhinoceros. With the use of grasshopper, the user can with a high degree of precision and efficiency develop scripts that produce complex geometry that would be cumbersome to do manually. It could be argued that Grasshopper is the go-to tool in terms of AAD and has by far the largest community support compared to its competitors.

3.4.1.2 Galapagos

Galapagos is an optimization routine, also developed by David Rutten(Rutten D. 2013), which is embedded within Grasshopper. Galapagos enables the user to define a set of input parameters which the algorithm can manipulate. Furthermore, these parameter are usually inputs to a problem which needs optimization. For Galapagos to learn which combination of the parameters that yields the best solution, a fitness criteria needs to be defined. The fitness criteria says something about the performance of that particular iteration given the associated parameter values. Subsequently, when the algorithm is set up as described, the routine can be set in motion. Before starting, Galapagos asks if the fitness score should be minimized or maximized. Finally, the user can choose from two different optimization techniques, Evolutionary Solver and Simulated Annealing. The Evolutionary Solver is by far the most common method as is also the one applied to the relevant cases in this thesis.

3.4.1.3 Interoperability

McNeel has enabled plug-in capabilities within both Rhinoceros and Grasshopper. In other words, this means that third party actors can develop applications and run them within the Rhinoceros-Grasshopper environment. Through these plug-ins, developers can enable a high degree of interoperability between their respective software and the extensive modelling capabilities of the Rhinoceros environment.

3.4.2 Tekla Structures

Tekla structures is a widely used BIM-modelling software developed by Trimble.

3.4.2.1 Interoperability

Trimble has developed a plug-in for Grasshopper that enables di-directional communication between the two software. This means that you can both gather geometric information from an existing Tekla model and use it at input for a Grasshopper script, as well as generate Tekla modelling elements from geometry defined in a Grasshopper script.

3.4.3 Solibri

Solibri is a software regularly used to check models for errors and clashing and serve as a tool for quality control of digital 3D models.

3.4.3.1 Interoperability

Solibri accepts most of the commonly used model exchange formats like .dwg and .IFC.

3.4.4 FEM-Design

FEM-Design is a widely used FEA software developed by Strusoft. It offers analysis of steel, concrete, timber and glued laminated timber structures. In addition, FEM-Design also offers possibility to define post-tensioned cables. The choice to go with FEM-Design is also related to being one of the preferred analysis software within the company.

3.4.4.1 Interoperability

FEM-Design offers different ways to import geometry directly from BIM-software like Tekla. Both IFC and their custom file format struXML are valid options. In addition, Strusoft has developed a comprehensive plug-in for Grasshopper. The capability within this plug-in almost directly mimics that of the stand-alone software.

3.4.5 Karamba3D

Karamba3D is a FEA plug-in for Grasshopper (Preisinger, C. 2013) which enables scripting of structural analysis in the same manner as is regularly done with geometry within Rhinoceros. It is very "light-weight", providing fast solutions to structural analysis problems defined by geometry and information programmed in a Grasshopper script. This capability makes it a prime candidate to be paired with Generative Design routines like Galapagos. Exploiting this capability will be further studied in this thesis.

3.4.5.1 Interoperability

In comparison with other FEA software that needs to run in parallel with Grasshopper to exchange the analysis model, Karamba3D runs within the Grasshopper environment and thereby achieves a high level of interoperability and near instant feedback of results from the analysis.

3.5 SOFTWARE FOR DIFFERENT AAD METHODS

The software used for the different AAD methods can be seen in Figure 9.

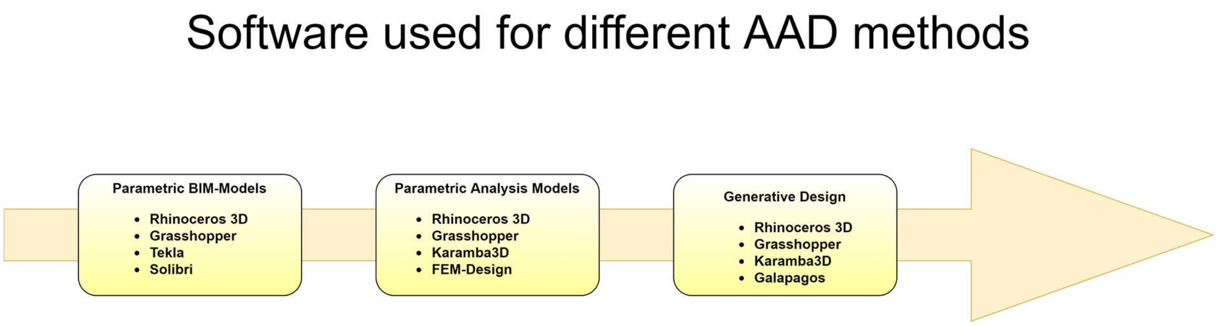


Figure 9 Software used for different AAD methods

4 PARAMETRIC BIM-MODEL

4.1 BACKGROUND

With the advent of new and more powerful technologies, designers and architects are facing lower thresholds when trying to realize increasingly complex structures (Banfi, F. et al. 2017). Structural engineers are often tasked with taking such concepts from an idea to a product which is buildable and structurally sound, while adhering to the initial design. As structural engineers, the final delivery will often be in the form of a highly detailed and information rich 3D-model (Model based delivery), traditional 2D-drawings, or a combination of the two. The purpose of such deliverables is to serve as the reference for the builders at the building site. Naturally, these references need to be of high quality and free of errors. To achieve this, all the aforementioned deliveries are regularly generated in some form of BIM software such as Tekla or Revit (Kovacic, I., & Filzmoser, M. 2014, July). These software' offer easy collaboration between project team members and enables thorough quality control procedures. Consequently, proficiency in such tools is fast becoming a necessity to keep up in an environment where the bar is raised continuously (Russell, D. et al. 2014). As a result, efficient modelling methodologies such as Parametric Design has seen increasing presence in the typical structural engineering workflow. Furthermore, as this methodology is seeing more use, new and inventive workflows are proving to alter the ways structural engineers work on daily basis. With this in mind, the following chapter seeks to investigate cases where Parametric Design has been applied and evaluate how they performed.

4.2 TRADITIONAL MODELLING

Traditionally, BIM-models are entirely made within modelling software such as Tekla or Revit without the use of modelling assistance tools like Grasshopper. Elements are typically placed one by one and their location is only governed by where the user initially placed them. Consequently, modelling large and complex structure is a substantial task. In addition, keeping the model up to date when changes occur is a cumbersome manual process taking up much time.

4.3 PARAMETRIC MODELLING

Parametric modelling make use of scripting and logic to place the elements making up the BIM-model. The location of all elements are therefore governed by programmable logic that the user defines. By having a parametrically defined structure, the model becomes much more customizable. Seeing that changes often occur throughout the project life cycle, having a customizable model could help reduce the time needed to continuously keep the model up to date.

4.4 CASES

In the following chapter this thesis will present real world cases where Parametric Design was deployed. Furthermore, the cases will be evaluated with respect to the hypotheses stated earlier.

4.5 OBJECTIVE

The main objective of this chapter is to investigate a set of case studies where Parametric Design has been applied. Furthermore, these cases will be evaluated on how they performed with regards to certain hypotheses.

4.5.1 Improve customizability

One of the main characteristics of a project is that it is a progressive elaboration(Paul D. Gardiner, 2005) i.e., constantly evolving, and changes occur frequently. As previously described, models are traditionally built element by element, or by duplication. In other words, when changes happen, all effected elements must be moved manually. Consequently, a lot of time is spent on correcting the model after receiving change orders. Furthermore, projects which experience extensive unforeseen problems or changes suffer greatly. As a result, suboptimal solutions might be chosen due to pressing time constraints. By having a structure which is defined parametrically, all elements will have a designated position described by the algorithm. In other words, the model becomes much more customizable. As a result, the project is less prone to delays due to significant changes. Correspondingly, using Parametric Design enables a more iterative modelling environment, and conceptual ideas can be tested without wasting substantial resources.

4.5.2 Increase efficiency

As previously mentioned, traditional modelling commonly places each element manually. When dealing with more complex structures, placing the elements “by-hand” can become very cumbersome. By utilizing certain algorithmic modelling workflows, precise placement becomes trivial and efficiency can be improved. Consequently, a higher quality product can be produced within the same timeframe.

As the construction sector is undergoing extensive digitization (Alaloul, W. S. et al. 2018), more projects will rely on high level BIM environments. To accommodate this, new workflows must be established to efficiently assign the correct information to all objects present in the model. Using certain Parametric Design workflows described in this thesis this process can be automated. If similar automation can be seen is projects in general, it could encourage the industry to change their view of BIM and a higher adoption can be achieved.

4.5.3 Identify modelling task which are suitable for parametric design

In the structural engineering community, there are different perceptions regarding use of Parametric Design (Yanning, M. X. X. 2002), some see it as a tool mainly used by architects and therefore mostly neglect it, while others are eager to apply in all their projects. Either view is likely too pessimistic or optimistic and it will be vital to find common ground to increase future adoption. For the community to advance it will be important to highlight where Parametric Design has been successfully applied, and to what extent it was utilized. Common workflows should be established and constantly improved at least within organizations. By doing so it will ease the journey for newcomers, and drastically lower the barrier to entry. With the outcome of the studied case studies, the perception of parametric modelling will be evaluated among industry professionals in the form of questionnaires.

4.6 BUSSVEIEN

Bussveien is a bus rapid transit system being constructed to connect urban municipalities Sola, Stavanger and Sandnes(ROGFK, 2020). It is the largest project within the portfolio of projects known as “Bymiljøpakken”(ROGFK, 2019) which is a cooperative effort run by Statens vegvesen, Jernbanedirektoratet, Fylkesmannen i Rogaland, Rogaland fylkeskommune, Stavanger kommune, Sandnes kommune, Sola kommune and Randaberg kommune. Their main objective is to improve accessibility for pedestrians, cyclist and public transport. In total 50km of road is being renovated and is due to finish in 2023.

Multiconsult is responsible for the engineering on multiple of the subprojects within Bussveien. In addition, these projects aim to be model based, i.e. deliveries should be in the form of BIM-models with minimal use of 2D-drawings. To accommodate this, new workflows needed to be established some of which utilized Parametric Design. The Following subchapter will describe some projects within Bussveien where Parametric Design was applied, both for modelling and for assigning BIM-information.

4.6.1 Case 1 – Sheet pile structure

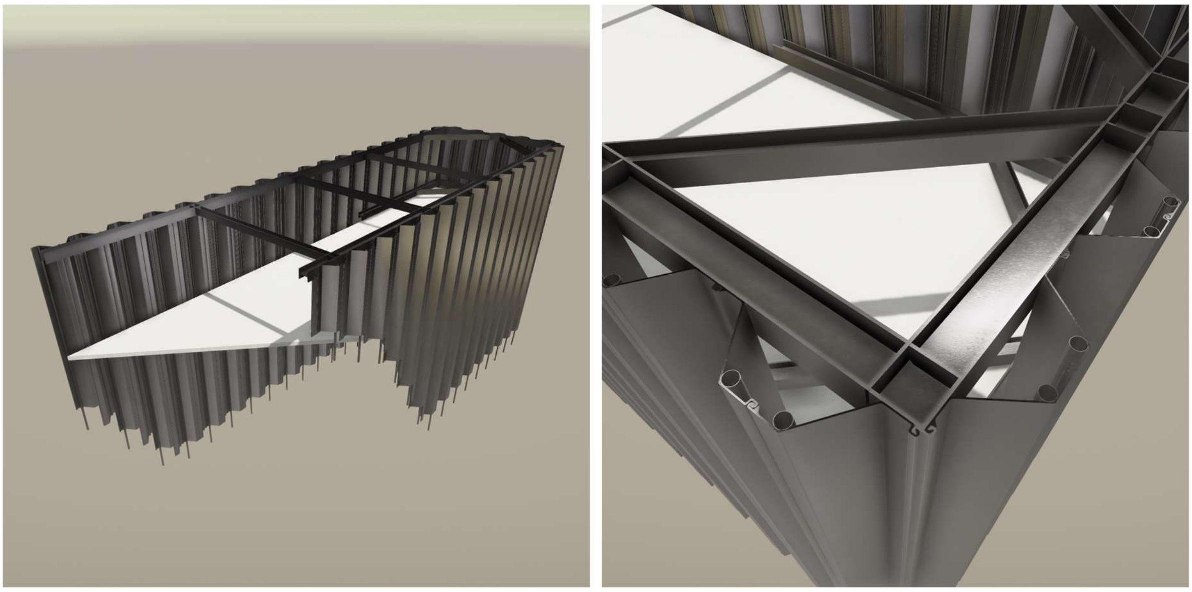


Figure 10 Case 1 - Sheet piling structure

4.6.1.1 Description of project

The task in this project was to place sheet piling structures(Figure 10) at given locations, going from the bedrock to a given height. The locations for the sheet piling were defined by lines, while the presence of the bedrock was represented by a mesh. Both inputs were provided by the geotechnical department by use of the DWG-format. Furthermore, the structural analysis and dimensioning had been done beforehand. In other words, the objective was to place all the structural element. In addition, this project was supposed utilize a high level of BIM. Consequently, a large amount of information was to be attached to each element describing what would normally be presented on drawings. To achieve this, a predefined Excel sheet was constructed which could later be read by the algorithm. This Excel sheet contained all necessary information needed for the different elements. The Excel sheet was set up and structured in a way which made it easy for the algorithm to interpret.

During the project lifetime, the shape of the structure was changed multiple times. Primarily, two different changes were present. The most frequent change was to the overall shape of the structure. Secondly, the Bedrock was updated with regular intervals after the geotechnical surveys was conducted.

4.6.1.2 Description of workflow

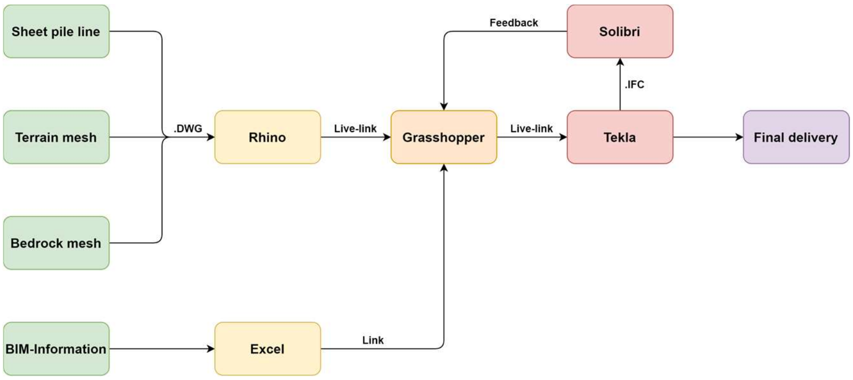


Figure 11 Case 1 - Workflow

To complete this project a workflow was established. As there existed limited experience regarding the particular form of modelling and delivery, the workflow went through multiple iterations. The final workflow is presented in Figure 11.

4.6.1.3 Importing reference material

First all reference material is imported into Rhino. In this case, the line describing the location of the sheet pile and the mesh describing the bedrock was needed as can be seen in Figure 12.

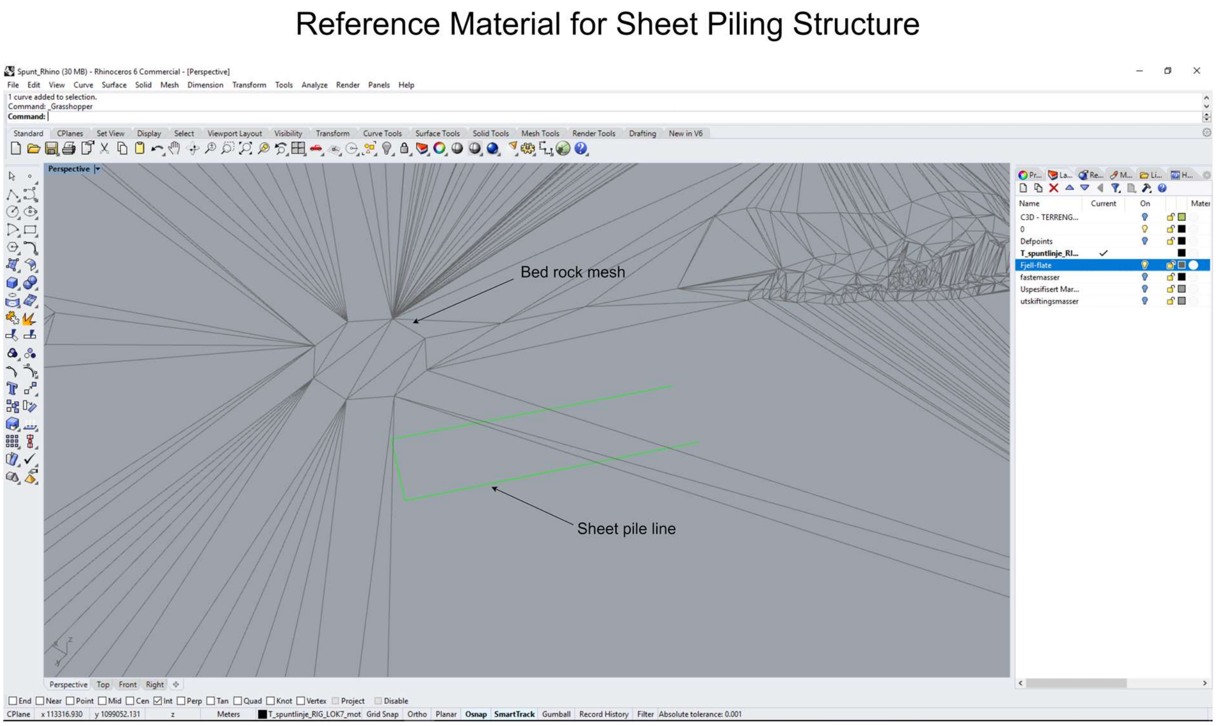


Figure 12 Case 1 - Reference Material

4.6.1.4 BIM-information

The amount of information needed in this model was quite extensive, any question that could arise at the building site which was not visible in the model should be addressed as a note within the element properties. As an example, much of the information that typically would appear on 2D-Drawings needed to be present. Assigning all individual elements manually could be done but integrating a pre-existing workflow developed in the company, this process could be automated. To enable this automation a excel sheet with all necessary information was constructed. With the use of Grasshopper this information could then be accessed by the algorithm. As a result, the algorithm could assign information to all elements present in the model.

4.6.1.5 Developing the algorithm

The majority of the time was spent developing and tweaking the algorithm. The algorithm takes all needed reference material as input, then process it, and finally “prints” the model to Tekla as an output. Developing the algorithm was an iterative process, along the project life it was continuously optimized when new and better solutions were discovered. Finally, the following procedure was developed.

First the reference material is gathered using the mesh and curve nodes, then the sheet pile line is sectioned into 630mm long segments which is the width of one sheet pile profile AZ16-630. Then the height from the given top level (contour 12) to the bedrock is measured and stored. Each vector describing the direction of each segment is compared to the global y-axis to determine the rotation of each individual sheet pile profile. Now all parameters for placing the sheet piles are calculated i.e. position, rotation and height. Simultaneously each sheet pile profile has an attached rock dowel to anchor it in place at the bottom. The location for both the rock dowel and the guiding pipe for placing it is given by the position of their respective sheet pile profile and are offset by their local coordinates to end up at the desired location. Furthermore, to stabilize the structure beams were placed along the inside of the sheet pile profiles and bracings at regular intervals. The locations of these beams were gathered from offsetting the sheet pile line to coincide with the inside of the sheet pile profiles. Lastly, placements for the bracing were determined by placing points at said lines with a predetermined distance of 6m apart. At contour 10 a concrete slab was to be placed. As seen in Figure 13 the top level as well as the sheet profile width could be controlled by sliders, while the sheet pile line, bedrock mesh and terrain mesh was imported from Rhino.

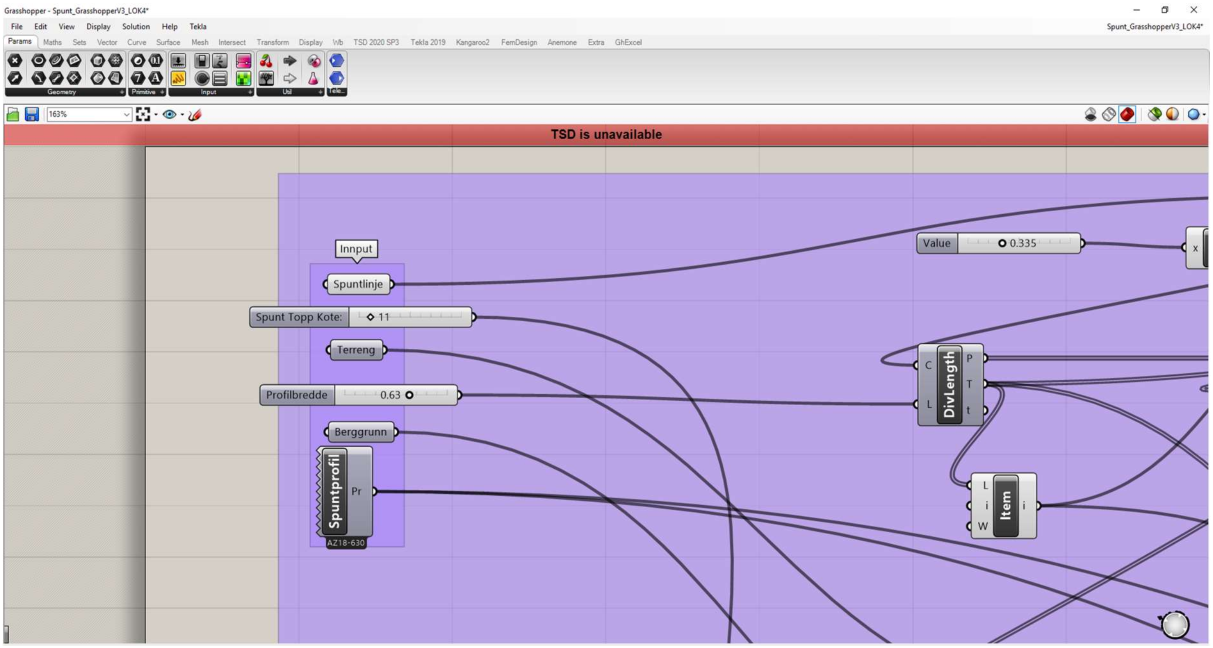


Figure 13 Case 1 - Inputs

4.6.1.6 Printing and exporting the model

Through the Tekla live-link, components in Grasshopper enables the algorithm to print the geometry defined in the script to Tekla. These components convert the geometry defined in the script to elements within Tekla with given cross-sectional properties, as well as all BIM information gathered from the Excel sheet. Following this operation, the model could be exported to the industry standard model format known as IFC. An illustration of how the structured appeared in Tekla can be seen in Figure 14.

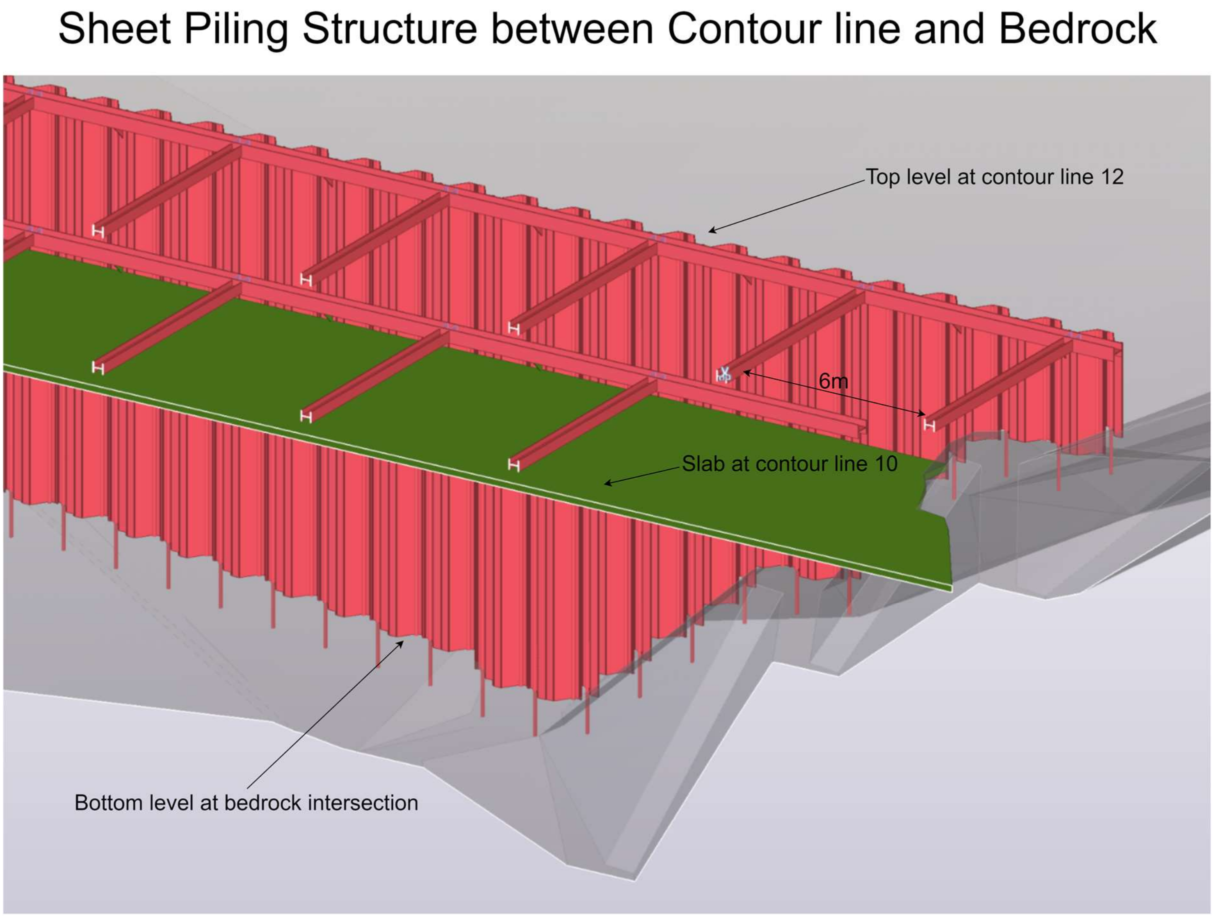


Figure 14 Case 1 - Model in Tekla

4.6.1.7 Quality control and feedback

To assure quality standards were met, quality controll procedures were done using Solibri. Solibri imports the IFC of the model generated in Tekla and is evaluated according quality control routines. Subsecently, feedback from said evaluation was then intergrated back in the algorithm. The algorithm was then improved to fix the shortcomings, and a new model was generated. This process repeated until the model was free of errors and at met quality standards. The final model was then approved for final delivery.

4.6.2 Case 2 – Noise barrier

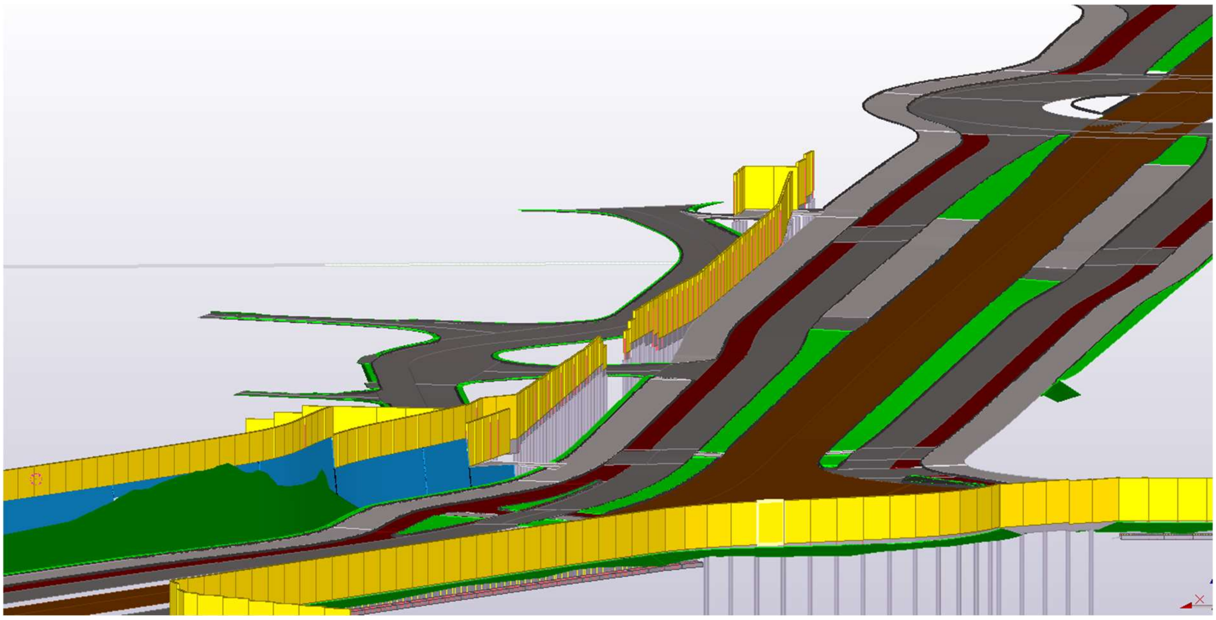


Figure 15 Case 2 - Noise barrier

4.6.2.1 Description of project

Along the renovated road, barriers are being put up(Figure 15) to shelter the neighbors from the sounds generated by the ongoing traffic. The height of the barriers is given by the acoustic engineers and was represented by lines. Together with the lines defining the top of the barrier, the terrain was also given as a mesh. These were imported into Rhino which enabled the script made in Grasshopper to place the barriers between the given reference geometry. In total roughly 700m of noise barriers should be modeled with varying height, width and shape.

4.6.2.2 Description of workflow

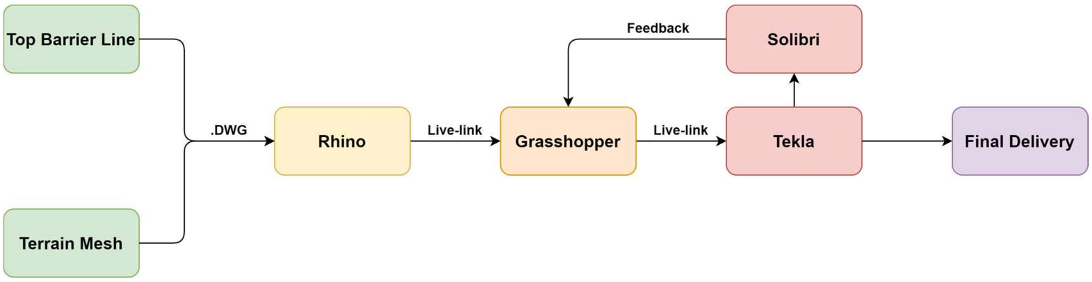


Figure 16 Case 2 - Workflow

Modelling the noise barrier followed a workflow similar to case 1 and can be seen in Figure 16. After importing the top barrier line and terrain mesh it is integrated into the Grasshoppper script. The script was set up such that it first divided the top barrier line into sections of given length 2m. This length is the total width of one noise barrier module. The height of all given modules were determined by the height from of their respective top line to the terrain mesh. At the bottom of every noise barrier module, concrete foundation blocks were placed. Every 2m, steel columns were placed together with foundation poles going into the soil.

4.6.3 Case 3 – Trellis wall

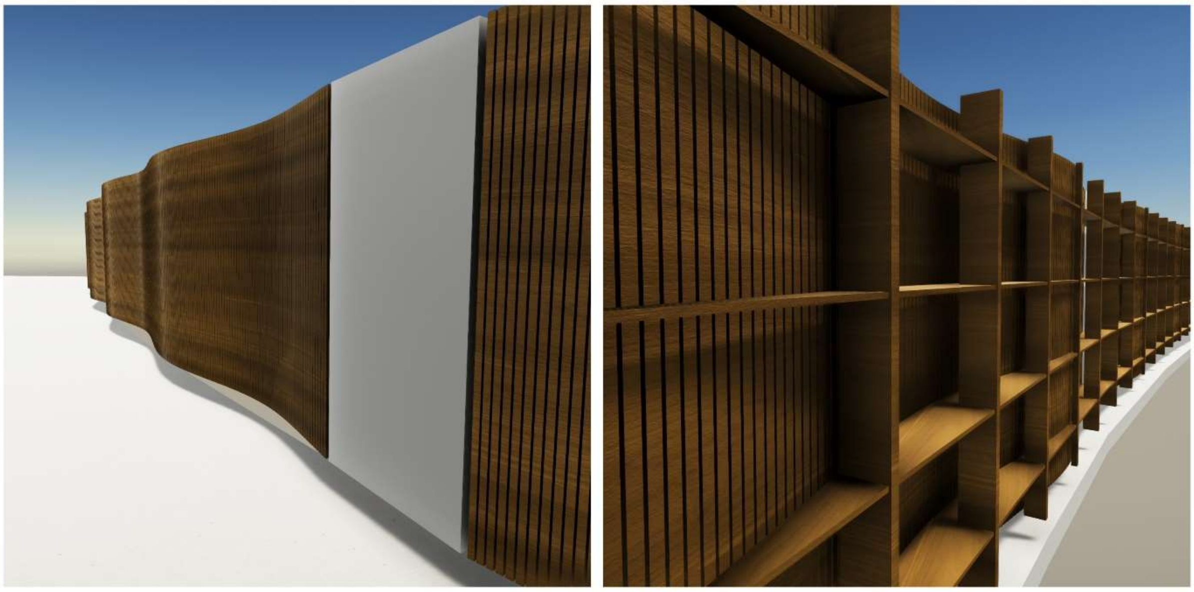


Figure 17 Case 3 - Trellis wall

4.6.3.1 Description of project

In an underground passageway, architects had envisioned wooden trellis along the walls. Not only should they follow the curved nature of the walls, but an additional sinusoidal displacement was also introduced as can be seen in Figure 17.

4.6.3.2 Description of workflow

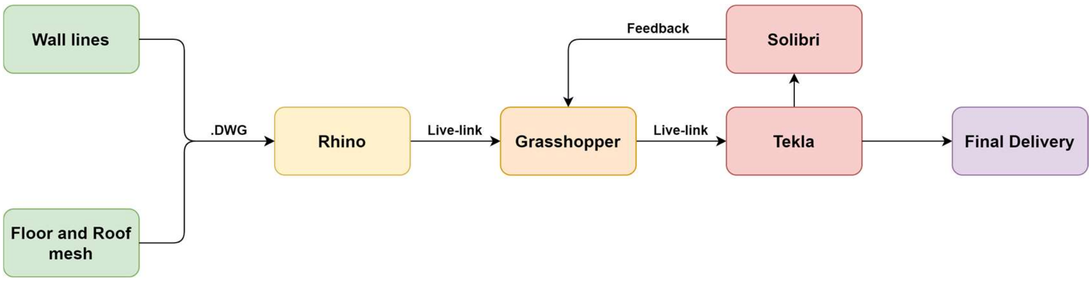


Figure 18 Case 3 - Workflow

To produce the model for the trellis wall, Parametric Design was used following the procedure described in Figure 18. In this case, the necessary reference material was the lines describing the walls of the passageway, as well as two mesh representing the roof and floor. They served as foundation for the script which was developed in Grasshopper. The scripts interprets the wall line, offset it to a set amount and introduces a sinusoidal displacement. This line is then divided up with set intervals for determining the points where each trellis should be placed. To determine the height of each trellis, the distance from each of the aforementioned points and the closest position of the roof/floor is measured and stored. A line going through these points is created and shortened so the trellis does not touch the roof or floor. The wooden beams mounting the trellis structure to wall got their position form dividing the wall lines at given distance. Lastly, the plates connecting the trellis to the mounting beams were defined by finding the perimeter described by the sinusoidal curve and the wall line. Furthermore, this perimeter was offset three times to get the location for all four plate levels.

After the script had been defined the model was printed to Tekla, where the model was exported as an IFC. Furthermore, quality control routines were done in Solibri and feedback was given to the engineers.

4.6.4 Case 4 – Drywall:

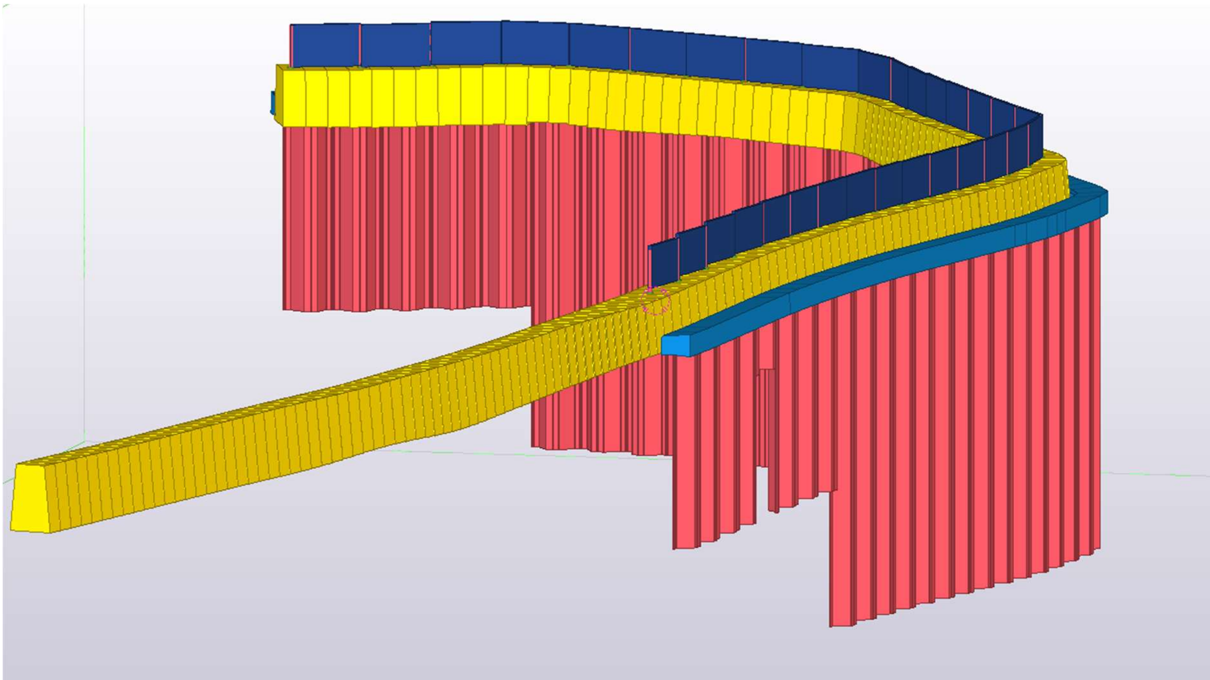


Figure 19 Case 4 - Drywall beside sheet piling structure

4.6.4.1 Description of project

In this project a rock drywall was put up beside a sheet piling structure (Figure 19). On parts of the drywall, a wooden fence was placed. To anchor the fence to the drywall, steel poles were put at 2m intervals.The reference provided for modelling this structure was a mesh of the pre-existing drywall as well as the top beam from the sheet piling structure. Much like the sheet pile structure mentioned Case 1 the delivery of this project was supposed to be model based. BIM-information was added to the different elements following the same procedure, with a pre-defined excel sheet which was then read by the script.

4.6.4.2 Description of workflow

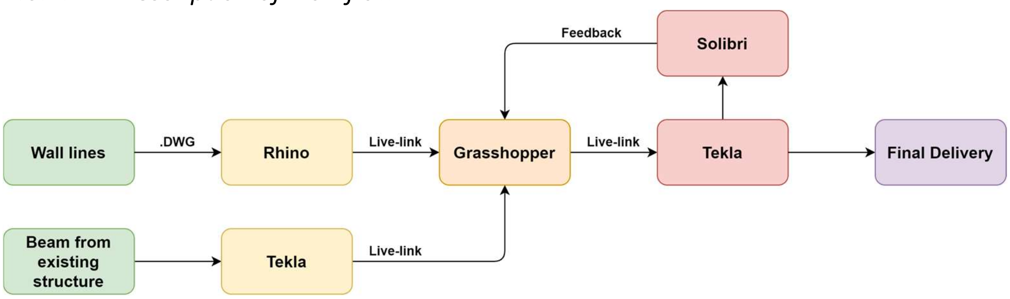


Figure 20 Case 4 - Workflow

The procedure that was followed to complete this project is described in Figure 20. First the mesh describing the terrain and existing drywall was imported into Rhino. Then the top beam from the nearby sheet piling structure was Imported through the Tekla-Grasshopper live link. Furthermore, these references served as foundation for the logic defined in the grasshopper script. The script generated a guiding line for the drywall using the existing drywall-mesh and the top beam. Afterwards, this line was divided at regular intervals where points were generated. The distance from these points to the terrain surface was measured and stored. This data was then used to determine the placement of the drywall profiles. For the drywall to be properly constrained, it was extended 0.5m under the terrain. As the distance from the top of the drywall to the terrain varied, the profile of the drywall also needed to change with it. In addition, near the existing sheet pile structure point were placed on the guiding line 2m apart to determine the position of the fence and poles. Finally, all elements were printed to Tekla. Quality control procedures were done in Solibri, feedback was then taken into account by altering the script and generating new models. This procedure continued until the model was free of errors and met quality standards.

4.7 KLEPP AKTIVITETSPARK

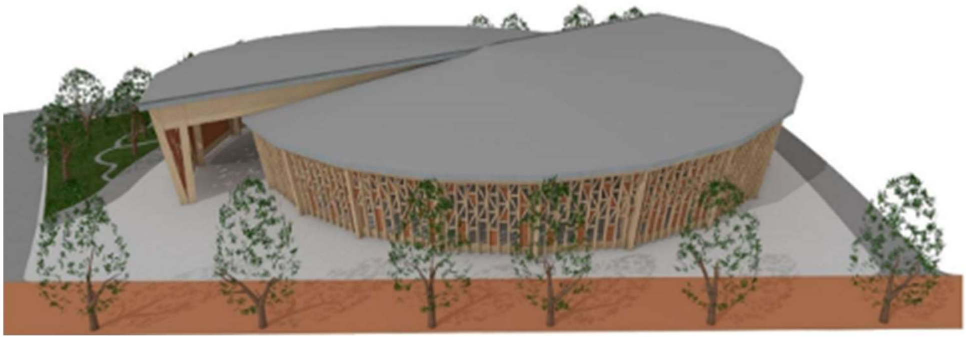


Figure 21 Case 5 - Klepp Aktivitetspark Render

Klepp municipality is in the process of planning a new park area known as aktivitetsparken(Figure 21). Within this park, a structure to shelter a skating arena is to be constructed. Multiconsult is responsible for the engineering of this structure which is called Klepp Paviljong.

4.7.1 Case 5 – Complex timber roof structure

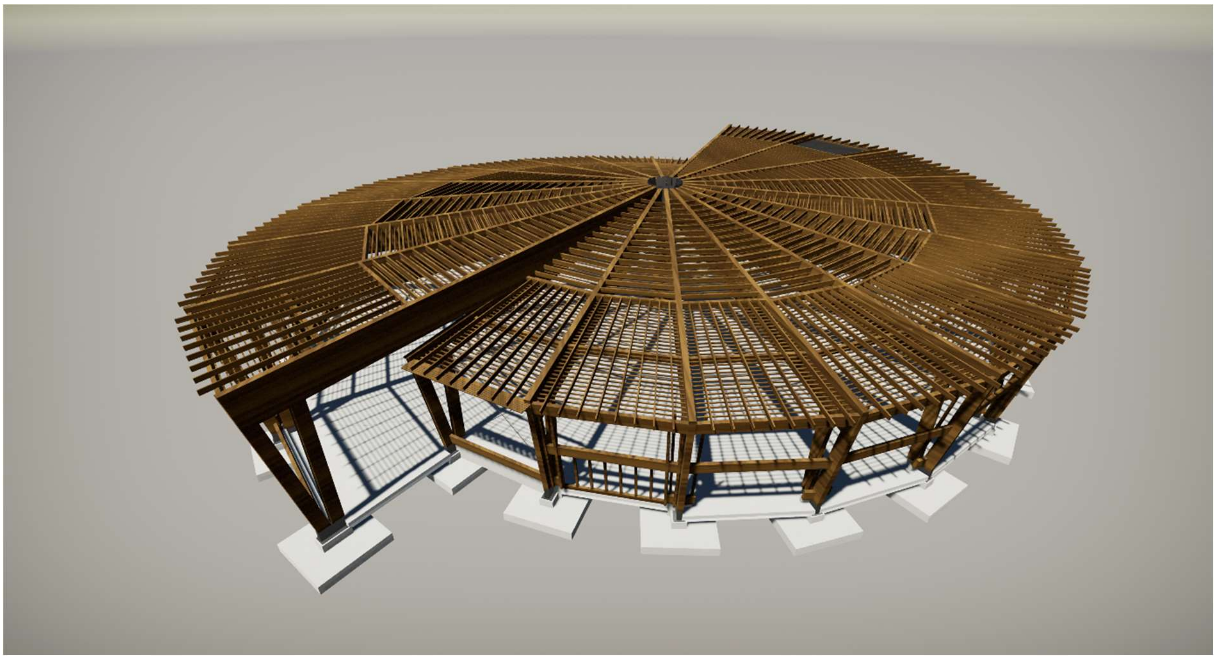


Figure 22 Case 5 - Complex timbre roof structure

4.7.1.1 Description of project

In this project, the main structure had been done using traditional modelling methods, however the elements making up the majority of the roof structure remained (Figure 22). After some experimentation, it was decided that the remaining part of the roof should be done using Parametric Design. The roof structure is made up of 22 triangle shaped section. All the sections are of varying size and slope. Each section consists of load bearing beams, acoustic plates, and wooden trellis. All these elements needed to follow the slope of the given section and placed at the predefined position. In total 3000 individual elements needed to be placed. Consequently, completing the modelling of the roof structure by traditional methods would be a cumbersome and time-consuming task. By use of

Parametric Design the logic for the location of each element was defined once, and then looped over each section to automatically print all elements in one go.

4.7.1.2 Description of workflow

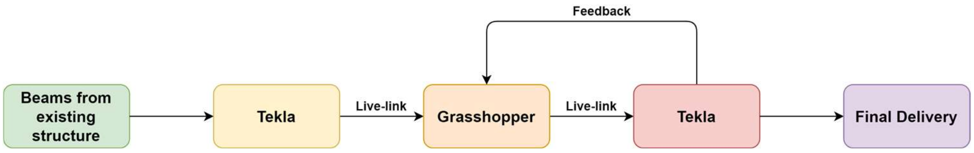


Figure 23 Case 5 - Workflow

In contrast to the sheet pile structure, the reference for placing all element were not imported from DWG files. Instead, the necessary reference geometry was obtained from the existing model. The geometry which served as foundation for placements of the remaining roof structure was the main load bearing beams. These beams were imported using the Tekla to Grasshopper live-link. Afterwards the reference lines for the beams were extracted using built in functions in Grasshopper. The logic for placing the roof element were then defined as an algorithm in Grasshopper. Finally, the elements were printed in Tekla. Quality control was done within the Tekla environment and after getting feedback, adjustments was made to the algorithm, and a new model was generated. This process went on until the model was free of errors and met quality standards. Finally, the model was exported and sent for final delivery. The Workflow is illustrated in Figure 23.

4.7.1.3 Importing reference material

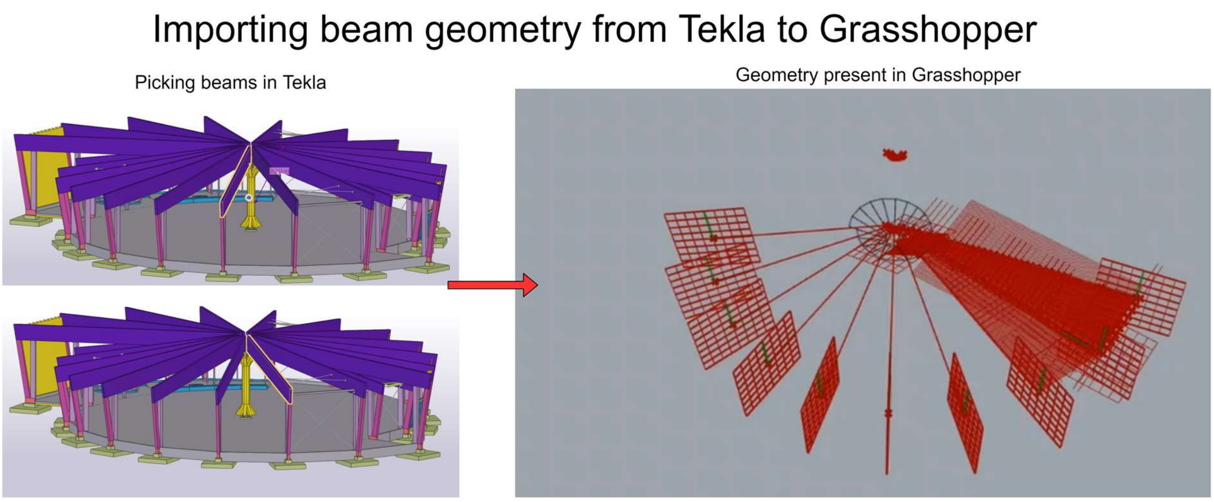


Figure 24 Case 5 - Importing beam geometry from Tekla to Grasshopper

To gather enough information for the algorithm to place the roof elements, the geometry of all the main beams were imported into Grasshopper as seen in Figure 24.

4.7.1.4 Developing the algorithm

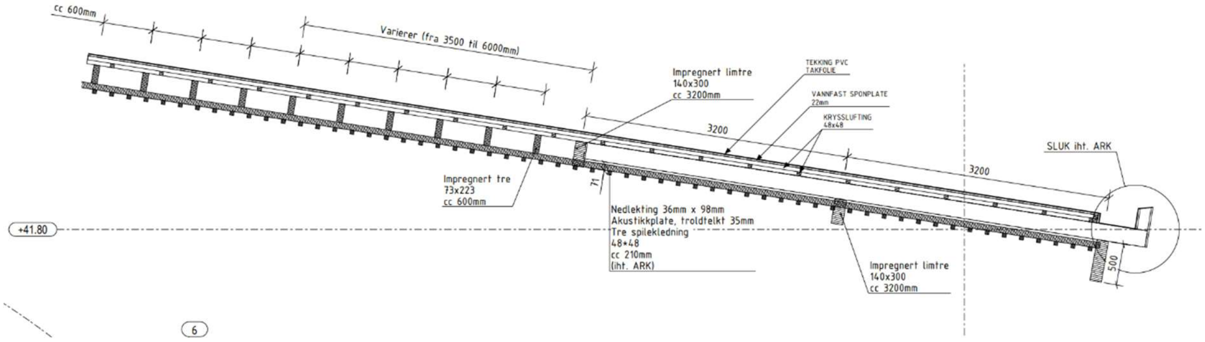


Figure 25 Case 5 - Architectural drawing of roof section

Following the design proposed by the architect(Figure 25), the script for placing the roof element were constructed. For each section, the respective left and right main beam served as foundation. They described the plane which all elements within that section needed to follow to maintain the curvature of the roof. In addition, all elements were also rotated to match the slope of the section. In general, each section contained one 98x498mm beam at the end, two 140x300mm beams placed 3.2m and 6.2m from the end, respectively. In addition, placed after the 140x300mm beam, 73x223 beams were placed with center-to-center distance of 600mm. These were to fill the remaining part of the section, going towards the middle. The amount of 73x223 beams would depend on the size of the given section. The same logic was utilized when placing the wooden trellis 48x48mm which were place from the start to end of each section with center-to-center distance of 210mm. Finally, an acoustic plate was placed filling up the entirety of the section. This logic was only defined once, and then run on each section individually. In total, 3103 elements were placed.

4.7.1.5 Printing and exporting the model

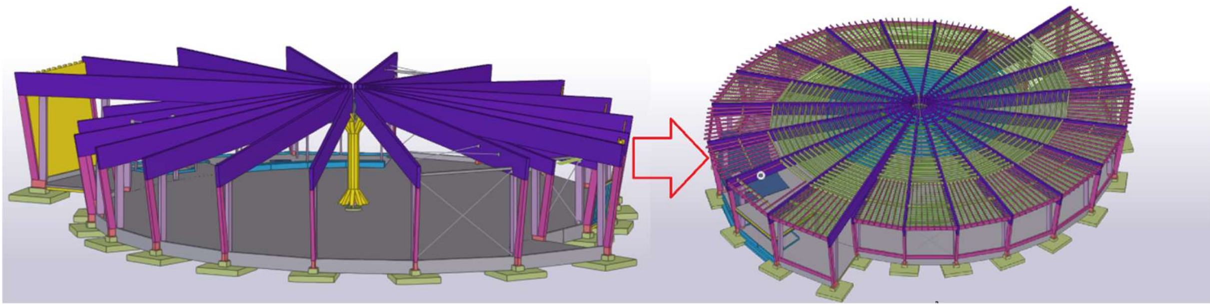


Figure 26 Case 5 - Roof elements printed to Tekla

Through the Tekla-live-link, Grasshopper printed all roof elements to Tekla as seen in Figure 26. In addition, all elements were also cut to match the structured they were mounted on. This meant that there was limited refinement needed to clean up the model before undergoing quality control checks. Cutting and adjusting elements within a model is done regularly in all projects, seeing the complex geometry and vast number of elements contained in the roof structure, automating these actions meant that the modelling process was greatly accelerated.

5 PARAMETRIC ANALYSIS MODEL

5.1 BACKGROUND

Structural engineers regularly use FEA tools to evaluate the structural integrity of structures. To be able to do so, analytical models must be generated. In much the same fashion as building BIM-models, analytical models are typically built manually. In addition, although many FEA software offer geometry import solutions from BIM software, these have proven to inherit instabilities such as discontinuities between structural members unless the BIM-model has been built following strict guidelines. Consequently, this has been viewed as being too cumbersome and as a results the BIM and analytical model has commonly been generated separately, effectively doing the work twice.

5.2 TRADITIONAL METHOD

Typically, the analytical model is built up piece by piece. First the overall geometry of the model is modelled. While doing so, each individual member also need to be assigned a cross-section, material and end-conditions. Then the load cases are defined and the loads are applied. Furthermore, the load groups are set and the load combinations are generated. Subsequently the structural analysis can executed and calculation reports can be generated.

5.3 PARAMETRIC ANALYSIS MODEL

In comparison the traditional method, parametric analysis modelling automates many or all of the steps in the traditional method by defining the logic in a in a script. By doing so, the model becomes more customizable i.e. easy to change if necessary. In addition, by having the analysis model defined parametrically, new and innovative design capabilities like Generative Design are enabled, such capabilities will be explored in a later chapter in this thesis.

5.4 Case 6 – Ecofisk – FEM-Design

Figure 27 Case 6 - Ecofisk Render

5.4.1 Case description

Ecofisk is a land-based fish farm being planned in Tysvær which consist of several different sized halls containing the aquacultural equipment. To determine the sizing of the structural members making up these halls, a set input parameters were given. To transfer the loads from the roof to the columns, trusses span the width of each hall. The trusses are chosen depending on load and span in a catalogue of premade trusses made by manufacturer Maku (http://www.maku.se/default.asp?ID=SADELFACKVERK&sLang=nb-no). In other words, the design of the truss was not needed to be done in this case. However, the weight of each of the different trusses was needed to emulate the actual loadings on the columns.

5.4.2 Workflow

To generate the analytical models the following workflow was followed. First the input parameter are set, then through the logic programmed in the script the geometry is generated. Furthermore, this geometry is transferred to FEM-Design together with the loads described by the inputs. In FEM-Design, the model is evaluated through FEA to check if the structural members are sufficient to carry the loads. If not, FEM-Design can be used to find better suited structural members. Finally, the necessary design documentation can be generated.

5.4.3 Input

The inputs has been categorized into being either static or variable e.g. if a input is static, it will remain the same in all cases. On the other hand, if it is variable, it will differ on a case by case basis.

Static input

To represent the weight of the roof and solar panel a distributed surface load was applied, it had already been estimated that the weight of the roof was 0.4 kN/m^2 and solar panels 0.6 kN/m^2. In addition, the snow load was calculated to be 1.6 kN/m^2. Furthermore, the distance between the columns were set to be 6m.

Variable input

For each individual hall the self-weight of the truss is gathered and set as input to the script. Furthermore, the width, height and length of each hall needed to be set. Finally, the directions which each hall was exposed to wind needed to be defined. Lastly, the cross-section of the columns were chosen.

5.4.4 Algorithm

After the input parameters has been set the algorithm is set in motion, it first takes the overall dimensions given in the inputs and generates geometry, secondly it reads which of the directions that are exposed to wind. This information is used to generate the location and height of each of the columns. The cross-section of the columns is selected from a list of predefined profiles, typically, the columns exposed to wind loads shared a common cross-section while the inner columns was given an alternative profile. The bottom points of the column lines are used to find the location for the supports and, the top points on the other hand is used to define lines spanning the width of the halls where the trusses would be present. These lines are then used to place fictitious bar elements that represent the trusses inside the analysis model. In addition, using these lines, line loads are applied on each of the fictitious bars emulating the self-weight of each truss. Furthermore, surfaces are generated from the boundary of the roof and walls which have been defined as exposed to wind. These surfaces are then used to generate covers which is a FEM-Design element used to distribute uniform loads on beam and column members. On the roof cover, the self weight of the roof and snow load is applied with the correct load case and duration class assigned. Lastly, the lines making up the boundary of the roof are used to model beam elements with a predefined cross-section. At this point, the algorithm ends and the model can be printed to FEM-Design.

5.4.5 Printing the model

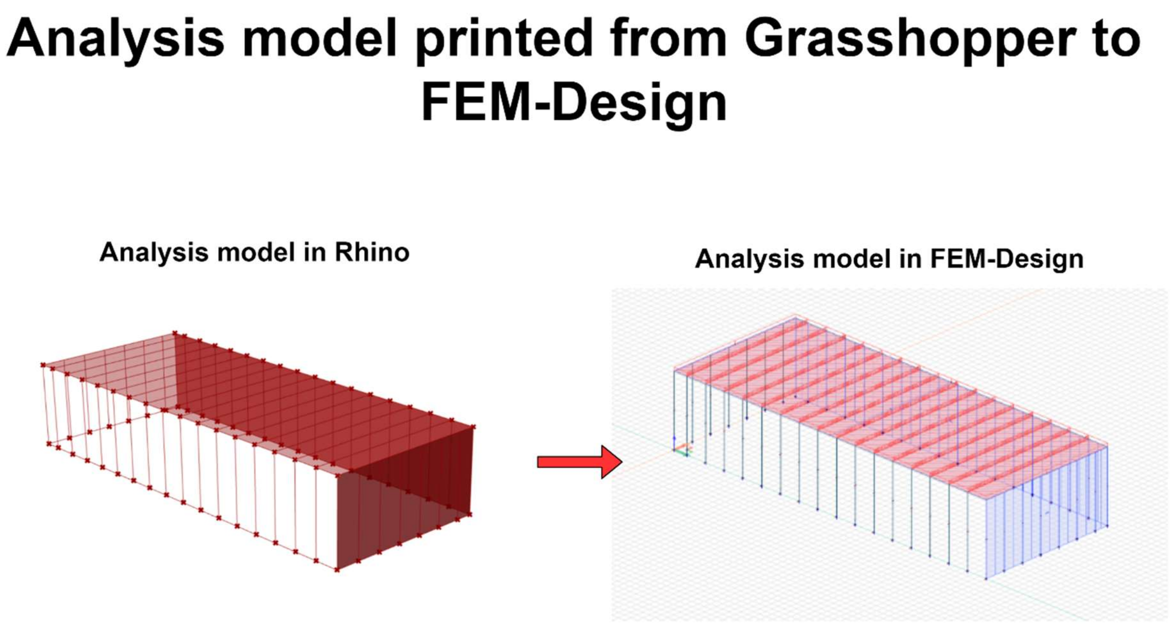


Figure 28 Case 6 - Analysis model printed from Grasshopper to FEM-Design

With the use of the FEM-Design plug-in, geometry, loads and load cases were sent and auto-generated inside FEM-Design as can be seen in Figure 28. All load except the wind load, as of now, the wind load generator tool that is available inside FEM-Design does not exist within their Grasshopper plug-in.

However, since the covers are modelled it is only a matter of selecting the wind exposed surfaces and the wind loads can be inserted with minimal effort.

5.5 Case 7 – Truss – Karamba3D

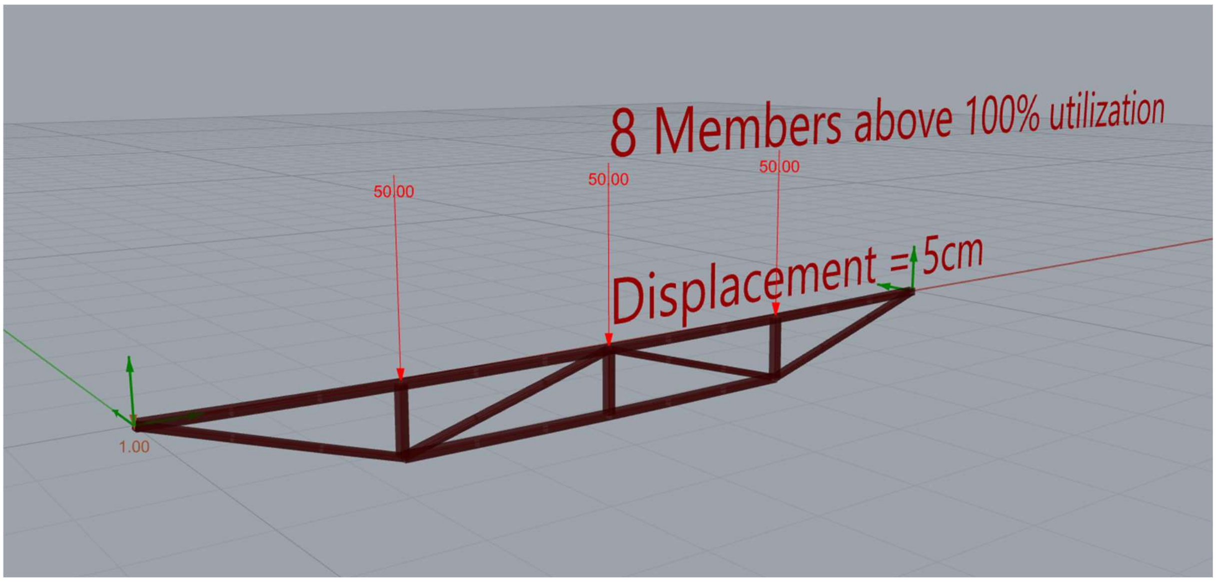


Figure 29 Case 7 - Truss

5.5.1 Case description

To explore the capabilities of Karamba3D, a script was made for generating a simple truss exposed to a set of point loads as well as its self-weight(Figure 29). The goal was to set up the script in such a way that it could easily be used for many different scenarios by being able to quickly alter the dimension and cross-sections of the structural members.

5.5.2 Input

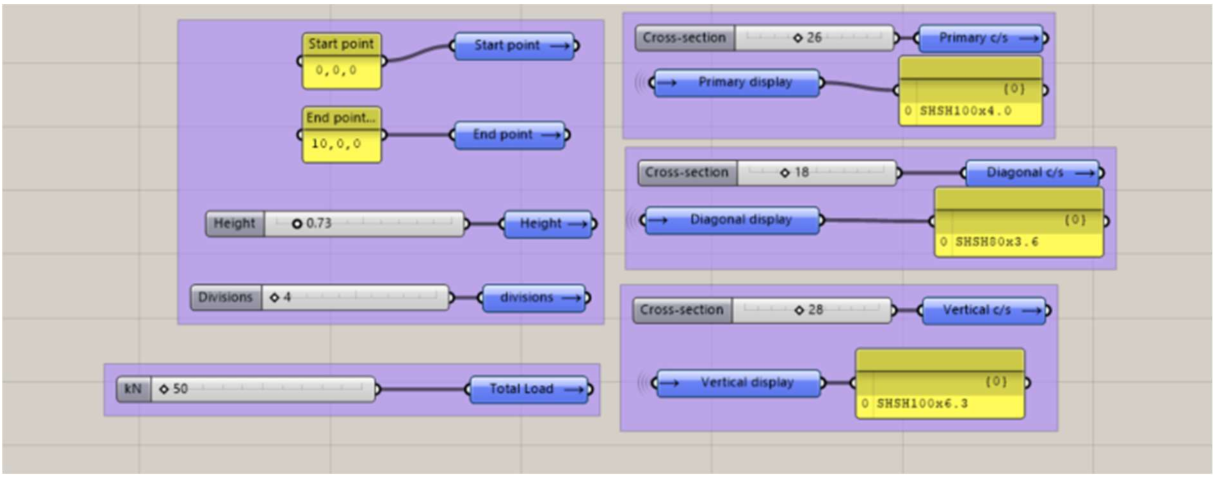


Figure 30 Case 7 - Inputs

To customize the truss the user can alter values of several parameters. The length of the truss is governed by start and end points, furthermore, the height and number of divisions can be changed. In addition, the cross-section for the diagonal, vertical and primary structural members can be chosen from a set of different steel profiles. Lastly, the total load applied to the truss is chosen. The inputs as seen in Grasshopper can be viewed in Figure 30.

5.5.3 Algorithm

After setting all variables, the algorithms draws line from the start and end point this line is subsequently offset in negative z-direction with the value found in the height parameter. These two lines are then fed into a truss generator that takes top and bottom line together with number of divisions to generate the geometry of a truss. The lines making up the truss is sent to karamba3D beam element nodes which also gathers information from the cross-section variable set before the start of the algorithm. The top point where the diagonals intersect the primary members are also gathered and used to place the point loads. The first and last point at the support is discarded and the variable controlling the total load applied to the truss is first divided depending on the amount of remaining points. This value is then set as the magnitude for the point loads on the remaining points. Supports are also placed at start and end points. Furthermore, all of this data is fed into the Karamba assembly and analyzed using Finite Element Method. This is done in real time and as a result the outcome of the analysis can be viewed instantly. The measured displacement and utilization of the members are displaced in the viewport in rhino.

6 GENERATIVE DESIGN OF STRUCTURES

6.1 BACKGROUND

The previous part of this thesis has thoroughly described the benefits of having an algorithmically defined structure with regards to building BIM and analysis models. However, by having an algorithmically defined structure, additional benefits are enabled. Seeing that the position of all elements are governed by the logic described by the script, optimization algorithms can be deployed which in turn can manipulate the geometry to achieve certain objectives. One goal structural engineers have is to optimize the structure in terms of the amount of material needed while maintaining the structural integrity of the building. To evaluate structures, structural engineers commonly use FEM-analyses software. In other words, for the optimization algorithm to properly asses each iteration of the structure, FEM-analyses needs to be incorporated into the automated workflow. With the use of previously described Grasshopper plug-in Karamba3D, such capabilities are enabled. With the power of Grasshopper, Karamba3D and optimization algorithms such as Simulated Annealing and Evolutionary Solver, structural engineers can let the algorithms turn out solutions in the preliminary design phase. Furthermore, being able to deploy algorithms which can aid in the finding of optimal solutions can provide significant yields both in terms of the overall price of the structure, as well as the time-savings related to the preliminary design phase. Subsequently, having integrated structural analysis within the parametric modelling routine will enables high levels if interoperability between the BIM-model and analysis model.

6.2 TRADITIONAL METHODS

Traditionally, optimizing structures is done iteratively, with a more trial-and-error approach. Obviously, an experienced engineer will have through his previous projects found solutions to problems that might strike resemblance to the task at hand. Their previous experience will then serve as a foundation for how to proceed in the pursuit of solving said task. This approach is tried and proven and with the collective experience of the project team will reliably produce adequate results. However, past solutions does not necessarily mean that it is the most optimal way of solving the particular problem. In addition, it is next to impossible to rule out biases based on past experiences. Consequently, the exploration of other and possibly superior alternatives might be neglected on the sole base that a deemed preferred solution has already been used.

6.3 OBJECTIVE

Through case studies, this chapter aims to illustrate workflows structural engineers might adopt in the future. Although the applications shown are limited, the fundamental purpose is to highlight the possibilities that exist in the employment of optimization algorithms in structural design. Finally, a general workflow will be suggested that describe how to attack a problem, with the aforementioned algorithms.

6.4 CASES

To study the potential of structural optimization algorithms a set of cases has been constructed. These cases was developed with input and guidance from industry professionals and stem from real cases they have experienced in their work.

6.4.1 Template

To study these cases a template of has been established, this template describes the problem and the workflow followed to solve it(Figure 31).

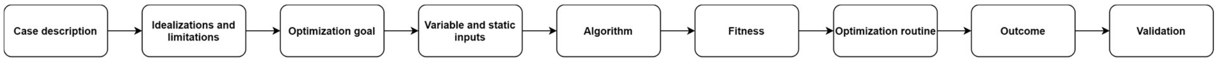


Figure 31 Generative Design of Structures - Template flowchart

Case description:

Brief description of the problem at hand which includes an explanation of the structure, why the problem is suitable for optimization.

Idealizations and limitations

Commonly, structural engineers idealize the structure when performing the structural analysis, the case specific idealizations that has been made in addition to the limitations of the procedure will be described here.

Optimization goal

Describe the wanted outcome of the optimization.

Variable and static inputs

To optimize a structure the algorithm needs a set of inputs. Furthermore, these inputs have been segregated into either static or variable. The static inputs are parameters that remains unaltered through optimization process effectively functioning as the constraints to the given problem. The variable inputs however, are the parameters the optimization algorithm can alter in the pursuit of finding the most optimal solution. Which inputs are static and variable will depend on the optimization goal and are therefore case specific.

Algorithm

In short terms elaborate on the workings of the algorithm.

Fitness

The performance of the structure will be a sum of parameters deemed important for the value of the given iteration. Parameters such as passing the preliminary SLS check as well as the total weight of the structures are examples of ways to measure the performance of the iteration.

Optimization routine

Describe how the optimization routine is set up.

Outcome

After the algorithm has run its course, the best solution with its accompanying genes and fitness is presented.

Validation

To validate the result, stand-alone FEA software such as FEM-Design are used. The top solution proposed by the optimization algorithm will be exported through automated workflows enabled in Grasshopper and more thorough analyses can be undertaken.

6.5 CASE 8 – STRUCTURAL OPTIMIZATION OF 65M STEEL TRUSS WITH RESPECT TO SELF-WEIGHT

6.5.1 Case description

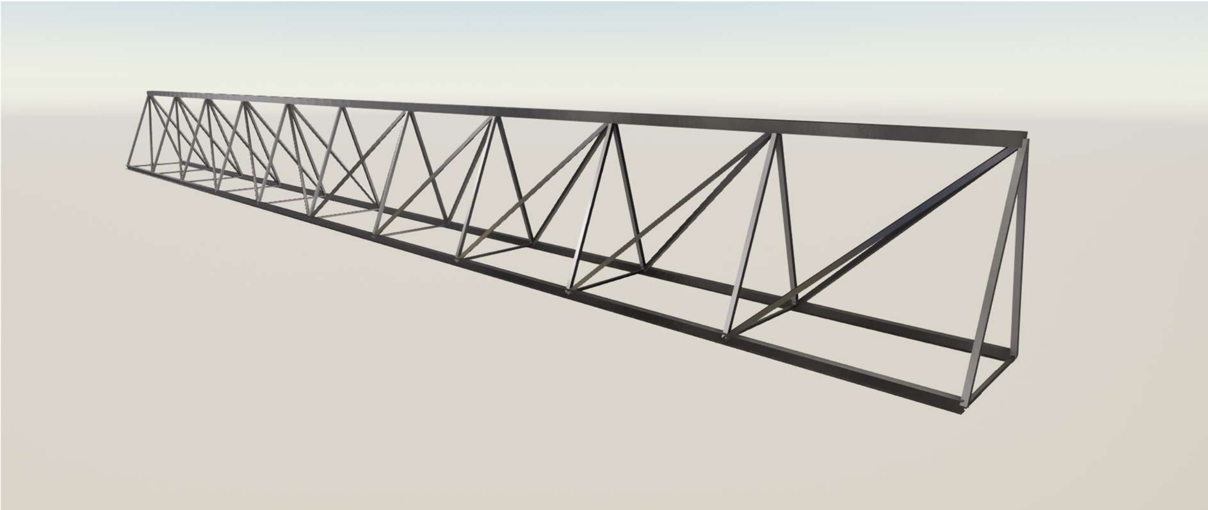


Figure 32 Case 8 - Truss Render

In this case, a structure being built demanded a specially built truss spanning a gap of 65m. The truss can be seen in Figure 32.

6.5.2 Idealizations and limitations

Only one load combination is included, the top and bottom chords have continuous cross-sections. i.e. will have same cross-section for the entire span. The middle web members all have same cross-section. Only one load combination is used during the optimization(SLS). Exactly how Karamba3D goes about selecting the optimal cross-sections is somewhat of a black box.

6.5.3 Optimization goal

In this case, the goal of the optimization was to find the lightest structure that still satisfied the constraint of 100mm maximal displacement given the applied loads.

6.5.4 Static inputs

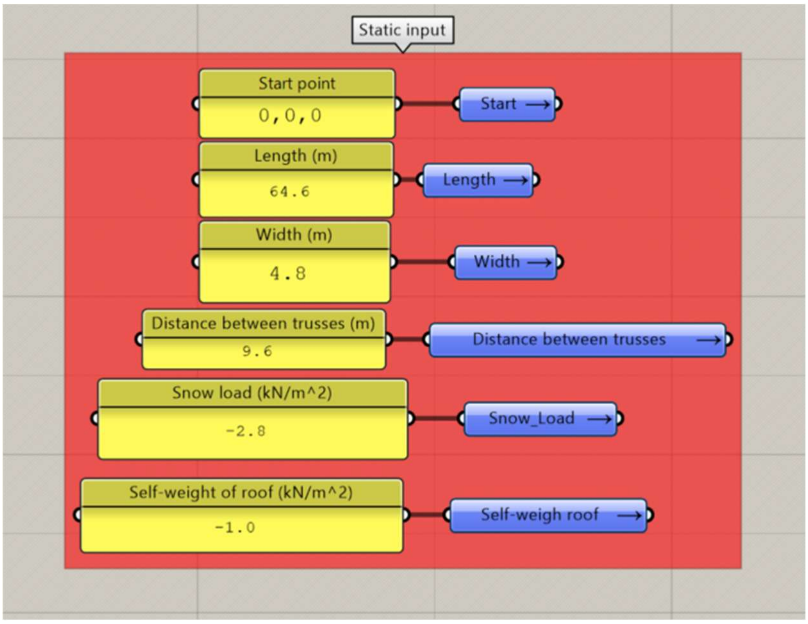


Figure 33 Case 8 - Static inputs

As seen in Figure 33, although these inputs remain static throughout the optimization, they could easily be changed to suit a new and differently sized truss with alternative imposed loads.

6.5.4.1 Geometry

In terms of geometry, the width, length and distance between trusses were given (Table 2).

Table 2 Case 8 - Static input - Geometry

Dimension	**Value**
Length	64.6m
Width	4.8m
Distance between trusses	9.6m

6.5.4.2 Supports

The structure was to be constrained from movement by the following supports(Table 3Table 8).

Table 3 Case 8 - Static input - Supports

Point	**Translation**	**Rotation**
Point 1	X-Direction = Restrained Y-Direction = Restrained Z-Direction = Restrained	X-Axis = Free Y-Axis = Free Z-Axis = Free
Point 2	X-Direction = Restrained Y-Direction = Free Z-Direction = Restrained	X-Axis = Free Y-Axis = Free Z-Axis = Free
Point 3	X-Direction = Free Y-Direction = Free Z-Direction = Restrained	X-Axis = Free Y-Axis = Free Z-Axis = Free
Point 4	X-Direction = Free Y-Direction = Free Z-Direction = Restrained	X-Axis = Free Y-Axis = Free Z-Axis = Free

6.5.4.3 Loading

The truss was to be imposed with loading from both the roof and the snow that could accumulate on it(Table 4).

Table 4 Case 8 – Static input - Loading

Load	**Value**
Snow load	2.8 kN/m^2
Self-weight of roof	1.0 kN/m^2

6.5.4.4 Safety factors

As the SLS criteria of max 100mm displacement will be the governing parameter in designing this truss, the safety factors for SLS(NS-EN 1990:2002+NA:2008) will be used for the load-combination in the optimization routine(Table 5)

Table 5 Case 8 - Static input - Safety factors(NS-EN 1990:2002+NA:2008)

Safety factor	**Value**
γ_G	1.0
γ_Q	1.0

6.5.4.5 Maximum displacement

A maximum value of displacement was also given(Table 6). *Table 6 Case 8 – Static input - Maximum displacement*

Dimension	**Value**
Maximum displacement	100mm

6.5.4.6 Material properties

Material property for the steel used in the truss members(Table 7).

Table 7 Case 8 - Static input - Material properties

Material	**Value**
Steel	S355

6.5.5 Variable inputs

To be able to optimize the structure, the variable inputs need to be defined.

6.5.5.1 Geometry

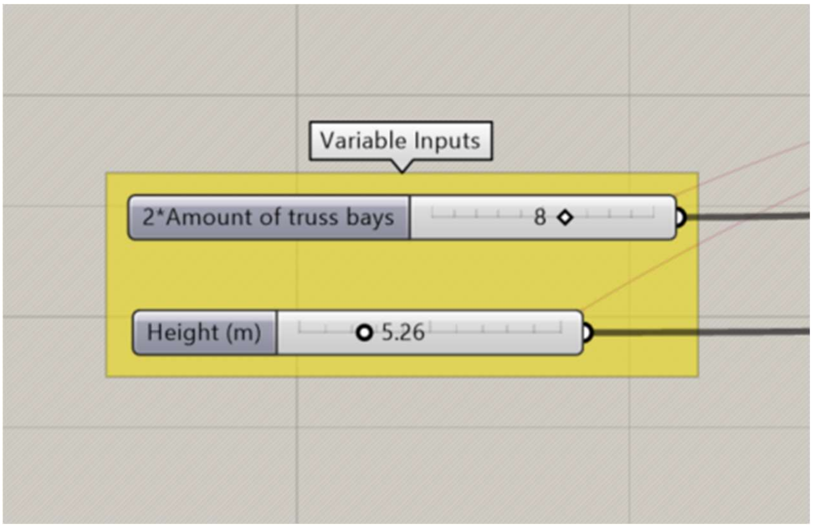


Figure 34 Case 8 – Variable input - Geometry

The algorithm got two genes to alter in order to find the most optimal solution, the total amount of truss bays, and the height of the truss. These can be seen in Figure 34 and Table 8.

Table 8 Case 8 - Variable input - Geometry

Dimensions	**Span of values**
Height	[4.80 , 6.64]m
Amount of truss bays	[10 , 20] Number of bays

6.5.5.2 Cross sections

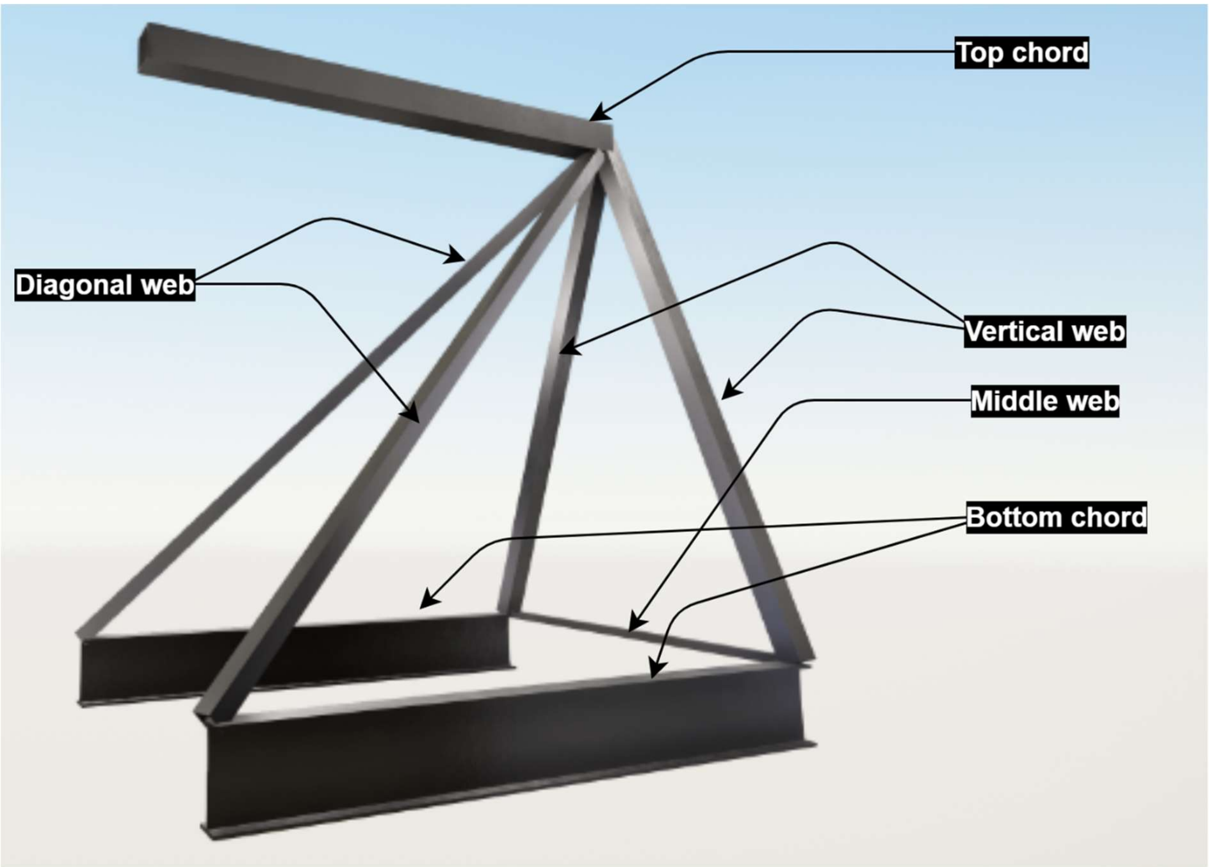


Figure 35 Case 8 – Variable input – Cross sections

To optimize the structure, the algorithm could use a pool of different cross-sections, the diagonal web members, vertical web members, middle web members and top chord could pick from a list of rectangular hollow sections (RHS), while the bottom chord picked from a pool of HEB sections. The different structural members as well as the span of possible cross-sections can be seen in Figure 35 and Table 9.

Table 9 Case 8 – Variable input – Cross sections

Member	**Span of values**
Diagonal web	[RHS20x20x2 , RHS400x400x16]
Vertical web	[RHS20x20x2 , RHS400x400x16]
Middle web	[RHS20x20x2 , RHS400x400x16]
Top chord	[RHS20x20x2 , RHS400x400x16]
Bottom chords	[HEB100 , HEB1000]

6.5.6 Algorithm

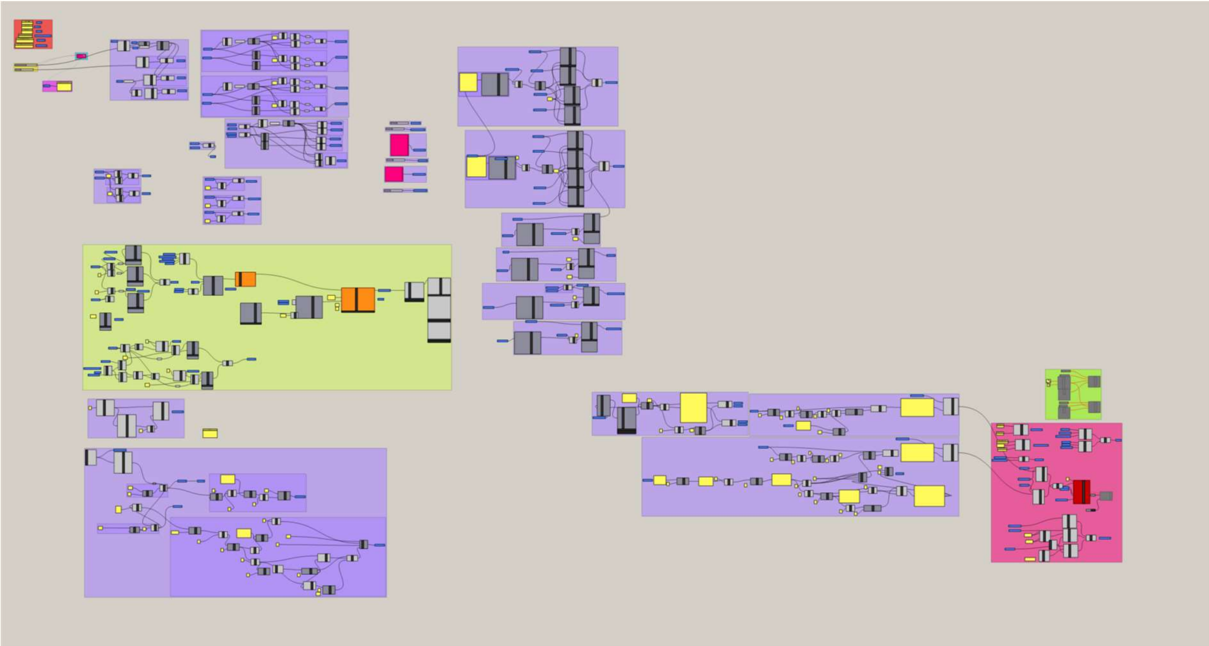


Figure 36 Case 8 - Algorithm

After setting all inputs, the algorithm which can be seen in Figure 36 is set in motion, first the lines which will later represent truss members are drawn up and all the top points where the diagonals intersect the top chord is gathered. Furthermore, all lines are then assigned a random cross-section picked from a pool of predefined sections. Subsequently, self-weight and snow load is applied as point loads to the previously gathered top points of the truss. Depending on the amount of truss bays, the magnitude of the loads will vary. The location of the support points is set and supports are made with the appropriate degrees of freedom. Now Karamba3D has enough information to evaluate the structure, when it is finished, Karamba determined the best combination of cross-section for each member to meet the constraint of maximum displacement while not exceeding the utilization of each member. When all members has been given a new cross-section, the total mass of the structure is calculated. The total mass will be the fitness of that particular iteration and is sent back to Galapagos. This is repeated until it finds the lightest structure that still fulfills the requirements. Once Galapagos has found a suitable solution it is sent to FEM-Design for validation. In addition, if needed, the structure can also be sent to Tekla to populate a BIM-model.

6.5.7 Fitness

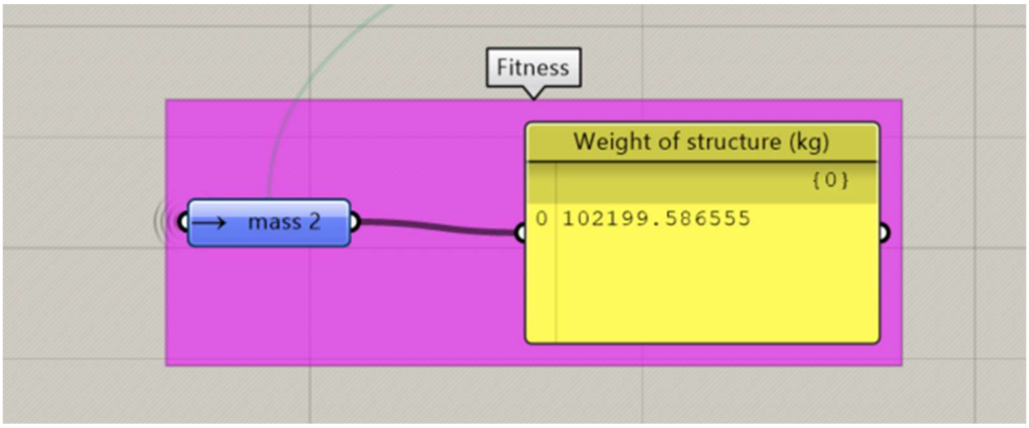


Figure 37 Case 8 – Fitness

The fitness was solely based on the total weight of the structure as can be seen in Figure 37.

6.5.8 Optimization routine

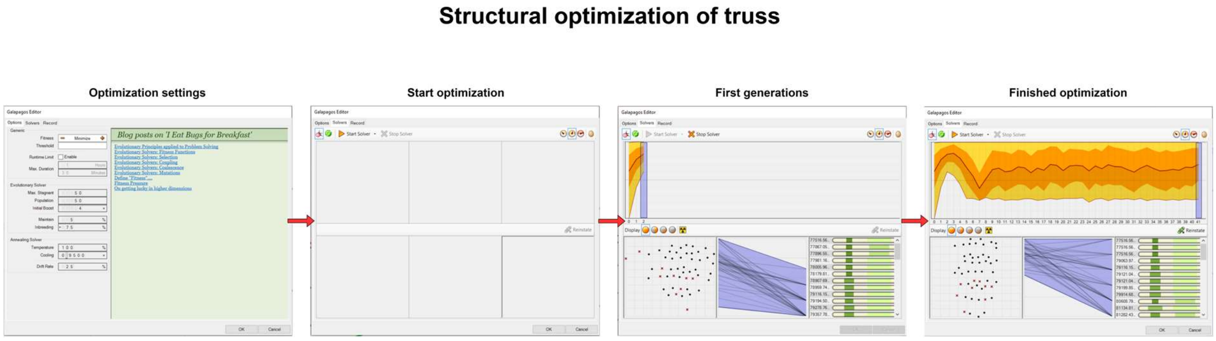


Figure 38 Case 8 - Structural optimization of truss

The optimization routine make use of the evolutionary solver within Galapagos(Figure 38). We want the lightest structure that still satisfies the given constraints, i.e. algorithm was set to minimize the fitness value. The total population of each generation was bound by maximum of 50 genomes, this should be sufficient to properly explore the fitness landscape while keeping the runtime of the optimization routine within reasonable limits. The initial boost was set to 4, i.e. generation 0 will have 4 times as many genomes than the following generations. This was done to thoroughly cover the fitness landscape such that the following generations did not colonize local optima's instead of the best global one. With a total runtime of 15 minutes, the evolutionary solver converged towards a solution after 41 generations yielding a total weight of 77516.56 kg.

	Weight	**Generation**	**Runtime**
Optimized solution	77516.56 kg	41	15:20 minutes

6.5.9 Outcome

After running the optimization routine the following conditions were present in the fittest genome.

6.5.9.1 Optimized geometry

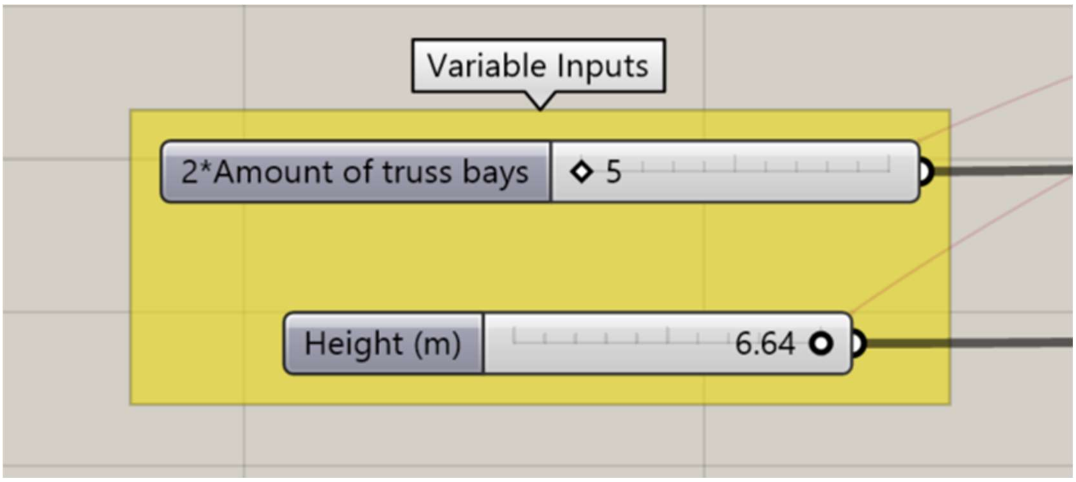


Figure 39 Case 8 - Fittest genome

The genome that yielded the best results had genes with the following value(Table 10 Figure 39).

Table 10 Case 8 - Fittest genome

Gene	Value
Height	6.64m
Amount of truss bays	10

6.5.9.2 Loads

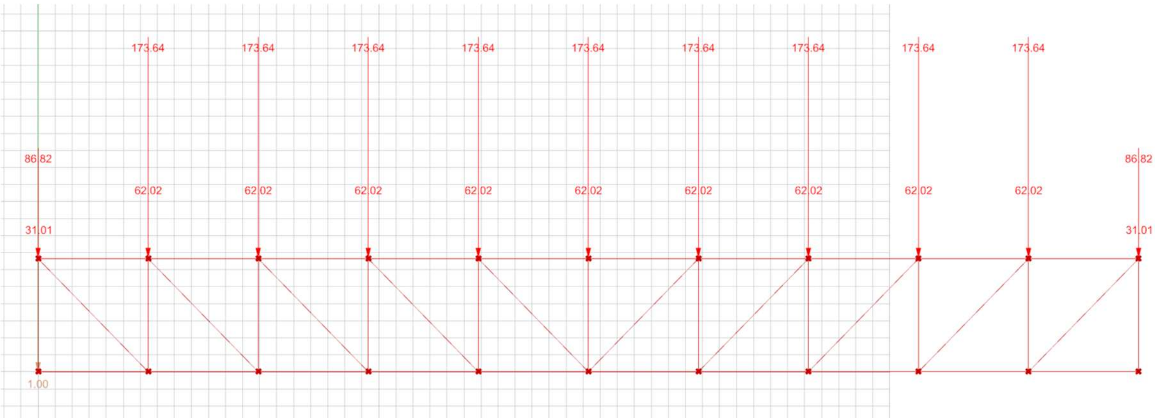


Figure 40 Case 8 - Distribution of loads for optimized genome

With 10 truss bays there are 11 top points, the following table shows the load applied at each point. As shown in Figure 40 and Table 11 the loads on the start and end points are half of the others due to the influence area being 50% smaller than the rest.

Table 11 Case 8 - Magnitude of applied laods

Point number	Roof dead load	Snow load
1	31.01 kN	86.82 kN
2	62.02 kN	173.64 kN
3	62.02 kN	173.64 kN
4	62.02 kN	173.64 kN
5	62.02 kN	173.64 kN
6	62.02 kN	173.64 kN
7	62.02 kN	173.64 kN
8	62.02 kN	173.64 kN
9	62.02 kN	173.64 kN
10	62.02 kN	173.64 kN
11	31.01 kN	86.82 kN

6.5.9.3 Optimized cross-sections

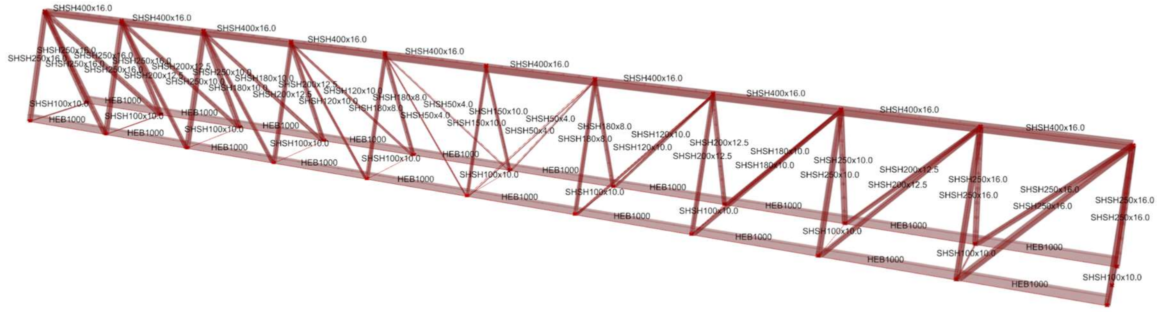


Figure 41 Case 8 - Optimized Cross-sections

Given these parameters, Karamba3D had assigned the following cross-sections to the different structural members(Figure 41, Table 12, Table 13, Table 14,Table 15, Table 16)

Diagonal web members

Table 12 Case 8 - Optimized Diagonal web members

Member id	Profile
Diagonal 1	**SHS250x250x16**
Diagonal 2	**SHS200x200x12.5**
Diagonal 3	**SHS180x180x10**
Diagonal 4	**SHS120x120x10**
Diagonal 5	**SHS50x50x4**
Diagonal 6	**SHS50x50x4**
Diagonal 7	**SHS120x120x10**
Diagonal 8	**SHS180x180x10**
Diagonal 9	**SHS200x200x12.5**
Diagonal 10	**SHS250x250x16**

Vertical web members

Table 13 Case 8 - Optimized Vertical web members

Member id	Profile
Vertical 1	**SHS250x250x16**
Vertical 2	**SHS250x250x16**
Vertical 3	**SHS250x250x10**
Vertical 4	**SHS200x200x12.5**
Vertical 5	**SHS180x180x8**
Vertical 6	**SHS150x150x10**
Vertical 7	**SHS180x180x8**
Vertical 8	**SHS200x200x12.5**
Vertical 9	**SHS250x250x10**
Vertical 10	**SHS250x250x16**
Vertical 11	**SHS250x250x16**

Middle web members

Table 14 Case 8 - Optimized Middle web members

Member id	Profile
Middle	**100x100x10**

Top chord

Table 15 Case 8 - Optimized Top chord

Member id	Profile
Top chord	**400x400x16**

Bottom chords

Table 16 Case 8 - Optimized Bottom chords

Member id	Profile
Bottom chords	**HEB1000**

6.5.10 Validation

To validate the results, the geometry, loads, cross-sections and supports was sent to FEM-Design. The process of doing so was automated through the FEM-Design plug-in for grasshopper.

6.5.10.1 Results

A thorough description of the analysis can be viewed in appendix B. The following are the outcome validating the results from the optimization routine.

Maximum displacement

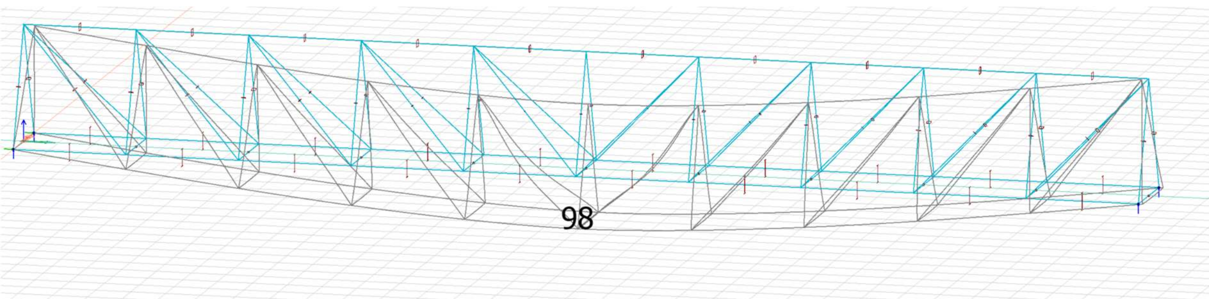


Figure 42 Case 8 - Validated result - Displacement

The results from the SLS load-combination yielded a maximum vertical displacement of 98mm(Figure 42).

Utilization

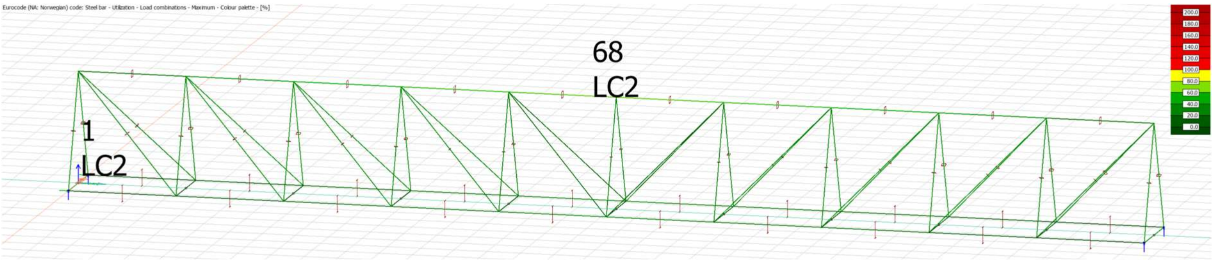


Figure 43 Case 8 - Validated result - Utilization

The results from the maximum load-combination yielded a maximum utilization of 68%(Figure 43)

6.5.11 Print to Tekla

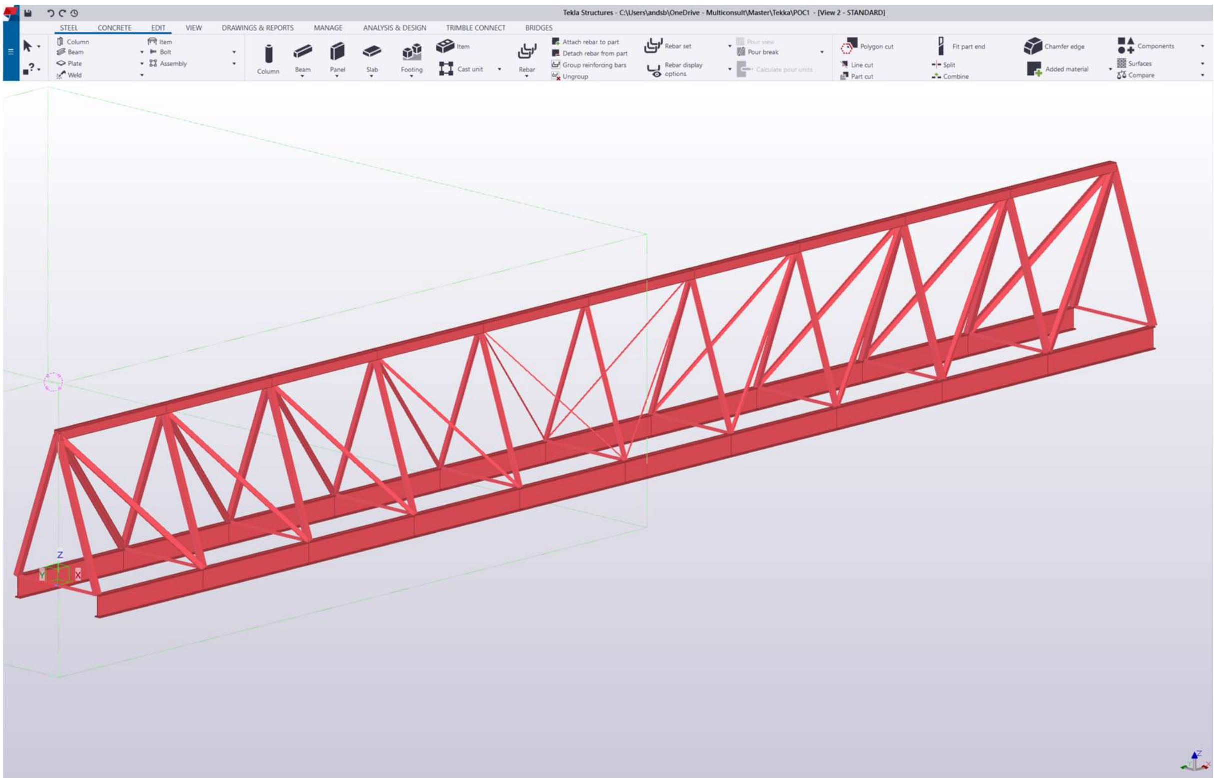


Figure 44 Case 8 - Optimized truss printed to Tekla

With the structural integrity validated within FEM-Design, the truss was printed to Tekla(Figure 44).

6.6 CASE 9 – OPTIMIZATION OF TENDON PROFILE FOR A MULTI-SPAN POST-TENSIONED BEAM

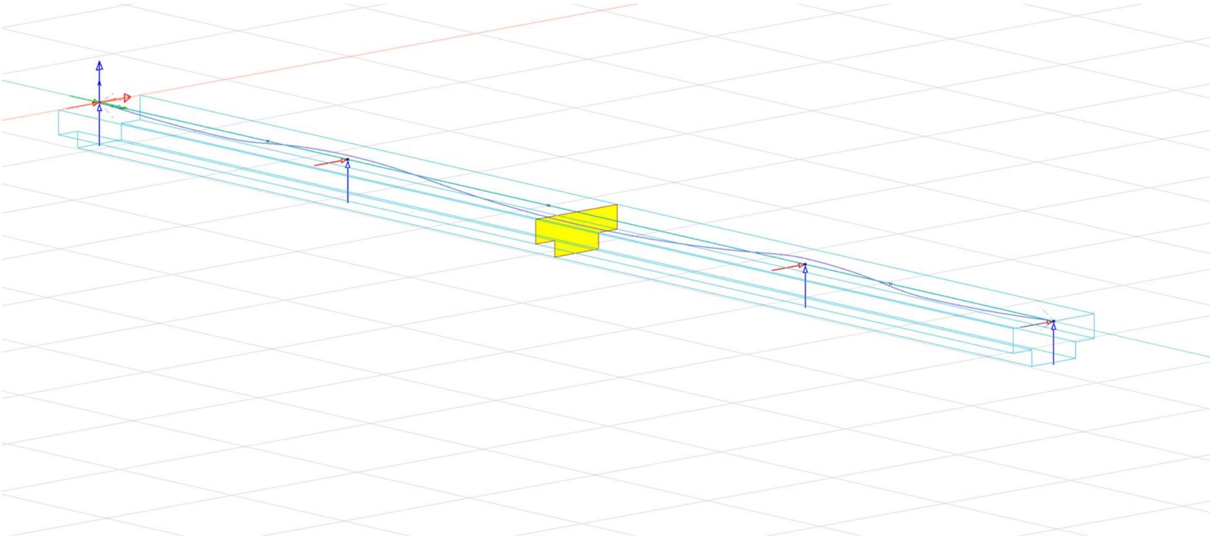


Figure 45 Case 9 - Post-Tensioned multi-span beam

6.6.1 Case description

To accommodate larger open areas within buildings, columns needs to be placed further apart. Consequently, longer spanning beams are needed. At these spans, regular reinforced concrete solutions are no longer feasible. Subsequently, structural engineers often turn to post-tensioned systems to solve this problem. These systems offer the engineer options to achieve structural integrity while keeping the beams relatively slender. The process of designing post-tensioned beams is done iteratively where the main outcome is to determine the necessary cross-sectional area of the beam, the tendon profile and finally the required tendon force. Initially, some assumptions regarding losses, trial cross-section and tendon profile is made. Furthermore, the necessary tendon force is calculated to balance the loads vs. the applied forces. Finally, as the geometry of the tendon and the needed force is known, the actual losses can be calculated. Compared to the initial assumptions, the engineer can now go back and re-iterate to optimize the structure further. This process continues until the performance of the solution is deemed acceptable. The following case will present an automated approach to designing a post-tensioned system. The case draws inspiration from a real structure.

6.6.2 Idealizations and limitations

In reality the distributed load acting on the beam by the post-tensioned tendon is not uniform i.e. it varies with the slope. In other words, the idealizations that has been made in this case is that the distributed loads are uniform within each parabola section. Furthermore, the optimization routine does not include losses in tendon force due to friction, relaxation and alike. In addition the beam is only subjected to one load-combination(SLS) during the optimization.

6.6.3 Optimization goal

For this case the optimization goal was to find a tendon profile that needed the least amount of jacking force while still maintaining compression throughout the beam.

6.6.4 Static inputs

6.6.4.1 Geometry

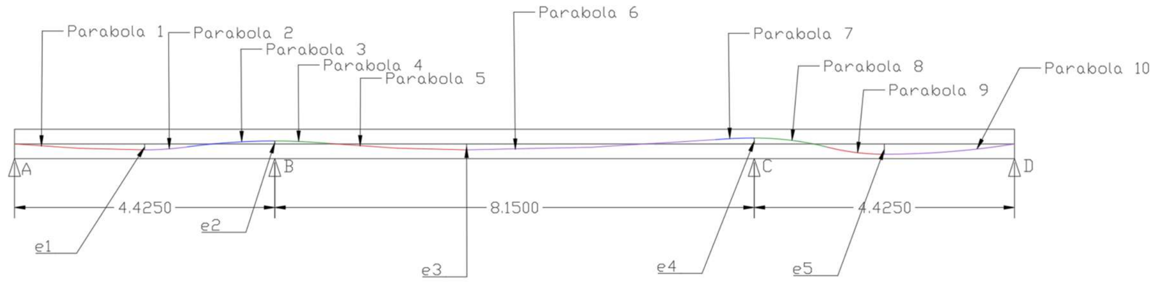


Figure 46 Case 9 – Post-Tensioned beam (Dimensions in meter)

Supports

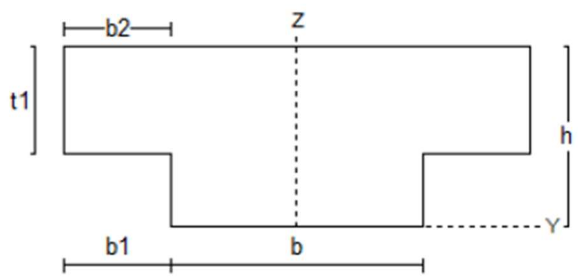
The structure(Figure 46) was to be constrained from movement by the following supports(Table 17).

Table 17 Case 9 - Static inputs - Supports

Point id.	**Coordinate**	**Translation**	**Rotation**
Point A	X = 0	X-Direction = Restrained	X-Axis = Free
	Y = 0	Y-Direction = Restrained	Y-Axis = Free
	Z = 0	Z-Direction = Restrained	Z-Axis = Free
Point B	X = 4.425m	X-Direction = Free	X-Axis = Free
	Y = 0	Y-Direction = Restrained	Y-Axis = Free
	Z = 0	Z-Direction = Restrained	Z-Axis = Free
Point C	X = 12.575m	X-Direction = Free	X-Axis = Free
	Y = 0	Y-Direction = Restrained	Y-Axis = Free
	Z = 0	Z-Direction = Restrained	Z-Axis = Free
Point D	X = 17m	X-Direction = Free	X-Axis = Free
	Y = 0	Y-Direction = Restrained	Y-Axis = Free
	Z = 0	Z-Direction = Restrained	Z-Axis = Free

Cross-section

The cross-section that was chosen has the dimensions as shown in Figure 47.



b	700	mm
b1	300	mm
b2	300	mm
h	500	mm
t1	300	mm
t2	0	mm
Zt	284	mm
Areal	5,30E+05	mm2
Iy	9,83E+09	mm4

Figure 47 Case 9 - Static Inputs - Cross-Section

6.6.4.2 *Loading*
In addition to the self-weight of the beam, three point is placed, one on each span with the following coordinates and magnitude(Table 18)

Table 18 Case 9 - Static inputs - Loading

Point	**Coordinates**	**Magnitude**
Point load 1	X = 3m Y = 0 Z = 0	X = 0 Y = 0 Z = -210kN
Point load 2	X = 8 Y = 0 Z = 0	X = 0 Y = 0 Z = -115kN
Point load 3	X = 14.095 Y = 0 Z = 0	X = 0 Y = 0 Z = -115kN

6.6.4.3 *Material properties*
Concrete

The concrete characteristics are set to C35

6.6.4.4 *Safety factors*
As the SLS crack criteria of no tension in the cross-section will be the governing parameter in designing this post-tensioned beam, the safety factors for SLS(NS-EN 1990:2002+NA:2008) will be used for the load-combination in the optimization routine(Table 19).

Table 19 Case 9 - Static input - Safety factors (NS-EN 1990:2002+NA:2008)

Safety factor	**Value**
γ_G	1.0
γ_Q	1.0

6.6.5 Variable inputs
To be able to optimize the structure, the algorithm can alter a set of variables. In this case, the variables are the following.

6.6.5.1 Tendon profile

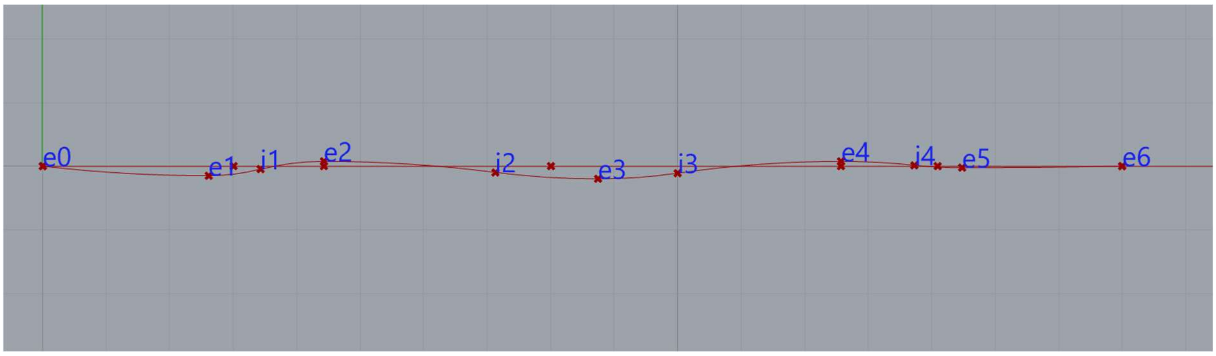


Figure 48 Case 9 - Tendon profile point of interest

To define the shape of the tendon profile the algorithm can alter the location of a set point of interest(Figure 48). The variable inputs for the algorithm was set up in such a way that they alter the locations of the given point of interest by a fraction of the dimensions of the given structure e.g. span length and cross-sectional height. By doing so, it would be a trivial task optimize a different beam with altering span length and cross-section.

Eccentricities

One parameter that controls the magnitude of the equivalent loads generated from the tendon is the maximum eccentricities at each span and support(Table 20).

Table 20 Case 9 - Variable inputs - Eccentricities

Eccentricity id.	**Span of values**	**Description**
e_1	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity in span 1
e_2	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity at support B
e_3	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity in span 2
e_4	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity at support C
e_5	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity in span 3

X-coordinate of eccentricities and inflection point

In addition to manipulating the magnitude of the eccentricities, the algorithm was also able to alter the position at which the eccentricity was located. In addition, it could also alter the location of the inflection points(Table 21).

Table 21 Case 9 - Variable inputs - Position of eccentricities and inflection point

Location id.	**Span of values**	**Description**
a_1	[0.4 , 0.6]% of span 1 length	Controls the x-coordinate of eccentricity e_1
a_2	[0.1 , 0.9]% of distance between e_1 and support B	Controls the x-coordinate of inflection point i_1
a_3	[0.4 , 0.6]% of span 2 length	Controls the x-coordinate of eccentricity e_3
a_4	[0.1 , 0.9]% of distance between e_3 and support B	Controls the x-coordinate of inflection point i_2
a_5	[0.1 , 0.9]% of distance between e_3 and support C	Controls the x-coordinate of inflection point i_3
a_6	[0.4 , 0.6]% of span 3 length	Controls the x-coordinate of eccentricity e_5
a_7	[0.1 , 0.9]% of distance between e_5 and support C	Controls the x-coordinate of inflection point i_4

6.6.5.2 Tendon force

The magnitude of the force applied to the post-tensioned tendon is the last of the variable inputs(Table 22).

Table 22 Case 9 - Variable inputs - Tendon force

	Span of values	**Description**
Tendon force	[200 , 2000] kN	Directly correlated with the equivalent uniformly distributed loads acting on the beam from the post-tensioned tendon

6.6.6 Algorithm

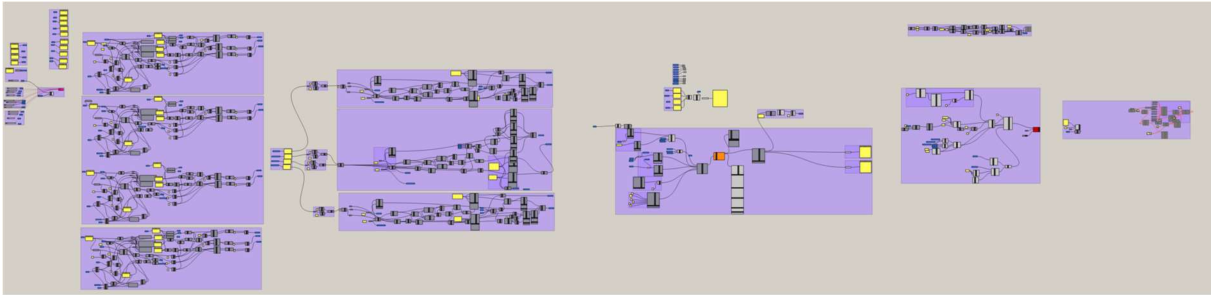


Figure 49 Case 9 - Algorithm

To determine the tendon profile the algorithm(Figure 49) draws inspiration from the procedure described in Gilbert(2017). It describes how it is possible to idealize the tendon profile as parabolas with a given radius of curvature. Subsequently, the radius of curvature is curvature, together with the applied tendon force is directly related to the equivalent uniformly distributed load acting on the beam from the tendon. The algorithm uses the equations making up the approach and automates it. Initially, after all variable and static inputs have been set, the algorithm is set in motion. The following is a description of the steps the algorithm takes to arrive at an optimized tendon profile.

6.6.6.1 Span 1

Location of inflection point

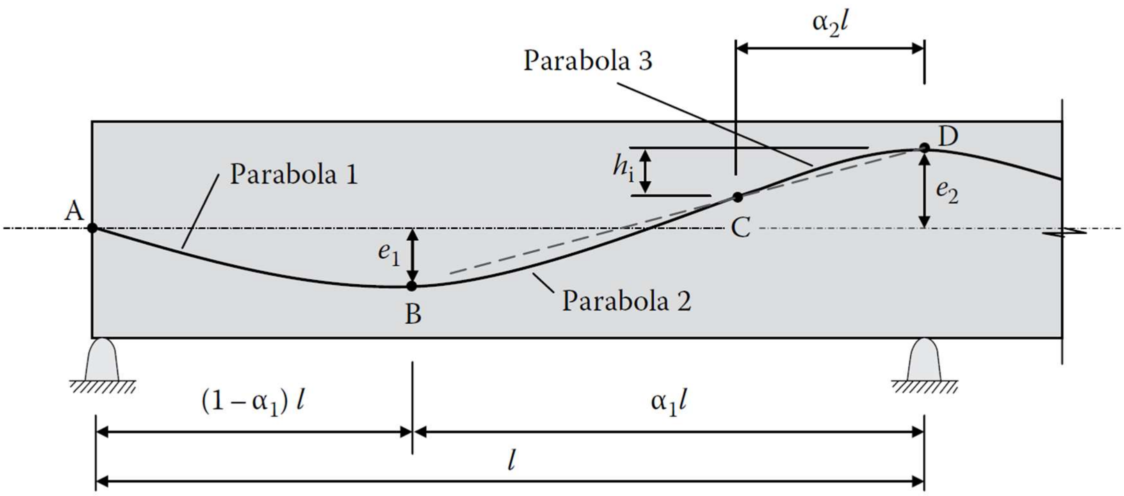


Figure 50 Case 9 - Illustration of tendon profile parabolas(Gilbert, 2017)

First the distance which inflection point i_i is offset e_2 is calculated.

$$h_{i_1} = \frac{\alpha_2}{\alpha_1}(e_1 + e_2)$$

Radius of curvature for parabolas

Now the algorithm has all the variable it needs to calculate the radius of curvature for the three parabolas in span 1.

$$r_1 = \frac{l^2(1-\alpha_1)^2}{2e_1}$$

$$r_2 = \frac{l^2(\alpha_1-\alpha_2)^2}{2(e_1+e_2-h_{i_1})}$$

$$r_3 = \frac{\alpha_1\alpha_2 l^2}{2(e_1+e_2)}$$

Equivalent loads

When the radius of curvature is known the equivalent uniformly distributed loads can be calculated using the following formula.

$$q_i = Pk_{P_i} \; where \; P = Force \; in \; post-tensioned \; tendon \; and \; k_{P_i} = \frac{1}{r_i}$$

This yields the following formula for the three equivalent loads for span 1.

$$q_1 = Pk_{P_1}$$

$$q_2 = Pk_{P_2}$$

$$q_3 = Pk_{P_3}$$

6.6.6.2 Span 2

Location of inflection point

Offset for i_2 and i_3 is calculated

$$h_{i_2} = \frac{\alpha_4}{\alpha_3}(e_2+e_3)$$

$$h_{i_3} = \frac{\alpha_5}{\alpha_3}(e_3+e_4)$$

Radius of curvature for parabolas

Radius of the four parabolas in span 2 can then be found.

$$r_4 = \frac{\alpha_3\alpha_4 l^2}{2(e_2+e_3)}$$

$$r_5 = \frac{l^2(\alpha_3-\alpha_4)^2}{2(e_2+e_3-h_{i_2})}$$

$$r_6 = \frac{l^2(\alpha_3-\alpha_5)^2}{2(e_3+e_4-h_{i_3})}$$

$$r_7 = \frac{\alpha_3\alpha_5 l^2}{2(e_3+e_4)}$$

Equivalent loads

With the radius of curvature, the four equivalent uniformly distributed loads can be calculated.

$$q_4 = Pk_{P_4}$$

$$q_5 = Pk_{P_5}$$

$$q_6 = Pk_{P_6}$$

$$q_7 = Pk_{P_7}$$

6.6.6.3 Span 3

Location of inflection point

Offset for i_4 is calculated.

$$h_{i_4} = \frac{\alpha_7}{\alpha_6}(e_4 + e_5)$$

Radius of curvature for parabolas

Radius of the three parabolas in span 3 can then be found.

$$r_8 = \frac{\alpha_6 \alpha_7 l^2}{2(e_4 + e_5)}$$

$$r_9 = \frac{l^2(\alpha_6 - \alpha_7)^2}{2(e_4 + e_5 - h_{i_4})}$$

$$r_{10} = \frac{l^2(1 - \alpha_6)^2}{2e_1}$$

Equivalent loads

With the radius of curvature, the three equivalent uniformly distributed loads can be calculated.

$$q_8 = Pk_{P_8}$$

$$q_9 = Pk_{P_9}$$

$$q_{10} = Pk_{P_{10}}$$

Drawing tendon profile

Using the coordinates of the eccentricities and inflection points together with the now known radius of curvature for each parabola, all parabolas can be drawn in rhino as curves(Table 23). These curves will later be used to print the tendon shape to Tekla.

Table 23 Case 9 - Parabola start and end points

Parabola id.	**Start point**	**End point**
Parabola 1	e_0	e_1
Parabola 2	e_1	i_1
Parabola 3	i_1	e_2
Parabola 4	e_2	i_2
Parabola 5	i_2	e_3

Parabola 6	e_3	i_3
Parabola 7	i_3	e_4
Parabola 8	e_4	i_4
Parabola 9	i_4	e_5
Parabola 10	e_5	e_6

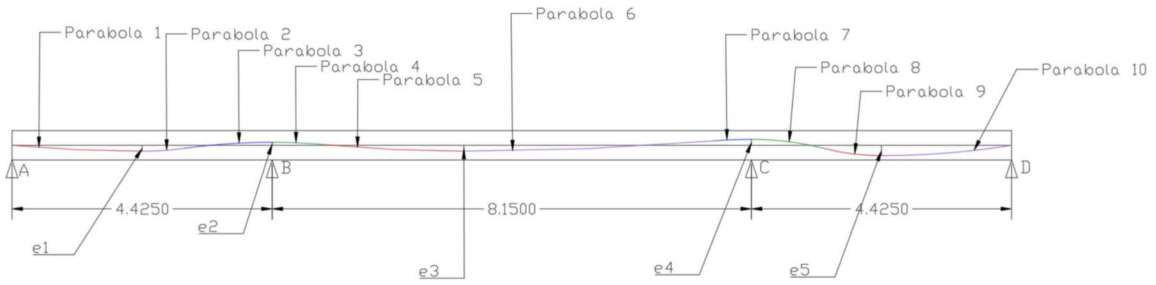


Figure 51 Case 9 - Parabolas

6.6.6.4 Karamba

Now that the coordiantes for each parabola and equivalent loads are calculated, it is time to build the FEA model. Individual beam elements are modelled between each of the parabolas, 10 in total(Figure 51). Futhermore, the equivalent loads and point loads are applied. The outcome of the analysis is the stress state at predefined points of interest. These stress states are finally used to evaluate the performance of the structure and enables Galapagos to find the most optimal solutions. Furthermore, the equivalent uniformly distributed loads are now made available to the FEA nodes in the Karamba plug-in. Together with the predefined beam elements and boundary conditions, the Karamba structural analysis node evaluates stresses in the cross-section at 12 points of interest. The stress conditions together with the applied tendon force is fed to Galapagos as the fitness for the optimization

6.6.7 Fitness

To measure the performance of each iteration a fitness condition is constructed. In this case, the fitness conditions depend on two different inputs. The first input is the applied force to the post-tensioned tendon, the second is a sum of a condition-based equation determined by the stress-condition at the 12 points of interest. For every point with stress above 0 MPa i.e. tensile stress, a penalty value of 2000 is added, e.g. if all 12 points are in tension a penalty of 24000 will be added. On the other hand, if all points are in compression, no penalty is added.

6.6.8 Optimization routine

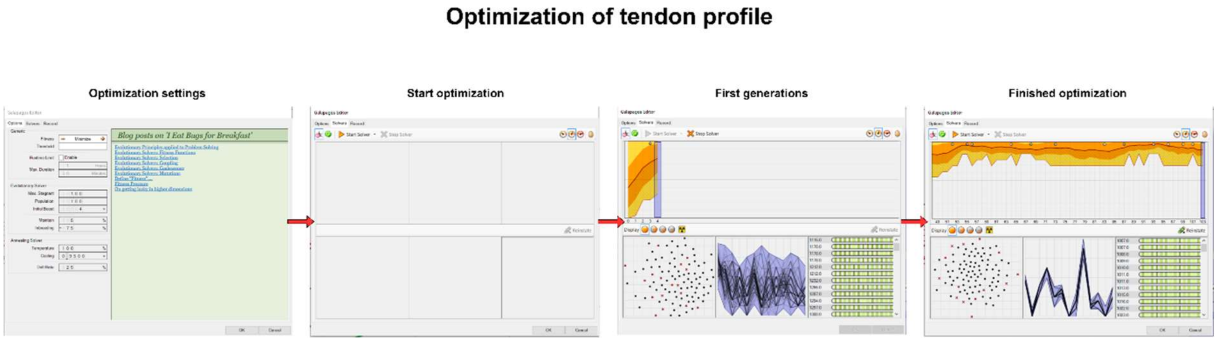


Figure 52 Case 9 - Optimization of tendon profile

Now that the function of the algorithm is explained, the variable inputs has been set up and a way to assess the performance of each iteration has been added, Galapagos has enough information to start the optimization routine(Figure 52). Galapagos has control of all the variable inputs is given instant feedback on the performance through the fitness condition. By doing so it gradually learns which combination of the variables yields the best performance and after a set amount of time it presents the best solutions it could find. After a runtime of 45 minutes and 103 generations, Galapagos converged towards a solution only requiring 1007 kN of force.

6.6.9 Outcome

The best genome had the following combination of input variables(Table 24).

Table 24 Case 9 - Genes of fittest genome

Input variables	**Value**
a_1	0.41
a_2	0.226
a_3	0.47
a_4	0.331
a_5	0.316
a_6	0.43
a_7	0.261
e_1	0.6
e_2	0.3
e_3	0.8
e_4	0.3
e_5	0.1

6.6.9.1 *Optimized tendon profile*

The input variables produced a tendon profile intersection the different point of interest at the following coordinates(Table 25).

Table 25 Case 9 - Point of interest coordinates

Point of interest	**Coordinate**
e_0	(0 , 0 , 0)mm
e_1	(2611 , 0 , -150)mm
i_1	(3425 , 0 , -49)mm
e_2	(4425 , 0 , 75)mm
i_2	(7123 , 0 , -97)mm
e_3	(8745 , 0 , -200)mm
i_3	(10000 , 0 , -110)mm
e_4	(12575 , 0 , 75)mm
i_4	(13730 , 0 , 14)mm
e_5	(14478 , 0 , -25)mm
e_6	(17000 , 0 , 0)mm

6.6.9.2 *Optimized tendon force and equivalent loads*

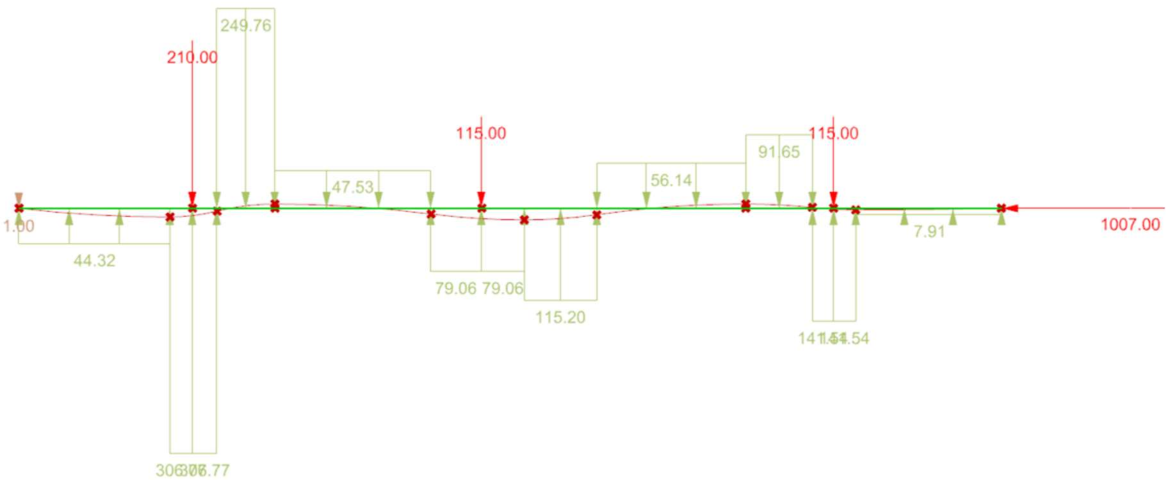


Figure 53 Case 9 - Illustration of loads

The magnitude and position of each equivalent load can be viewed in Figure 53 and Table 26.

Table 26 Case 9 - Magnitude of equivalent loads and tendon force

Load	**Coordinate**	**Description**
P	1007 kN	Tendon force
q_1	44.32 kN/m	Equivalent loads from parabola 1
q_2	306.77 kN/m	Equivalent loads from parabola 2
q_3	-249.76 kN/m	Equivalent loads from parabola 3

q_4	-47.53 kN/m	Equivalent loads from parabola 4
q_5	79.05 kN/m	Equivalent loads from parabola 5
q_6	115.2 kN/m	Equivalent loads from parabola 6
q_7	-56.14 kN/m	Equivalent loads from parabola 7
q_8	-91.64 kN/m	Equivalent loads from parabola 8
q_9	141.53 kN/m	Equivalent loads from parabola 9
q_{10}	7.91 kN/m	Equivalent loads from parabola 10

6.6.10 Validation

To validate the result the beam was also analyzed in FEM-Design. All geometry the geometry, loads, and load cases were sent automatically through the FEM-Design Grasshopper plug-in. However, as of now it is not possible to model post-tensioned cables through the plug-in. The tendon profile and applied force was therefore manually generated inside FEM-Design(Figure 54) with the known locations for the point of interest.

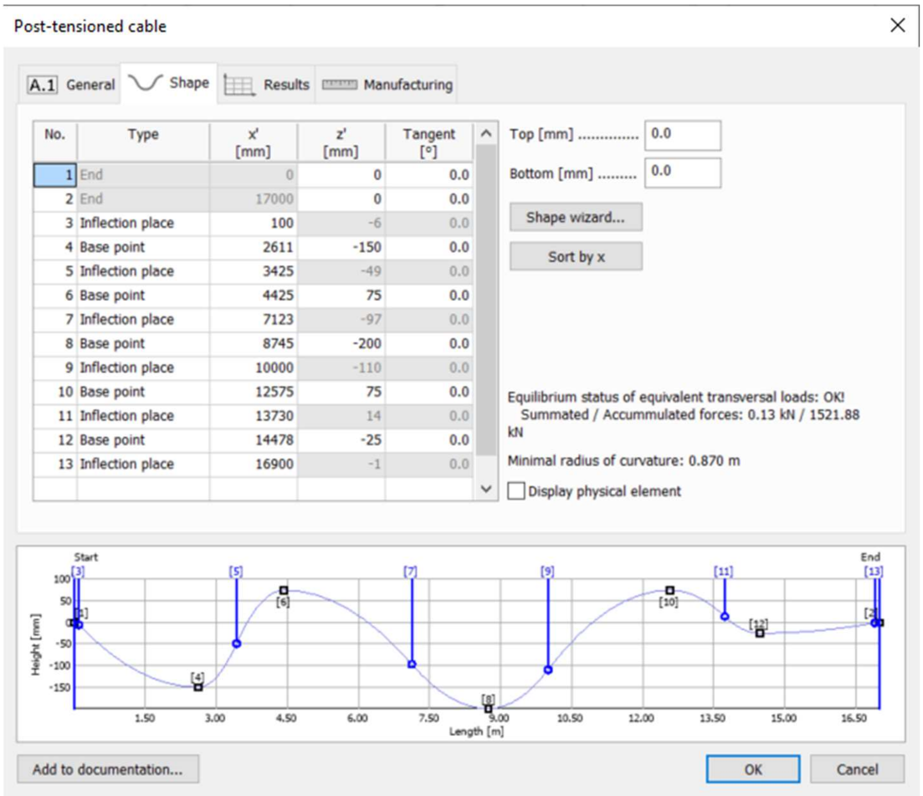


Figure 54 Case 9 - Tendon point of interest manually inserted into FEM-Design

6.6.10.1 Results

After running the analysis the following results was found(Figure 55). A more thorough description of the analysis can be viewed in appendix A.

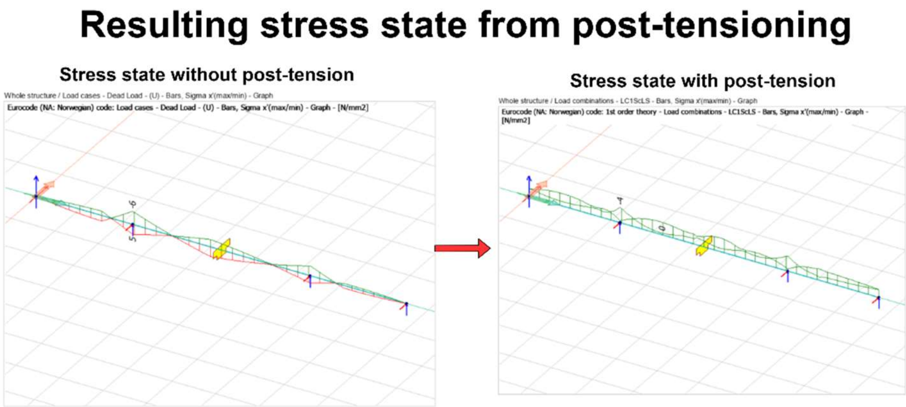


Figure 55 Case 9 - Validation of results

With the post-tensioning applied, the following stress state was observed(Table 27).

Table 27 Case 9 - Stress results from FEM-Design

Observations	**Value**
Max stress	4 MPa (Compression)
Min stress	0 MPa

Not only is the entirety of the beam in compression as was intended, the minimum stress is 0 MPa indicating a well optimized profile and tendon force.

6.6.11 Printing to Tekla

Finally the geometry was automatically printed to Tekla to populate a BIM-model as can be seen in Figure 56.

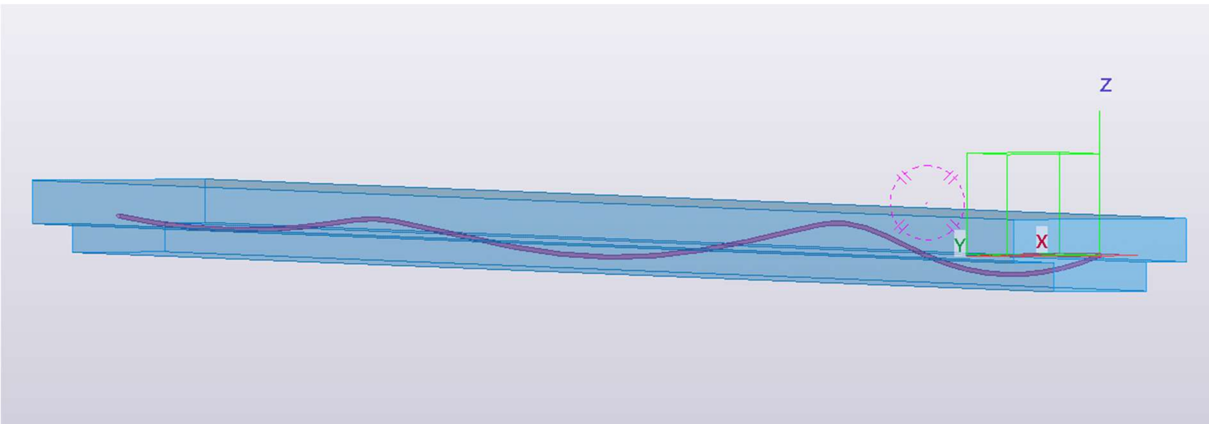


Figure 56 Case 9 – Beam and optimized tendon profile printed to Tekla

7 DISCUSSION

In the pursuit of exploring the capabilities of Algorithms-Aided Design this thesis has presented 9 cases within 3 different areas, parametric BIM-modelling, parametric analysis models and lastly, Generative design of structures. As the author was the developer of the scripts and algorithms for all the presented cases, his views together with feedback from industry professionals will serve as input to the following chapter discussing the potential of AAD.

7.1 PARAMETRIC BIM-MODELLING

7.1.1 Case 1 – Sheet pile structure

Utilizing Parametric Design in this project was a learning experience for all parties involved. The model was supposed to serve as the main deliverable, with minimal reliance on regular 2D-drawings. To accommodate this, new workflows needed to be established seeing that there was limited experience of projects of this kind. Inevitably, some time was spent establishing said workflows. Thereby, it is reasonable to think that future projects will be able to reap the benefits of the experiences gained and will achieve a higher degree of efficiency. Overall, the utilization of Parametric Design accelerated the pace of modelling when changes occurred and made it easy to assign all BIM-information to the element present in the model. When changes occurred, it was only needed to either update the references such as sheet pile lines or bedrock mesh. Then, with minimal adjustments to the algorithm, the new structure was generated. This accelerated process enabled faster iterations of the structures which quickly revealed unforeseen problems. As a result, more time was available to solving said problems, and a higher quality product was achieved.

During the project, an article was published in the Norwegian construction newspaper Bygg.no (https://www.bygg.no/article/1439555) describing a workflow similar to the one applied here, they highlight many of the same benefits which were observed in this project.

When asked about how Parametric Design affected this project(Appendix C), the geo technicians responsible for this structure responded saying it was a very effective way of working and easy to make changes. However, they pointed out that some manual modelling was still required. When asked to estimate time savings by modelling parametrically versus traditionally, they had a hard time seeing that similar models had not been made before, and that making such models was a rather new experience for them. Finally, they added that going forward, they are positive to use Parametric Design in their projects.

7.1.2 Case 2 – Noise barrier

Given the extensive length of the barriers to put up, Parametric Design served as an amazing tool to offer some form of automation. To place elements along the height-varying terrain and top lines using traditional methods would be very cumbersome. Much like the sheetpile structure, the noise barriers underwent regular changes. Seeing how customizable the model became when utilizing Parametric Design, responding to these changes was done with relative ease.

In response to a questionnaire(Appendix C) evaluating the use of Parametric Design in this project, the responsible structural engineer responded that the geometry could be generated quite rapidly with a high degree of precision, also the ease of assigning metadata to the structural elements was highlighted. However, concerns were raised with respect to how dependent the project becomes on the originator of the script. For instance, if changes occur and the originator is unavailable, it can be very difficult for someone to take over. Consequently, changes are done manually and the parametric nature of the model is somewhat lost. Furthermore, when asked whether Parametric Design had sped up the modelling work in this project, the answer was no. However, it was not the fault of Parametric Design but rather the fact that too many changes occurred throughout the project life cycle. In addition, they point out that now that a procedure and script for placing noise barriers is in place, future projects could see greater benefits. Lastly, it is mentioned that they are overall positive to using Parametric Design in future projects.

7.1.3 Case 3 – Trellis wall

In this case, Parametric Design was extensively used for form finding purposes. The fast iterative nature of parametric modelling enabled the engineers to try a variety of different designs without investing too much time into it. In addition, modelling such a complex structure traditionally would be very cumbersome. Overall the outcome of this project drew upon many of the benefits of utilizing parametric design, the overall process was accelerated, feedback was quickly implemented and metadata was added to all structural members with relative ease.

7.1.4 Case 4 – Drywall

This project utilized several benefits offered from Parametric Design workflows. Not only did it use reference material in the form of DWG files, it also integrated the existing sheet pile model using the interoperability of Tekla and Grasshopper. Lastly, much like the sheet pile structure, assigning BIM-information was trivialized using the Excel-Grasshopper-Tekla workflow.

7.1.5 Case 5 – Complex timber roof structure

This project was a prime candidate to apply Parametric Design seeing the repetitive yet varying pattern of the roof structure. It also illustrates how both traditional and parametric modelling could be combined and expertise from both worlds can be applied. The benefits of applying Parametric Design were both evident when initially modelling the roof, as well as later when the dimensions of the load bearing members were changed.

To evaluate the use of Parametric Design a questionnaire(Appendix C) was sent to the structural engineers responsible for this structure. Given the complex nature of the roof, they point out that Parametric Design likely was the only reasonable modelling technique to conquer this challenge. Traditional modelling methods would also be critically susceptible to delays if changes were to occur. As Parametric Design was both used to do the initial modelling and the remodeling after changes arose at a later stage, it is estimated that time savings compared to the traditional method was roughly 4 days although it is hard to give an exact figure. Lastly, the structural engineers are positive to using Parametric Design in future projects.

7.1.6 Summary

The lessons learned through the aforementioned cases show that Parametric Design have been proven to be a great modelling tool that has improved efficiency, precision and customizability of BIM-Models. Valid concerns has been raised in regards to how reliant a project is on the originator of the scripts. To overcome this, a standardized layout for scripting should be formalized so that it is easier for someone to take over if needed. In addition, if Parametric Design becomes a more common modelling methodology, the general competence within Grasshopper and similar tools will increase and it will be easier to find someone with adequate experience to take over a script in the middle of a project.

A video demonstrating case 1 and 5 can be seen here https://youtu.be/TdXXDJRirIU

7.1.7 Proposed workflow

Based on the experience gained through case 1-5, the following workflow for Parametric BIM-Modelling is proposed. It contains the process that after trial and error yielded the most reliable and consistent results.

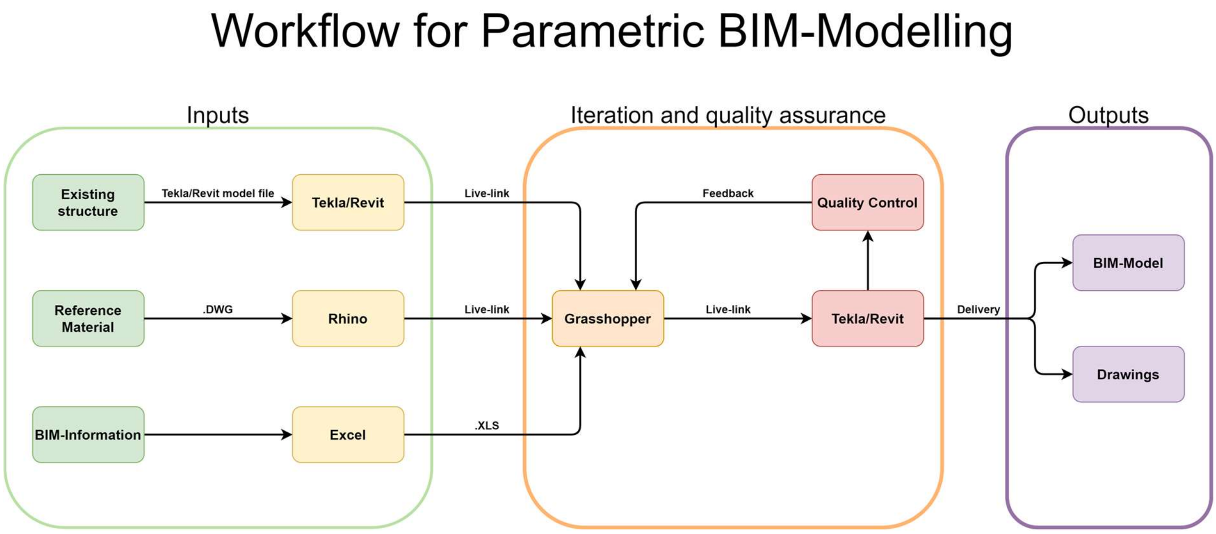


Figure 57 Proposed Workflow for Parametric BIM-Modelling

1. If an existing structure is present, import it using live-link between either Tekla or Revit
2. Reference material is imported to Rhino
3. BIM-information(metadata) is imported using Excel
4. Script is generated and model is printed to Tekla/Revit
5. Quality control is done and feedback sent back to developer of script if changes are needed
6. Repeat step 4 and 5 until model meets quality standard
7. Produce deliverables such as the final BIM-model and drawings

7.2 Parametric Analysis Model

7.2.1 Case 6 – Ecofisk – FEM-Design

Modelling the analysis model parametrically saw many of the same benefits as parametrically defined BIM-Models. Iterating on design was done quickly through the FEM-Design plug-in, which proved beneficial when modelling 9 halls of different dimension. When assessing this workflow it is important to highlight that some time was designated to developing the script and learning to use the FEM-Design plug-in i.e. the potential time saving is not as high as they could be. However, now that the script has been developed, it may see future use, which can save time in coming projects. Lastly, although it was not done in this case, one could easily expand the script to also print the model to a BIM-modelling tool like Tekla or Revit achieving a high degree if interoperability between the analysis and BIM model.

7.2.2 Case 7 –Truss – Karamba3D

While working on this case, it becomes obvious what a capable tool karamba is. Even though this is somewhat of an trivial example, It illustrates the capabilities that similar scripts can offer the structural engineer in his daily tasks. As the script is set up now it can be used for any span, with a truss with any number of divisions and members with a user defined cross-section. It can serve as a great tool to quickly prototype ideas before committing to a more extensive analysis within a more traditional finite element software.

7.2.3 Questionnaire

When asked(Appendix D) if structural engineers saw the potential in the workflows described in case 6 and 7 they responded saying that it being able to set up the analysis model parametrically indeed was valuable. Some concerns were raised point out that the geometry of structures seldom is repeating and therefore the script might become hard to make.

7.2.4 Summary

It is possible to exchange data between Grasshopper and a multitude of different FEA-software in the same manner described in case 6. In this case it was used to quickly model 9 structures with varying loads and geometry, and functioned somewhat as a testbed to trial the technology. Overall it performed as expected and a parametric analysis model drew on many of the same benefits as a parametric BIM-Model i.e. efficient, precise and highly customizable. Furthermore, the conceptual procedure described in case 7 shows great potential, with the use of Karamba, the user gets instant feedback from the FEA engine and can quickly prototype different solutions. This could be done to quickly iterate on designs and when a satisfying solution is found, it can be sent to FEM-Design for validation and generation of calculation reports.

A video demonstrating case 6 and 7 can be seen here https://youtu.be/UN6KfcI-RRQ

7.2.5 Proposed workflow

Based on the experience gained through case 6 and 7, the following workflow for Parametric Analysis Modelling is proposed. It contains the process that after trial and error yielded the most reliable and consistent results.

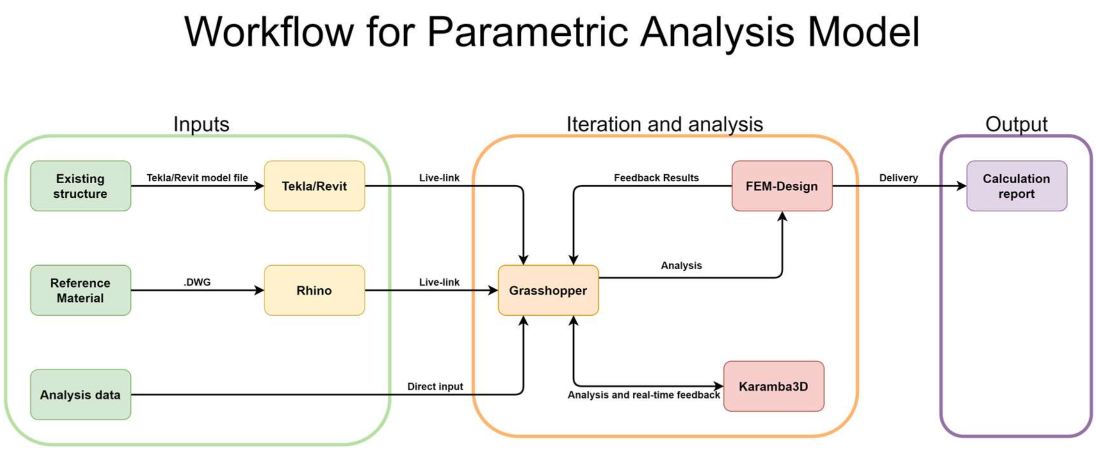


Figure 58 Proposed Workflow for Parametric Analysis Model

1. If an existing structure is present, import it using live-link between either Tekla or Revit
2. Reference material is imported to Rhino
3. Analysis data is gathered in defined within grasshopper
4. Generate Analysis model
    a. FEM-Design
        i. Script is generated and model is printed to FEM-Design
        ii. Quality control is done and feedback is sent back to developer of script if changes are needed
    b. Karamba3D
        i. Script is generated and analysis model is produced within Rhino

ii. As the analysis is done in real-time the developer can tweak the script while getting instant results until the quality of the analysis model is at a satisfactory level
iii. Furthermore this analysis model can be sent to FEM-Design for generation of calculation reports

5. Repeat step 4 until model meets quality standards
6. Produce deliverables such as calculation report

7.3 GENERATIVE DESIGN OF STRUCTURES

7.3.1 Case 8 – Structural optimization of 65m steel truss with respect to self-weight

The process of setting up this script provided great insight in into the intricacies of using optimization routines. Not only was the script set up to optimize the structure with the Karamba3D-Grasshopper-Galapagos interoperability, It also had to find an efficient way of gather the optimized structure and export it to FEM-Design for validation. Lastly, the possibility for Karamba to pick cross-sections for each iteration was not discovered before late in the writing of this thesis. Initially, the given cross-section for all structural members was a variable input to Galapagos. By having so many inputs, the optimization routine was very slow to converge towards a reasonable solution.

7.3.2 Case 9 – Optimization of tendon profile for a multi-span post-tensioned beam

Building the script to run this optimization algorithm was quite time consuming, in fact, doing it the traditional way would probably be faster. However, since the script is set up in such a way that it is trivial to change the loadings, dimensions, and span lengths, it is not farfetched to think that the next time there is a use for a similar optimization routine significantly less time is needed to set it up. Furthermore, the results show that there is a satisfying correlation between the stress evaluation in Karamba and FEM-Design.

7.3.3 Questionnaire

In similar fashion to the two preceding chapters, a questionnaire(Appendix E) was sent out to get feedback on how structural engineers view using optimization routines similar to the ones presented in this thesis. They came back saying that it could be used as a good tool in the early phase or in cases where slimming down on material costs is of significant priority. When asked mention some hurdles standing in the way of using such algorithms they mentioned the complexity of the scripts and the time needed to defined them. Overall, they are positive and agree that it could see use in the future.

7.3.4 Summary

Both case 8 and 9 show that it is indeed possible to set up routines to find reasonably good solutions to a problem, given a set of variables and some hard constraints. Whether the solutions presented is the very best possible is not known. However, the point of these cases was not necessarily to solve the presented problems, but to illustrate the degree of automation a structural engineer can enable with the technology currently available. With the ever growing prevalence of Machine Learning and AI, automation has and will affect all industries(Wang, W., & Siau, K. 2019), it is therefore naive to think that structural engineering will somehow escape this. Consequently, to stay competitive, similar workflows should be explored to harvest the benefits once the technology has reached adequate maturity. The cases described here can be considered stepping stones for fully atomized Machine Learning algorithms solving structural engineering problems autonomously.

A video demonstrating case 8 and 9 can be seen here https://youtu.be/I3tzQBqJzmM

7.3.5 Proposed workflow

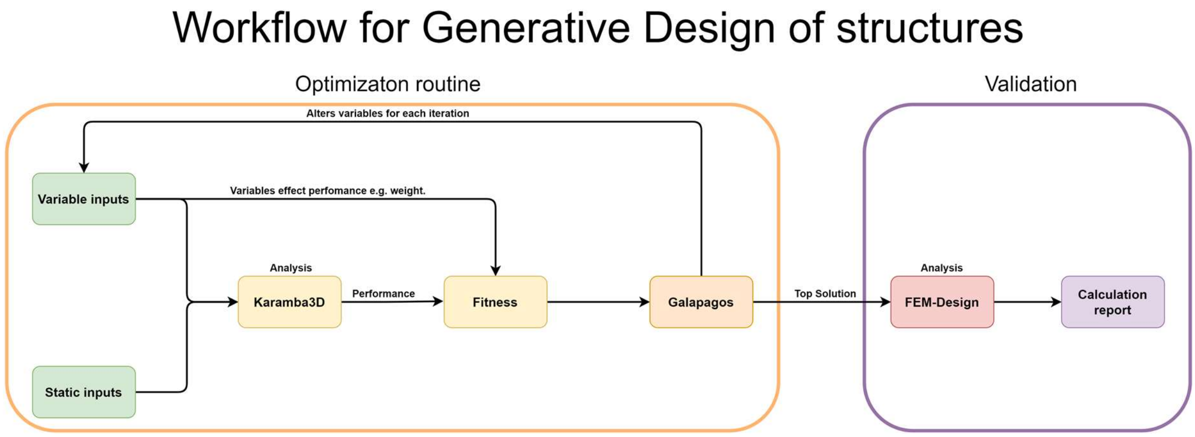


Figure 59 Proposed Workflow for Generative Design of structures

1. Static inputs are defined
2. Variable inputs(Genes) and the range of their values are defined
3. Said inputs define the structural problem which is furthermore fed into Karamba3D
4. Karamba3D analyses the structure outputs performance parameters in real-time
5. Together with the performance parameters, some of the variable inputs(Genes) will often make up the fitness of a given genome
6. The Fitness and Variable inputs(Genes) are made available to the optimization routine Galapagos
7. The optimization routine is run with a given optimization goal, either maximize or minimize
8. After the optimization routine has finished, the top solution is sent to FEM-Design for validation
9. After validating the structure, calculation reports can be generated

8 CONCLUSION

The objective of this thesis has been to explore cases to get an understanding for how AAD is currently used, which possibilities it brings and lastly, investigate what the future might hold. Parametric Design as a modelling method is already seeing noticeable adoption in the AEC industry(Lee, J. et al 2014), Case 1-5 show that it can increase efficiency, precision and customizability compared to traditional methods. Case 5 in particular emphasize the true potential of modelling parametrically, here it shortened the time needed to generate the rather complexly shaped timber roof structure by 4 days. However, valid concerns have been raised with respect to how reliant projects become on the script developer. Unless actions are taken, similar issues will persist and can cause project managers to deem the technology too risky for their projects. To overcome this, a formalized common structure for building scripts is needed, combined with a greater level of general competence within parametric design tools, this will result in projects being less reliant on single individuals.

Case 6 and 7 explored the use of parametric analysis models. Case 6 showcase how far the interoperability between Grasshopper and commonly used FEA software like FEM-Design has come in the short period it has been available to the public(Roughly 2 years). In the same manner as a parametric BIM-Model, having defined the analysis model parametrically yielded benefits such as high degree of customizability, precision and efficiency once the script was made. Case 7 on the other hand showed the great prototyping capabilities the Grasshopper – Karamba3D workflow offers. By being able to get real-time feedback from the analysis engine, structural engineers can quickly try different alternatives and get near instant results. Furthermore, it is important to emphasize that this is not limited to the problem displayed in case 7 i.e. a truss, and can be set up for any type of structure mainly limited by the imagination of the user.

By having the analysis model defined parametrically, new and innovative technologies are enabled. Generative Design, which is one of them was explored in case 8 and 9. The main objective of this chapter was to verify whether such optimization routines could produce reasonable solution, and as the verified results indicate both cases highlights structures that satisfy the given criteria. As Machine Learning and AI will affect all industries in the future(Wang, W., & Siau, K. 2019), the cases described in this chapter give a taste for how structural engineers might deploy computers to tackle the problems of tomorrow. A conference paper(Appendix F) has been drafted in collaboration with Associate Professor Samindi Samarakoon based on the findings from case 8 and 9 and will be further developed at a later stage with the aim to publish.

Lastly, as an outcome of the thesis, a set of proposed workflows has been presented. These workflows has been developed through trial and error when working on the different cases. Common for all presented workflows is that they all inherit characteristics that when followed yielded consistent results. Consequently, these workflows can serve as user guide for newcomers looking to make use of the technologies studied in this thesis.

8.1 FUTURE RECOMMENDATIONS

8.1.1 Speckle

When using reference material as input this thesis has mainly relied on importing them to Rhino as DWG to be processed. In larger projects, where there are a multitude of reference material which undergoes frequent updates, it can be cumbersome to rely on this form of import. Speckle, which is a cloud based reference database seeks to alter this, they offer sharing of the most commonly used file formats. Also, with their custom made plug-in for grasshopper, script can directly access all reference files that assigned to the project cloud storage. When a reference file is updated, it is only a simple matter of re-running the script and the and the algorithm should be up to date. Unfortunately, this was not explored thoroughly enough to be studied in detail, but show great potential.

8.1.2 Automatic modelling of reinforcement

Modelling reinforcement is a cumbersome task in any concrete structure, although placing rebar can be done parametrically in grasshopper, you still have to refer the calculation documentation to get the exact positions of all elements. However, with use of FEM-Design plug-in for grasshopper, it is possible to import the result from its auto-generated reinforcement placing back to grasshopper, this could in turn be used to automatically place the rebar in a BIM-model. By doing so, a lot of time could be saved. This capability was discovered too late to be included in this thesis but should be studied in the future.

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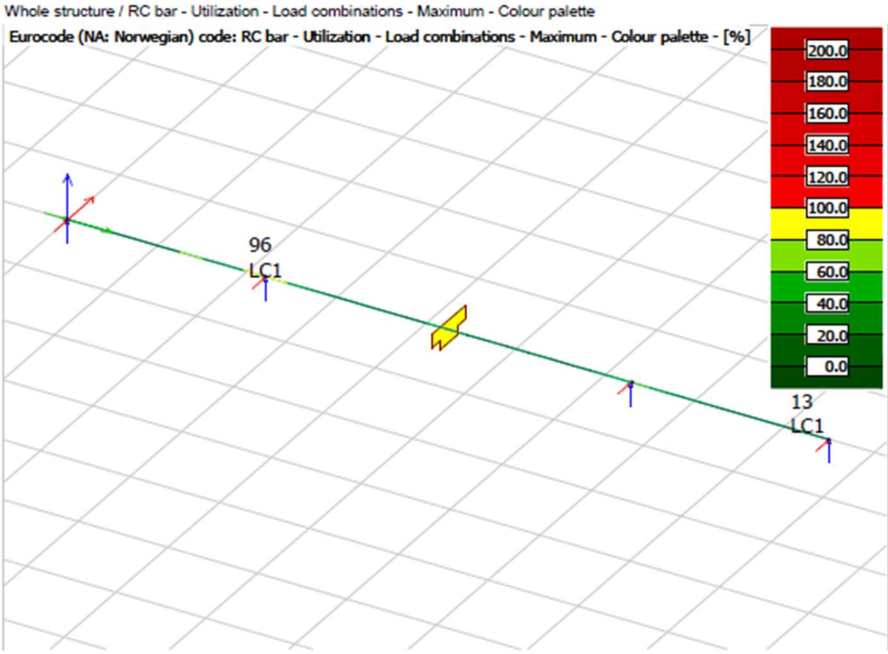
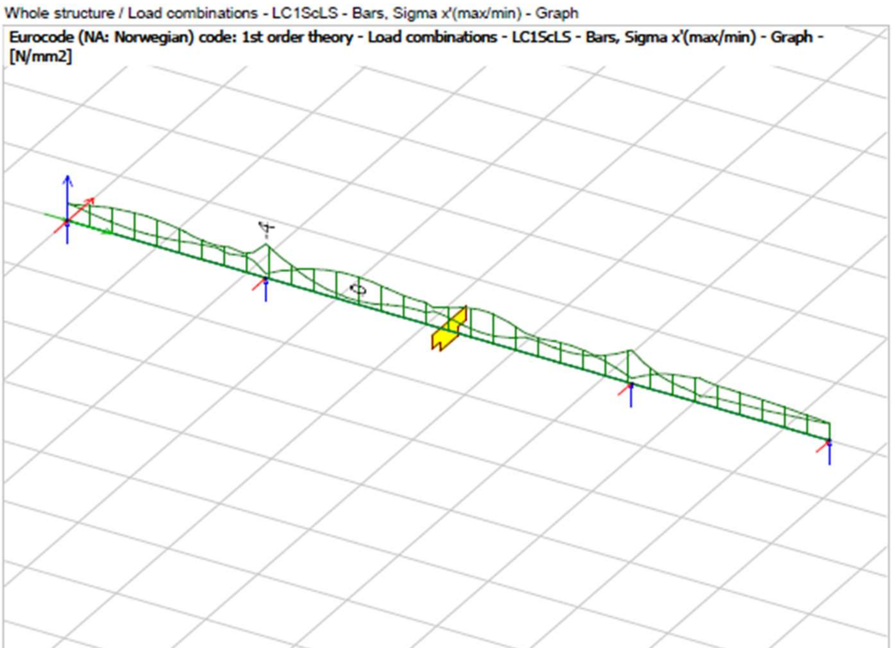
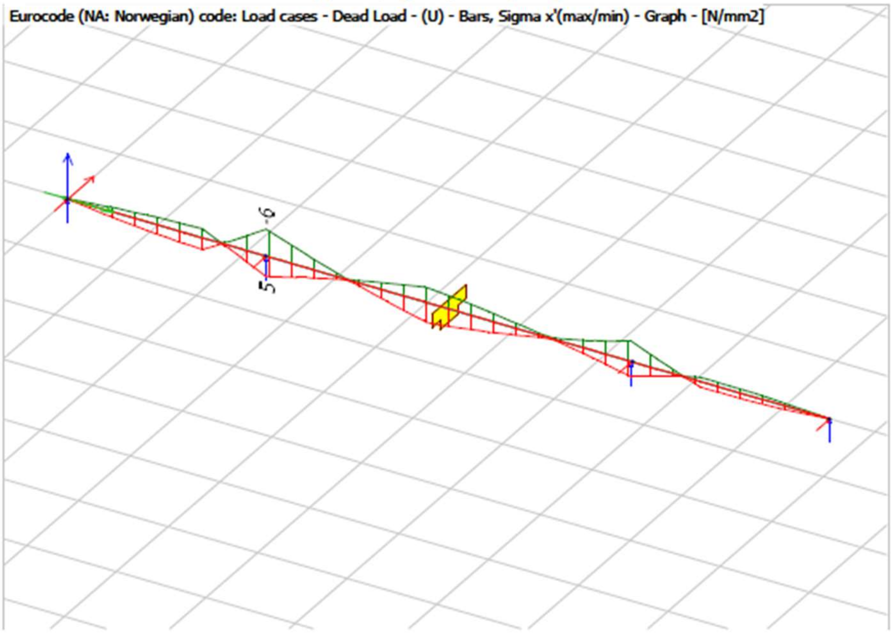
9 APPENDICES

9.1 APPENDIX A – CALCULATION REPORT – CASE 9

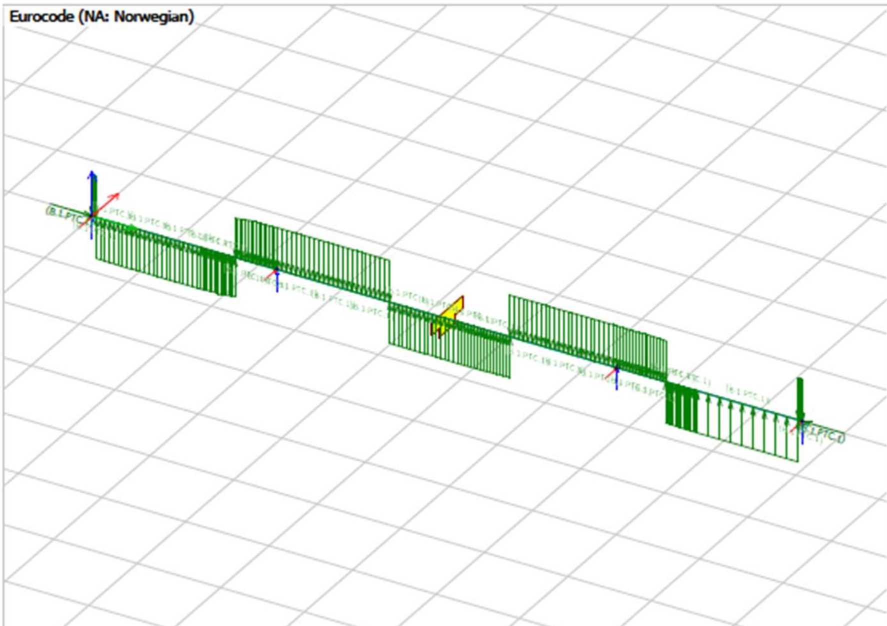




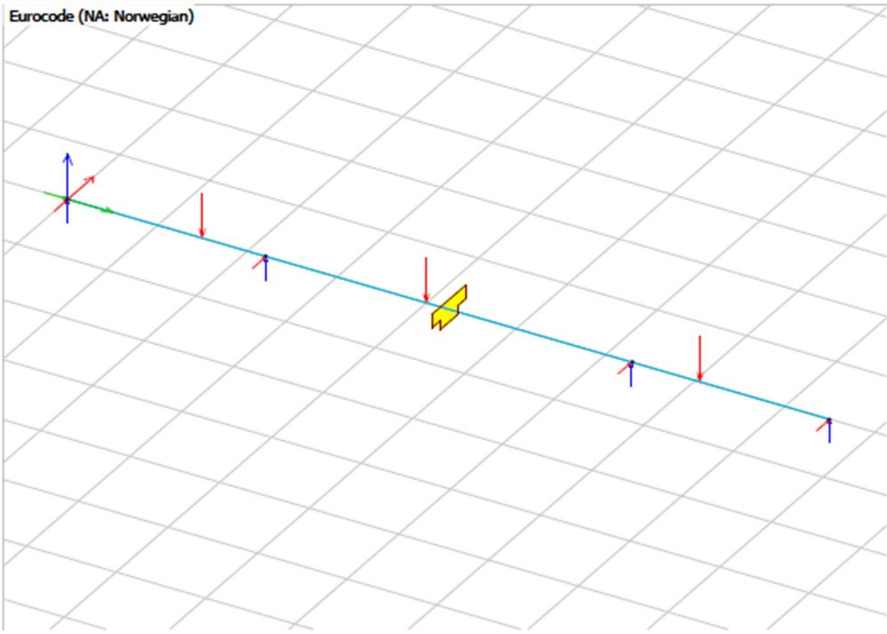
Whole structure / Load cases - Dead Load - (U) - Bars, Sigma x'(max/min) - Graph



Whole structure / PTC T0



Whole structure / Dead Load



Load combinations

No.	Name	Type	Factor	Load cases
1	LC1ULS	Ultimate	1.350	Dead Load (+Struc. dead load)
			1.350	PTC T0 (Post tensioning)
2	LC1ScLS	Characteristic	1.000	Dead Load (+Struc. dead load)
			1.000	PTC T0 (Post tensioning)

Load cases

No.	Name	Type	Duration class
1	Dead Load	+Struc. dead load	Permanent
2	PTC T0	Post tensioning	Permanent
3	PTC T8	Post tensioning	Permanent

Strands

No	Name	f pk	A p	E p	Rho	Relaxation class	Rho 1000
[-]	[-]	[N/mm2]	[mm2]	[N/mm2]	[t/m3]	[-]	[%]
1	Y1860S7-15,7-F1-C1	1860.0	150	195000.0	7.810	Class 2	2.500

Post-tensioned cables

ID	Strand type	Strand No.	Jacking stress	Jacking side	Curvature c.	Wobble c.	Anchorage set slip
[-]	[-]	[-]	[N/mm2]	[-]	[-]	[1/m]	[mm]
B.1.PTC.1	Y1860S7-15,7-F1-C1	3	2240.0	Start	0.00	0.000	0.0

Elastic shortening loss	Creep stress loss	Shrinkage stress loss	Relaxation stress loss
[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]
0.0	0.0	0.0	0.0

Post-tensioned cable manufacture table

ID	x' shift	z' shift	Point ID	x'	z'
[-]	[mm]	[mm]	[-]	[m]	[mm]
B.1.PTC.1	0	500	1	0.000	500
			2	2.000	359
			3	4.000	553
			4	6.000	516
			5	8.500	302

ID	x' shift	z' shift	Point ID	x'	z'
[-]	[mm]	[mm]	[-]	[m]	[mm]
			6	10.000	390
			7	12.000	566
			8	14.000	491
			9	17.000	500

Post-tensioned cables secondary data

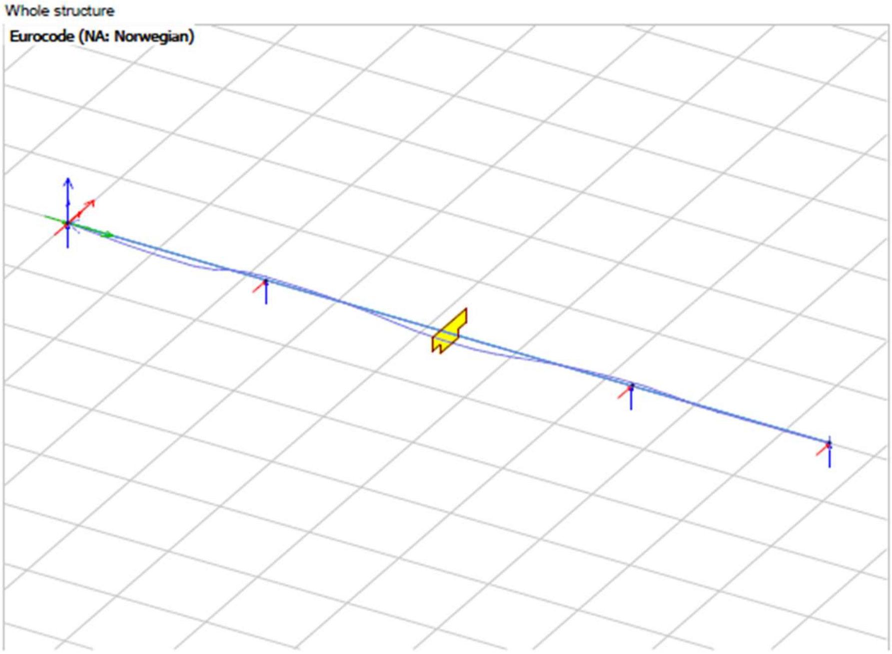
ID	Strand type	Strand No.	f pk	Stress T0 S	Stress T0 E	Stress T0 Avg	Stress T8 Avg
[-]	[-]	[-]	[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]
B.1.PTC.1	Y1860S7-15,7-F1-C1	3	1860.0	2240.0	2240.0	2240.0	2240.0

Min. radius of Curvature	Length (projected)	Length (real)	Length (all strand)	Volume	Mass
[m]	[m]	[m]	[m]	[m3]	[t]
0.870	17.000	17.053	51.158	0.008	0.060

Beams

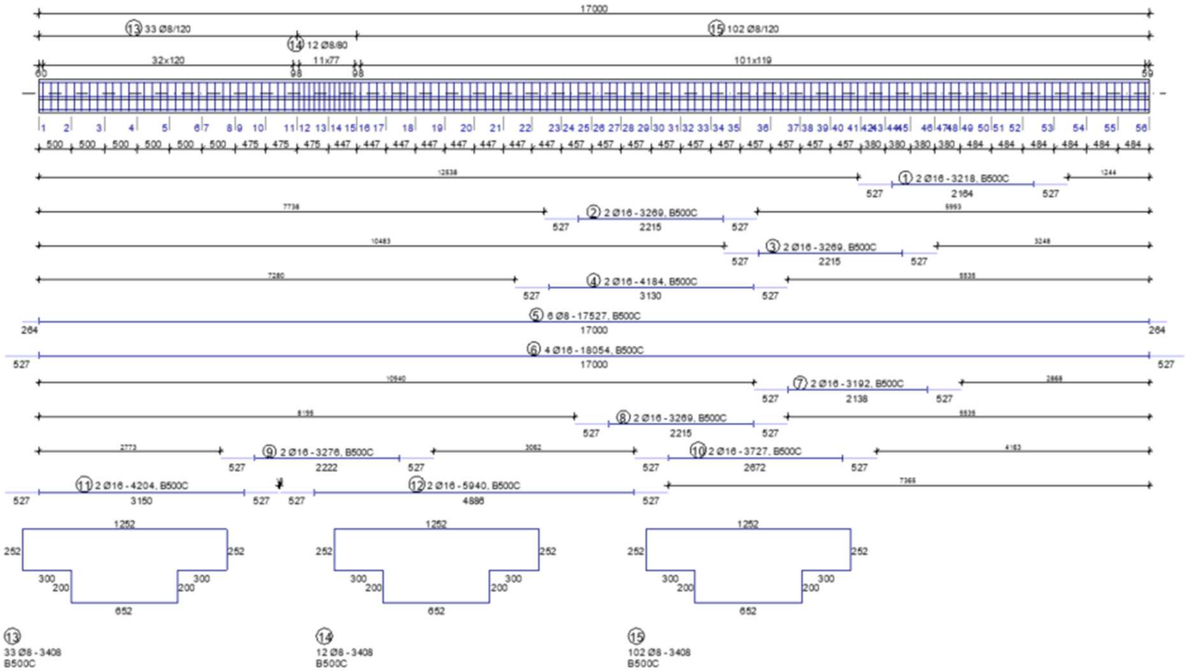
ID	Material	Section, start	Section, end	Ecc(x'), start	Ecc(y'), start	Ecc(z'), start
[-]	[-]	[-]	[-]	[m]	[m]	[m]
B.1.1	C35/45	Post_Tensioned 1300x50	Post_Tensioned 1300x50	0.000	0.000	0.000

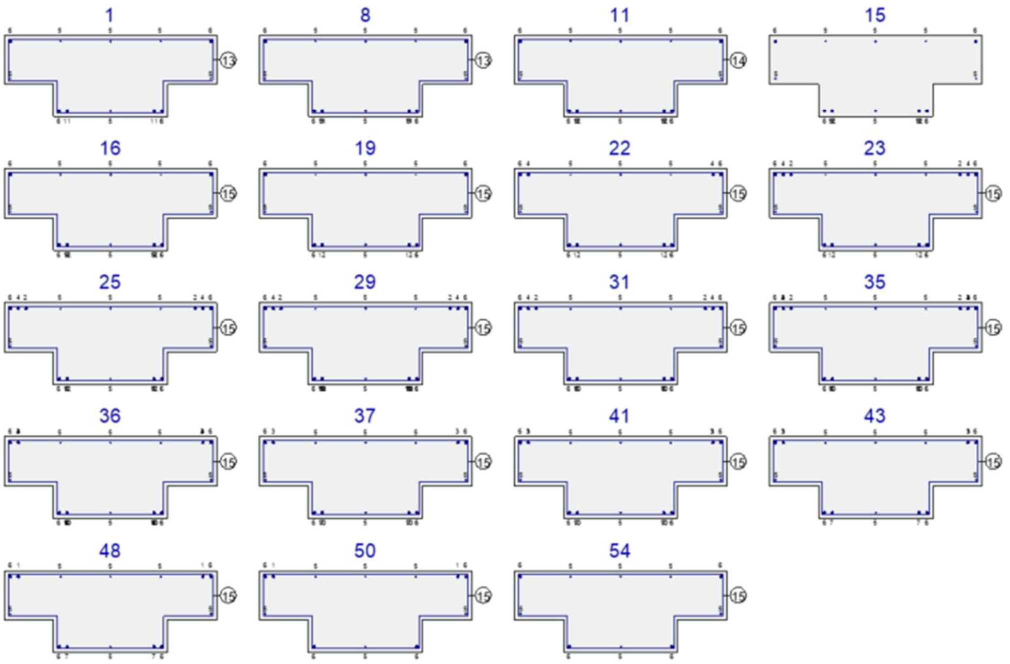
Ecc(x'), end	Ecc(y'), end	Ecc(z'), end	Ecc. mode.	Ecc. crack.	Sp. cond.	Ep. cond.
[m]	[m]	[m]	[-]	[-]	[-]	[-]
0.000	0.000	0.000	Release at END	No	FFFFFF	FFFFFF


Whole structure
Eurocode (NA: Norwegian)

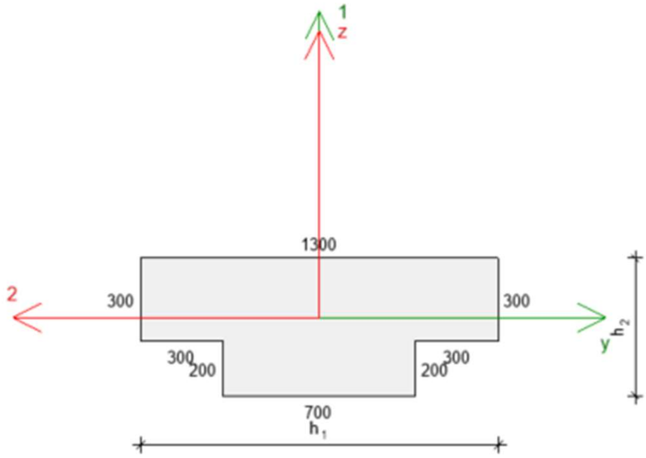
B.1.1
Maximum of load combinations

Reinforcement





Cross-section



h_1 = 1300 mm

h_2 = 500 mm

A_c = 530000 mm^2

I_{cy} = 9830345912 mm^4

I_{cz} = 60641666667 mm^4

I_{c1} = 60641666667 mm^4

I_{c2} = 9830345912 mm^4

Materials

C35/45

f_{ck}	=	35.00	N/mm^2
f_{ctm}	=	3.20	N/mm^2
$f_{ctk,0.05}$	=	2.20	N/mm^2
E_{cm}	=	34000.00	N/mm^2
α_{cc}	=	1.00	
α_{ct}	=	1.00	
γ_c	=	1.50	
γ_{CE}	=	1.20	
γ_s	=	1.15	
φ_{ef}	=	0.00	
$f_{cd} = \alpha_{cc}\, f_{ck} / \gamma_c$	=	23.33	N/mm^2
$f_{ctd} = \alpha_{ct}\, f_{ctk} / \gamma_c$	=	1.47	N/mm^2
$E_{cd} = E_{cm} / \gamma_{CE}$	=	28333.33	N/mm^2
ε_{c2}	=	0.00200	(Table 3.1)
ε_{cu2}	=	0.00350	(Table 3.1)
cot (Θ)	=	1.25	(Eq. 6.8)

B500C

$f_{yd} = f_{ywd}$	=	434.78	N/mm^2
E_s	=	200000.00	N/mm^2
$\varepsilon_{yd} = f_{yd} / E_s$	=	0.00217	
ε_{ud}	=	0.03000	

Section utilization for axial effects (Part 1.1: 5.8, 6.1)

Consideration of second order effects

$$\lambda = \frac{l_0}{i} \quad (5.14)$$

2nd order effect is considered according to nominal stiffness method. (Part 1.1: 5.8.7)

Sections	4	9	14	16	19	26	28	30	33	36	37	38	41	42	45	49	52
λ_{lim1} [-]	41.22	40.68	41.22	41.74	41.22	41.74	41.74	42.26	42.26	41.22	41.74	41.22	41.74	41.22	40.68	41.22	40.68
$l_{0,1}$ [mm]	4425	4425	4425	8150	8150	8150	8150	8150	8150	8150	8150	8150	4425	4425	4425	4425	4425
i_1 [mm]	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3	338.3
λ_1 [-]	13.08	13.08	13.08	24.09	24.09	24.09	24.09	24.09	24.09	24.09	24.09	24.09	13.08	13.08	13.08	13.08	13.08
2nd order effect in direction 1	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered	not considered
λ_{lim2} [-]	41.22	40.68	41.22	41.74	41.22	41.74	41.74	42.26	42.26	41.22	41.74	41.22	41.74	41.22	40.68	41.22	40.68
$l_{0,2}$ [mm]	4425	4425	4425	8150	8150	8150	8150	8150	8150	8150	8150	8150	4425	4425	4425	4425	4425
i_2 [mm]	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2	136.2
λ_2 [-]	32.49	32.49	32.49	59.84	59.84	59.84	59.84	59.84	59.84	59.84	59.84	59.84	32.49	32.49	32.49	32.49	32.49
2nd order effect in direction 2	not considered	not considered	not considered	considered	considered	considered	considered	considered	considered	considered	considered	considered	not considered	not considered	not considered	not considered	not considered

$n = N_{Ed} / (A_c f_{cd})$

$k_1 = \sqrt{f_{ck} / 20}$ (5.23)

$k_2 = \min\left(n \frac{\lambda}{170}, 0.20\right)$ (5.24)

$K_c = k_1 \cdot k_2 / (1 + \varphi_{ef})$ (5.22)

$K_s = 1.00$ (5.22)

$EI = K_c E_{cd} I_c + K_s E_s I_s$ (5.21)

$N_B = \frac{\pi^2 EI}{l_0^2}$ (5.17)

$M_{0Ed} = M^{I}_{Ed} + s_{Imperfection} \; N_{Ed} \frac{l_0}{400}$ (5.17)

$M^{II}_{Ed} = \frac{M_{0Ed}}{1 - |N_{Ed}| / N_B}$ (5.30)

$e_{min1} = \max(20 \text{ mm}, h_1 / 30) = \max(20 \text{ mm}, h_1 / 30) = 43 \text{ mm}$ (6.1(4))

$e_{min2} = \max(20 \text{ mm}, h_2 / 30) = \max(20 \text{ mm}, h_2 / 30) = 20 \text{ mm}$ (6.1(4))

$|M^{II}_{Ed}| \le |N_{Ed} e_{min}| \rightarrow M_{Ed} = s_{Minimal} \; N_{Ed} e_{min}$

$|M^{II}_{Ed}| > |N_{Ed} e_{min}| \rightarrow M_{Ed} = M^{II}_{Ed}$

Sections	4	9	14	16	19	26	28	30	33	36	37	38	41	42	45	49	52
LC	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS
N_{Ed} [kN]	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80
n [-]	-	-	-	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	-	-	-	-	-
k_1 [-]	-	-	-	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	-	-	-	-	-
$k_{2,1}$ [-]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$K_{c,1}$ [-]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$(E_s I_s)_1$ [N mm ^{2}]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$(EI)_1$ [N mm ^{2}]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$N_{B,1}$ [kN]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$M^{I}_{Ed,1}$ [kN m]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$s_{1\,Imperfection}$ [-]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$s_{1\,Second\,order}$ [-]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$s_{1\,Minimal}$ [-]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$M_{0Ed,1}$ [kN m]	-15.05	-15.05	-15.05	-27.73	-27.73	-27.73	-27.73	-27.73	-27.73	-27.73	-27.73	-27.73	-15.05	-15.05	-15.05	-15.05	-15.05
$M^{II}_{Ed,1}$ [kN m]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$M_{Ed,1}$ [kN m]	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97
$k_{2,2}$ [-]	-	-	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	-	-	-	-	-
$K_{c,2}$ [-]	-	-	-	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	-	-	-	-	-
$(E_s I_s)_2$ [N mm ^{2}]	-	-	-	1.6578e+13	1.2895e+13	1.6578e+13	1.6578e+13	2.0261e+13	2.0261e+13	1.2895e+13	1.6578e+13	1.2895e+13	-	-	-	-	-
$(EI)_2$ [N mm ^{2}]	-	-	-	3.0850e+13	2.7167e+13	3.0850e+13	3.0850e+13	3.4533e+13	3.4533e+13	2.7167e+13	3.0850e+13	2.7167e+13	-	-	-	-	-
$N_{B,2}$ [kN]	-	-	-	4583.98	4036.71	4583.98	4583.98	5131.25	5131.25	4036.71	4583.98	4036.71	-	-	-	-	-
$M^{I}_{Ed,2}$ [kN m]	51.20	-15.11	86.90	23.31	-69.32	23.74	58.34	66.20	6.05	-21.55	-6.19	-6.19	83.25	83.25	-15.17	-53.04	-33.37
$s_{2\,Imperfection}$ [-]	-1.00	1.00	-1.00	-1.00	1.00	-1.00	-1.00	-1.00	-1.00	1.00	1.00	1.00	-1.00	-1.00	1.00	1.00	1.00
$s_{2\,Second\,order}$ [-]	-1.00	1.00	-1.00	-1.00	1.00	-1.00	-1.00	-1.00	-1.00	1.00	1.00	1.00	-1.00	-1.00	1.00	1.00	1.00
$s_{2\,Minimal}$ [-]	-1.00	1.00	-1.00	-1.00	1.00	-1.00	-1.00	-1.00	-1.00	1.00	1.00	1.00	-1.00	-1.00	1.00	1.00	1.00
$M_{0Ed,2}$ [kN m]	66.26	-30.17	101.96	51.04	-97.04	51.46	86.07	93.93	33.78	-49.28	-33.91	-33.91	98.31	98.31	-30.23	-68.10	-48.42
$M^{II}_{Ed,2}$ [kN m]	-	-	-	72.59	-146.40	73.19	122.41	127.83	45.97	-74.34	-48.23	-51.16	-	-	-	-	-
$M_{Ed,2}$ [kN m]	66.26	-30.17	101.96	72.59	-146.40	73.19	122.41	127.83	45.97	-74.34	-48.23	-51.16	98.31	98.31	-30.23	-68.10	-48.42

Stresses and strains (Part 1.1: 6.1(2), 6.1(8), 3.1.7)

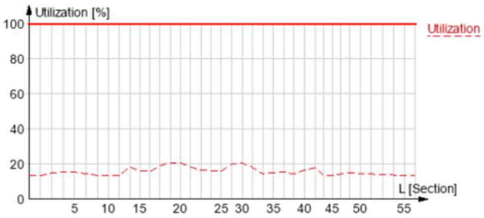
$\varepsilon_{steelLim} = \varepsilon_{ud}$

Section utilization

Ultimate internal forces: $N_{ult} = v\ N_{Ed}$; $M_{ult,1} = v\ M_{Ed,1}$; $M_{ult,2} = v\ M_{Ed,2}$

Utilization: $1\ /\ v$

Sections	4	9	14	16	19	26	28	30	33	36	37	38	41	42	45	49	52
LC	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS
N_{Ed} [kN]	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80
$M_{Ed,1}$ [kN m]	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97	-58.97
$M_{Ed,2}$ [kN m]	66.26	-30.17	101.96	72.59	-146.40	73.19	122.41	127.83	45.97	-74.34	-48.23	-51.16	98.31	98.31	-30.23	-68.10	-48.42
Utilization [%]	16	14	18	16	21	16	20	21	14	16	14	14	18	18	14	15	14



Stirrup utilization for shear and torsion (Part 1.1: 6.2, 6.3)

$C_{Rd,c}$ = is calculated according to National Annex

k_1 = is calculated according to National Annex

$$\sigma_{cp} = \min\left(\frac{N_{Ed}}{A_c},\ 0.2\ f_{cd}\right)$$

$$k = \min\left(1 + \sqrt{\frac{200}{d}},\ 2.0\right)$$

$$\rho_1 = \min\left(\frac{A_{sl}}{b_w\ d},\ 0.02\right)$$

v_{min} = is calculated according to National Annex

$V_{Rd,c}$ =

$$= \max\left(\left[C_{Rd,c}\ k\ (100\ \rho_1\ f_{ck})^{1/3} + k_1\ \sigma_{cp}\right] b_w\ d,\ (v_{min} + k_1\ \sigma_{cp})\ b_w\ d\right) \quad (6.2.a, 6.2.b)$$

$$V_{Rd,s} = \max\left(\frac{A_{sw}}{s}\ z\ f_{ywd}\ \cot(\Theta),\ V_{Rd,c}\right) \quad (6.8)$$

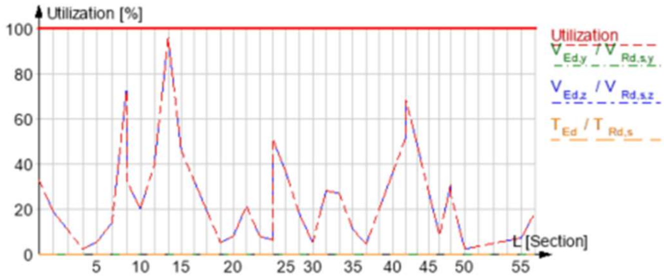
$$T_{Rd,c} = 2\ f_{ctd}\ t_{ef}\ A_k \quad (6.26)$$

$$T_{Rd,s} = \max\left(2\ \frac{A_{sw,min}}{s}\ f_{ywd}\ A_k,\ T_{Rd,c}\right) \quad (6.8, 6.26, 6.27)$$

Utilization: $\max\left(\frac{V_{Ed,y} + (T_{Ed}\ /\ A_k)\ d_y}{V_{Rd,s,y}},\ \frac{V_{Ed,z} + (T_{Ed}\ /\ A_k)\ d_z}{V_{Rd,s,z}}\right)$

If the stirrups are not correct by the detailing rules, the utilization is 1000%. (9.2.2 or 9.5.3)

Sections	8	14	42
LC	LC1ULS	LC1ULS	LC1ULS
N_{Ed} [kN]	-1360.80	-1360.80	-1360.80
$V_{Ed,y}$ [kN]	0.00	0.00	0.00
$V_{Ed,z}$ [kN]	195.20	273.38	183.27
T_{Ed} [kN m]	0.00	0.00	0.00
σ_{cp} [N/mm ^{2}]	2.57	2.57	2.57
A_{sl} [mm ^{2}]	0	0	0
d_y [mm]	1264	1264	1264
k_y [-]	1.40	1.40	1.40
$b_{w,y}$ [mm]	300	300	300
$\rho_{1,y}$ [-]	0.00000	0.00000	0.00000
$v_{min,y}$ [N/mm ^{2}]	0.34	0.34	0.34
$V_{Rd,c,y}$ [kN]	275.80	275.80	275.80
$(A_{sw,y}/s)\ f_{ywd}$ [N/mm]	364.24	546.36	364.24
z_y [mm]	1138	1138	1138
$V_{Rd,s,y}$ [kN]	517.95	776.93	517.95
$V_{Ed,y}/V_{Rd,s,y}$ [-]	0.00	0.00	0.00
d_z [mm]	464	464	464
k_z [-]	1.66	1.66	1.66
$b_{w,z}$ [mm]	700	700	700
$\rho_{1,z}$ [-]	0.00000	0.00000	0.00000
$v_{min,z}$ [N/mm ^{2}]	0.44	0.44	0.44
$V_{Rd,c,z}$ [kN]	268.48	268.48	268.48
$(A_{sw,z}/s)\ f_{ywd}$ [N/mm]	364.24	546.36	364.24
z_z [mm]	418	418	418
$V_{Rd,s,z}$ [kN]	268.48	285.20	268.48
$V_{Ed,z}/V_{Rd,s,z}$ [-]	0.73	0.96	0.68
A_k [mm ^{2}]	286674	286674	286674
t_{ef} [mm]	147	147	147
$T_{Rd,c}$ [kN m]	123.80	123.80	123.80
$(A_{sw,min}/s)\ f_{ywd}$ [N/mm]	182.12	273.18	182.12
$T_{Rd,s}$ [kN m]	123.80	156.63	123.80
$T_{Ed}/T_{Rd,s}$ [-]	0.00	0.00	0.00
Utilization [%]	73	96	68



Concrete utilization for shear and torsion (Part 1.1: 6.2, 6.3)

$$\sigma_{cp} = \min\left(\frac{N_{Ed}}{A_c}, 0.2\ f_{cd}\right)$$

$\alpha_{cw} = 1.0$ for non-prestressed structural elements.

$$\sigma_{cp} \le 0.25\ f_{cd} \rightarrow \alpha_{cw} = 1.0 + \frac{\sigma_{cp}}{f_{cd}} \quad (6.11.aN)$$

$$0.25\ f_{cd} \le \sigma_{cp} < 0.50\ f_{cd} \rightarrow \alpha_{cw} = 0.25 \quad (6.11.bN)$$

$$0.50\ f_{cd} \le \sigma_{cp} \rightarrow \alpha_{cw} = 2.5\left(1 + \frac{\sigma_{cp}}{f_{cd}}\right) \quad (6.11.cN)$$

$$v_1 = 0.60\left(1 - \frac{f_{ck}}{250}\right) \quad (6.6.N)$$

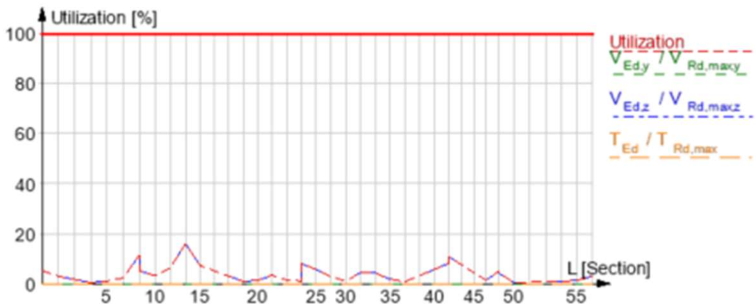
$$V_{Rd,max} = \frac{\alpha_{cw}\ b_w\ (0.9\ d)\ v_1\ f_{cd}}{\cot(\Theta) + \tan(\Theta)} \quad (6.9)$$

$$v = 0.60\left(1 - \frac{f_{ck}}{250}\right) \quad (6.6.N)$$

$$T_{Rd,max} = 2\ v\ \alpha_{cw}\ f_{cd}\ A_k\ t_{ef}\ \sin(\Theta)\ \cos(\Theta) \quad (6.30)$$

$$\text{Utilization:} \quad \frac{T_{Ed}}{T_{Rd,max}} + \max\left(\frac{V_{Ed,y}}{V_{Rd,max,y}}, \frac{V_{Ed,z}}{V_{Rd,max,z}}\right) \quad (6.29)$$

Sections	1	8	21	24	32	42	48	56
LC	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS
N_{Ed} [kN]	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80	-1360.80
$V_{Ed,y}$ [kN]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$V_{Ed,z}$ [kN]	88.87	195.20	58.05	137.99	76.06	183.27	83.01	51.13
T_{Ed} [kN m]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
σ_{cp} [N/mm ^{2}]	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57
α_{cw} [-]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
v_1 [-]	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
d_y [mm]	1264	1264	1264	1264	1264	1264	1264	1264
$b_{w,y}$ [mm]	300	300	300	300	300	300	300	300
$V_{Rd,maxy}$ [kN]	2004.40	2004.40	2004.40	2004.40	2004.40	2004.40	2004.40	2004.40
$V_{Ed,y}$ / $V_{Rd,maxy}$ [-]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
d_z [mm]	464	464	464	464	464	464	464	464
$b_{w,z}$ [mm]	700	700	700	700	700	700	700	700
$V_{Rd,maxz}$ [kN]	1716.85	1716.85	1716.85	1716.85	1716.85	1716.85	1716.85	1716.85
$V_{Ed,z}$ / $V_{Rd,maxz}$ [-]	0.05	0.11	0.03	0.08	0.04	0.11	0.05	0.03
v [-]	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
A_k [mm ^{2}]	286674	286674	286674	286674	286674	286674	286674	286674
t_{ef} [mm]	147	147	147	147	147	147	147	147
$T_{Rd,max}$ [kN m]	495.75	495.75	495.75	495.75	495.75	495.75	495.75	495.75
T_{Ed} / $T_{Rd,max}$ [-]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Utilization [%]	5	11	3	8	4	11	5	3

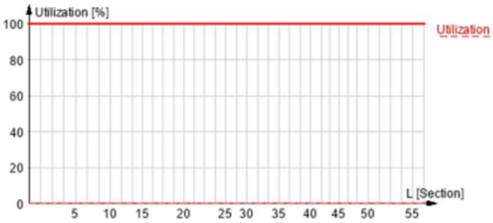


Torsional reinforcement utilization (Part 1.1: 6.3)

$$T_{Rd,sl} = 2\ A_k \frac{\Sigma\ (A_{sl}\ f_{yd})}{u_k} \tan(\Theta) \qquad (6.28)$$

Utilization: $\frac{T_{Ed}}{T_{Rd,sl}}$

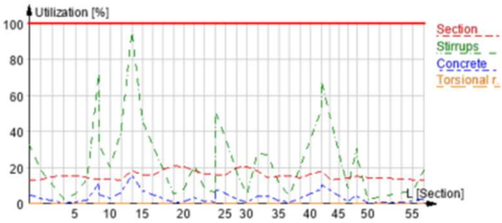
Sections	7	10	14	16	24	26	28	32	33	36	37	38	41	43	45	51	56
LC	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS	LC1ULS
T_{Ed} [kN m]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_k [mm ^{2}]	286674	286674	286674	286674	286674	286674	286674	286674	286674	286674	286674	286674	286674	286674	286674	286674	286674
u_k [mm]	3011	3011	3011	3011	3011	3011	3011	3011	3011	3011	3011	3011	3011	3011	3011	3011	3011
$\Sigma(A_{sl}f_{yd})$ [N]	655637	480800	655637	830473	655637	830473	830473	1005310	1005310	655637	830473	655637	830473	655637	480800	655637	480800
$T_{Rd,sl}$ [kN m]	99.87	73.24	99.87	126.51	99.87	126.51	126.51	153.14	153.14	99.87	126.51	99.87	126.51	99.87	73.24	99.87	73.24
Utilization [%]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



Crack width (Part 1.1: 7.3)

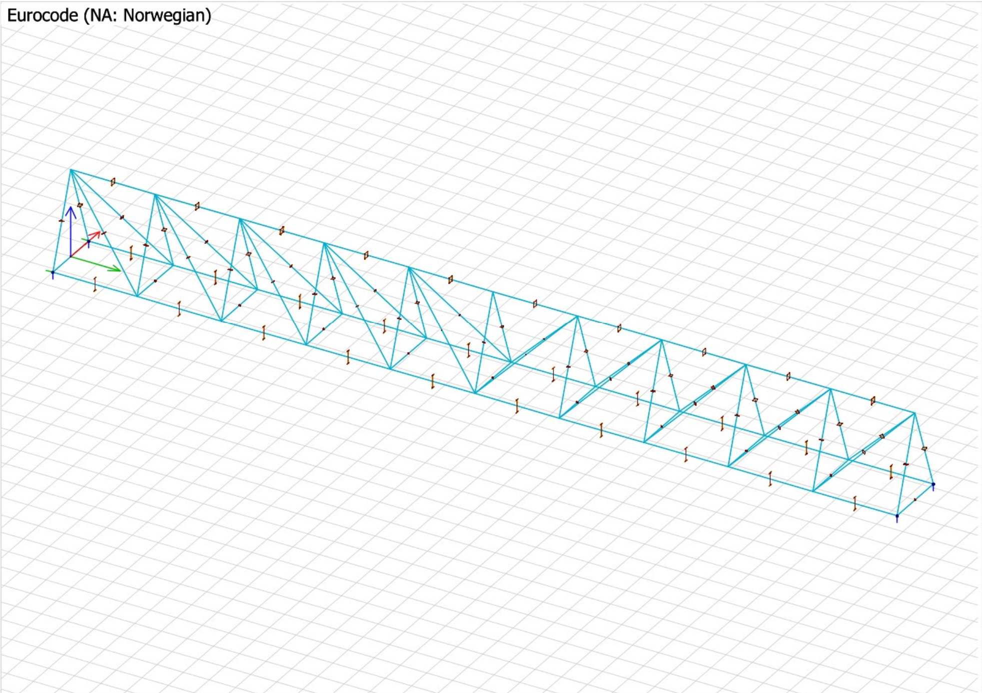
Not relevant

Summary



9.2 Appendix B – Calculation report – Case 8

Whole structure



Beams

ID	Material	Section, start	Section, end	Ecc(x'), start	Ecc(y'), start	Ecc(z'), start	Ecc(x'), end
[-]	[-]	[-]	[-]	[m]	[m]	[m]	[m]
B.1.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.2.1	S 355	VKR 200x200x12.5	VKR 200x200x12.5	0.000	0.000	0.000	0.000
B.3.1	S 355	VKR 180x180x10	VKR 180x180x10	0.000	0.000	0.000	0.000
B.4.1	S 355	VKR 120x120x10	VKR 120x120x10	0.000	0.000	0.000	0.000
B.5.1	S 355	VKR 50x50x4	VKR 50x50x4	0.000	0.000	0.000	0.000
B.6.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.7.1	S 355	VKR 200x200x12.5	VKR 200x200x12.5	0.000	0.000	0.000	0.000
B.8.1	S 355	VKR 180x180x10	VKR 180x180x10	0.000	0.000	0.000	0.000
B.9.1	S 355	VKR 120x120x10	VKR 120x120x10	0.000	0.000	0.000	0.000
B.10.1	S 355	VKR 50x50x4	VKR 50x50x4	0.000	0.000	0.000	0.000

Ecc(y'), end	Ecc(z'), end	Ecc. mode.	Ecc. crack.	Sp. cond.	Ep. cond.
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0.000	0.000	Release at END	No	FFFFFF	FFFFFF

ID	Material	Section, start	Section, end	Ecc(x'), start	Ecc(y'), start	Ecc(z'), start	Ecc(x'), end
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B.11.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.12.1	S 355	VKR 200x200x12.5	VKR 200x200x12.5	0.000	0.000	0.000	0.000
B.13.1	S 355	VKR 180x180x10	VKR 180x180x10	0.000	0.000	0.000	0.000
B.14.1	S 355	VKR 120x120x10	VKR 120x120x10	0.000	0.000	0.000	0.000
B.15.1	S 355	VKR 50x50x4	VKR 50x50x4	0.000	0.000	0.000	0.000
B.16.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.17.1	S 355	VKR 200x200x12.5	VKR 200x200x12.5	0.000	0.000	0.000	0.000
B.18.1	S 355	VKR 180x180x10	VKR 180x180x10	0.000	0.000	0.000	0.000
B.19.1	S 355	VKR 120x120x10	VKR 120x120x10	0.000	0.000	0.000	0.000
B.20.1	S 355	VKR 50x50x4	VKR 50x50x4	0.000	0.000	0.000	0.000
B.21.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.22.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.23.1	S 355	VKR 250x250x10	VKR 250x250x10	0.000	0.000	0.000	0.000
B.24.1	S 355	VKR 200x200x12.5	VKR 200x200x12.5	0.000	0.000	0.000	0.000
B.25.1	S 355	VKR 180x180x8	VKR 180x180x8	0.000	0.000	0.000	0.000
B.26.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.27.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.28.1	S 355	VKR 250x250x10	VKR 250x250x10	0.000	0.000	0.000	0.000
B.29.1	S 355	VKR 200x200x12.5	VKR 200x200x12.5	0.000	0.000	0.000	0.000
B.30.1	S 355	VKR 180x180x8	VKR 180x180x8	0.000	0.000	0.000	0.000
B.31.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.32.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.33.1	S 355	VKR 250x250x10	VKR 250x250x10	0.000	0.000	0.000	0.000
B.34.1	S 355	VKR 200x200x12.5	VKR 200x200x12.5	0.000	0.000	0.000	0.000

Ecc(y'), end	Ecc(z'), end	Ecc. mode.	Ecc. crack.	Sp. cond.	Ep. cond.
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B.35.1	S 355	VKR 180x180x8	VKR 180x180x8	0.000	0.000	0.000	0.000
B.36.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.37.1	S 355	VKR 250x250x16	VKR 250x250x16	0.000	0.000	0.000	0.000
B.38.1	S 355	VKR 250x250x10	VKR 250x250x10	0.000	0.000	0.000	0.000
B.39.1	S 355	VKR 200x200x12.5	VKR 200x200x12.5	0.000	0.000	0.000	0.000
B.40.1	S 355	VKR 180x180x8	VKR 180x180x8	0.000	0.000	0.000	0.000
B.41.1	S 355	VKR 150x150x10	VKR 150x150x10	0.000	0.000	0.000	0.000
B.42.1	S 355	VKR 150x150x10	VKR 150x150x10	0.000	0.000	0.000	0.000
B.43.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.44.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.45.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.46.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.47.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.48.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.49.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.50.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.51.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.52.1	S 355	VKR 400x400x16	VKR 400x400x16	0.000	0.000	0.000	0.000
B.53.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.54.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.55.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.56.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.57.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.58.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000

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B.59.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.60.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.61.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.62.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.63.1	S 355	VKR 100x100x10	VKR 100x100x10	0.000	0.000	0.000	0.000
B.64.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.65.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.66.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.67.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.68.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.69.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.70.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.71.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.72.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.73.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.74.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.75.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.76.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.77.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.78.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.79.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.80.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.81.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000
B.82.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000

Ecc(y'), end	Ecc(z'), end	Ecc. mode.	Ecc. crack.	Sp. cond.	Ep. cond.
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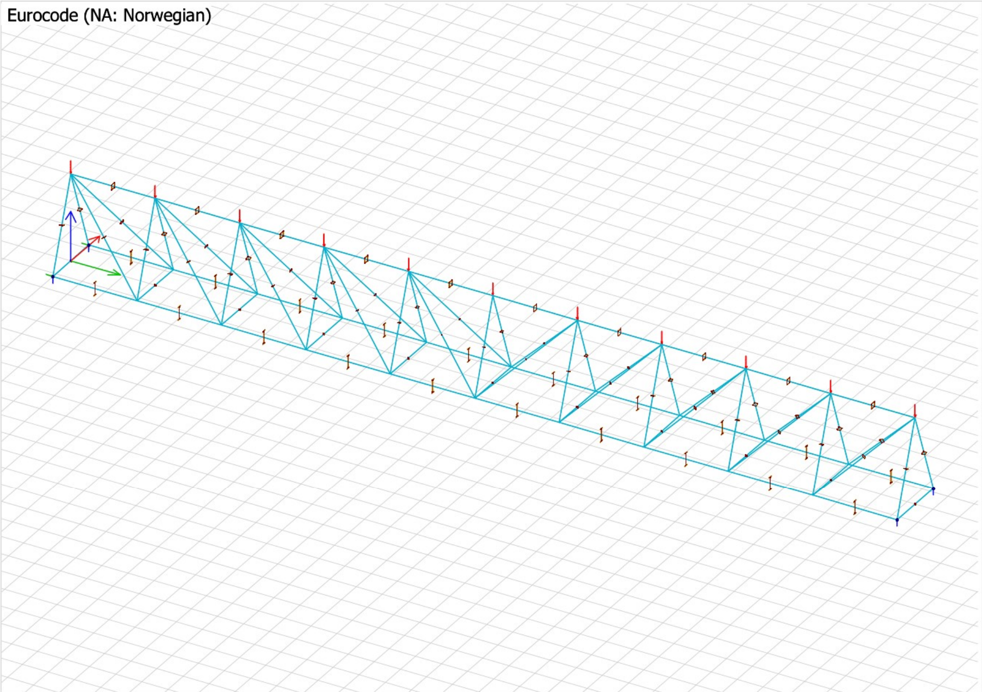
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF
0.000	0.000	Release at END	No	FFFFFF	FFFFFF

ID	Material	Section, start	Section, end	Ecc(x'), start	Ecc(y'), start	Ecc(z'), start	Ecc(x'), end
[-]	[-]	[-]	[-]	[m]	[m]	[m]	[m]
B.83.1	S 355	HE-B 1000	HE-B 1000	0.000	0.000	0.000	0.000

Ecc(y'), end	Ecc(z'), end	Ecc. mode.	Ecc. crack.	Sp. cond.	Ep. cond.
[m]	[m]	[-]	[-]	[-]	[-]
0.000	0.000	Release at END	No	FFFFFF	FFFFFF

Whole structure / Snow + Dead load



Load cases

No.	Name	Type	Duration class
1	Snow	Ordinary	Long-term
2	Dead load	+Struc. dead load	Permanent

Load groups

No.	Load group	Included load cases
1	Dead Load (Permanent, 1.00, 1.35, 1.00, 1.00, 0.89)	Dead load (+Struc. dead load)
2	Snow Load (Temporary, 1.50, 0.70, 0.50, 0.20, L, --, --)	Snow

Load combinations

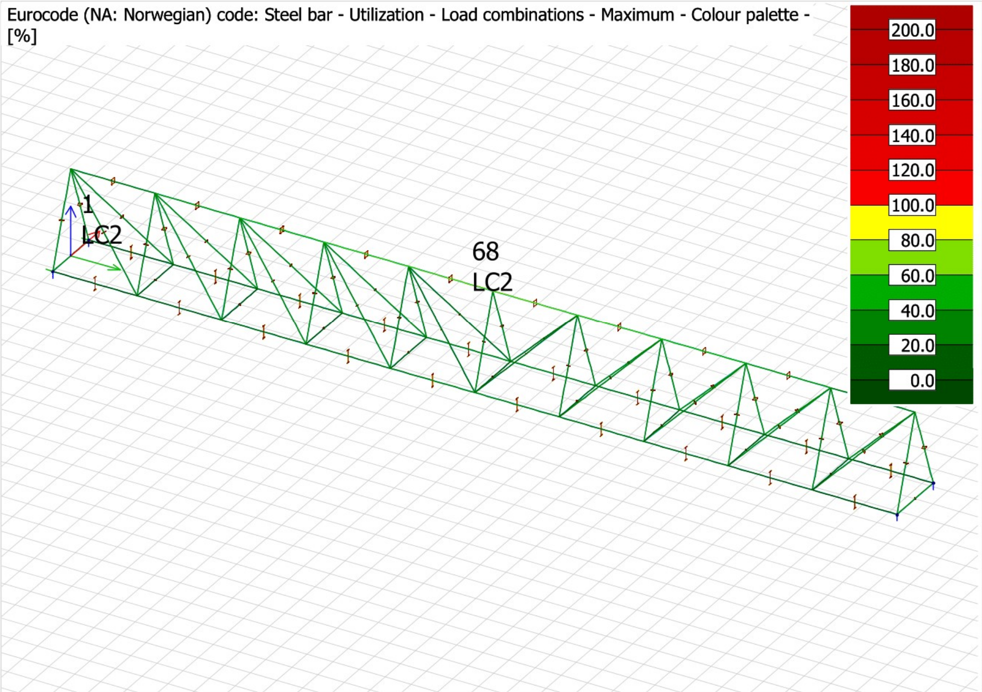
No.	Name	Type	Factor	Load cases
1	ULS 1	Ultimate	1.350	Dead load (+Struc. dead load)
			1.050	Snow
2	ULS 2	Ultimate	1.500	Snow
			1.202	Dead load (+Struc. dead load)
3	SLS	Characteristic	1.000	Snow

No.	Name	Type	Factor	Load cases
			1.000	Dead load (+Struc. dead load)

Point loads

No.	F	M	Load case	Comment	Applied on Ecc.	Assigned
[-]	[kN]	[kNm]	[-]	[-]	[-]	[-]
1	31.008	0.000	Dead load		No	-
2	62.016	0.000	Dead load		No	-
3	62.016	0.000	Dead load		No	-
4	62.016	0.000	Dead load		No	-
5	62.016	0.000	Dead load		No	-
6	62.016	0.000	Dead load		No	-
7	62.016	0.000	Dead load		No	-
8	62.016	0.000	Dead load		No	-
9	62.016	0.000	Dead load		No	-
10	62.016	0.000	Dead load		No	-
11	31.008	0.000	Dead load		No	-
12	86.822	0.000	Snow		No	-
13	173.645	0.000	Snow		No	-
14	173.645	0.000	Snow		No	-
15	173.645	0.000	Snow		No	-
16	173.645	0.000	Snow		No	-
17	173.645	0.000	Snow		No	-
18	173.645	0.000	Snow		No	-
19	173.645	0.000	Snow		No	-
20	173.645	0.000	Snow		No	-
21	173.645	0.000	Snow		No	-
22	86.822	0.000	Snow		No	-

Whole structure / Steel bar - Utilization - Load combinations - Maximum - Colour palette



Max. of load combinations, Bar, Utilization

Member	Section	Status	Maximum	Combination	RCS	FB	TFB	LTB,t	LTB,b	SB	IA
[-]	[-]	[-]	[%]	[-]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
B.1.1	VKR 250x250x16	Real	30	ULS 2	30	-	-	1	4	-	4
B.2.1	VKR 200x200x12.5	Real	36	ULS 2	36	-	-	2	4	-	4
B.3.1	VKR 180x180x10	Real	35	ULS 2	35	-	-	2	4	-	4
B.4.1	VKR 120x120x10	Real	33	ULS 2	33	-	-	2	4	-	5
B.5.1	VKR 50x50x4	Real	21	ULS 2	21	-	-	6	10	-	11
B.6.1	VKR 250x250x16	Real	30	ULS 2	30	-	-	1	4	-	4
B.7.1	VKR 200x200x12.5	Real	36	ULS 2	36	-	-	2	4	-	4
B.8.1	VKR 180x180x10	Real	35	ULS 2	35	-	-	2	4	-	4
B.9.1	VKR 120x120x10	Real	33	ULS 2	33	-	-	2	4	-	5
B.10.1	VKR 50x50x4	Real	21	ULS 2	21	-	-	6	10	-	11
B.11.1	VKR 250x250x16	Real	30	ULS 2	30	-	-	1	4	-	4
B.12.1	VKR 200x200x12.5	Real	36	ULS 2	36	-	-	2	4	-	4
B.13.1	VKR 180x180x10	Real	35	ULS 2	35	-	-	2	4	-	4
B.14.1	VKR 120x120x10	Real	33	ULS 2	33	-	-	2	4	-	5
B.15.1	VKR 50x50x4	Real	21	ULS 2	21	-	-	6	10	-	11
B.16.1	VKR 250x250x16	Real	30	ULS 2	30	-	-	1	4	-	4
B.17.1	VKR 200x200x12.5	Real	36	ULS 2	36	-	-	2	4	-	4
B.18.1	VKR 180x180x10	Real	35	ULS 2	35	-	-	2	4	-	4
B.19.1	VKR 120x120x10	Real	33	ULS 2	33	-	-	2	4	-	5
B.20.1	VKR 50x50x4	Real	21	ULS 2	21	-	-	6	10	-	11
B.21.1	VKR 250x250x16	Real	34	ULS 2	27	31	21	1	0	-	34
B.22.1	VKR 250x250x16	Real	31	ULS 2	26	27	18	1	1	-	31
B.23.1	VKR 250x250x10	Real	35	ULS 2	30	30	21	1	1	-	35
B.24.1	VKR 200x200x12.5	Real	33	ULS 2	22	30	15	1	1	-	33

Member	Section	Status	Maximum	Combination	RCS	FB	TFB	LTB,t	LTB,b	SB	IA
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B.25.1	VKR 180x180x8	Real	28	ULS 2	17	24	11	1	1	-	28
B.26.1	VKR 250x250x16	Real	34	ULS 2	27	31	21	1	0	-	34
B.27.1	VKR 250x250x16	Real	31	ULS 2	26	27	18	1	1	-	31
B.28.1	VKR 250x250x10	Real	35	ULS 2	30	30	21	1	1	-	35
B.29.1	VKR 200x200x12.5	Real	33	ULS 2	22	30	15	1	1	-	33
B.30.1	VKR 180x180x8	Real	28	ULS 2	17	24	11	1	1	-	28
B.31.1	VKR 250x250x16	Real	34	ULS 2	27	31	21	1	0	-	34
B.32.1	VKR 250x250x16	Real	31	ULS 2	26	27	18	1	1	-	31
B.33.1	VKR 250x250x10	Real	35	ULS 2	30	30	21	1	1	-	35
B.34.1	VKR 200x200x12.5	Real	33	ULS 2	22	30	15	1	1	-	33
B.35.1	VKR 180x180x8	Real	28	ULS 2	17	24	11	1	1	-	28
B.36.1	VKR 250x250x16	Real	34	ULS 2	27	31	21	1	0	-	34
B.37.1	VKR 250x250x16	Real	31	ULS 2	26	27	18	1	1	-	31
B.38.1	VKR 250x250x10	Real	35	ULS 2	30	30	21	1	1	-	35
B.39.1	VKR 200x200x12.5	Real	33	ULS 2	22	30	15	1	1	-	33
B.40.1	VKR 180x180x8	Real	28	ULS 2	17	24	11	1	1	-	28
B.41.1	VKR 150x150x10	Real	29	ULS 2	10	29	9	1	1	-	29
B.42.1	VKR 150x150x10	Real	29	ULS 2	10	29	9	1	1	-	29
B.43.1	VKR 400x400x16	Real	27	ULS 2	25	23	21	2	4	-	27
B.44.1	VKR 400x400x16	Real	44	ULS 2	40	41	37	3	3	-	44
B.45.1	VKR 400x400x16	Real	56	ULS 2	51	53	49	2	1	-	56
B.46.1	VKR 400x400x16	Real	63	ULS 2	58	61	55	2	-	-	63
B.47.1	VKR 400x400x16	Real	68	ULS 2	62	61	56	6	-	-	68
B.48.1	VKR 400x400x16	Real	68	ULS 2	62	61	56	6	-	-	68
B.49.1	VKR 400x400x16	Real	63	ULS 2	58	61	55	2	-	-	63
B.50.1	VKR 400x400x16	Real	56	ULS 2	51	53	49	2	1	-	56
B.51.1	VKR 400x400x16	Real	44	ULS 2	40	41	37	3	3	-	44
B.52.1	VKR 400x400x16	Real	27	ULS 2	25	23	21	2	4	-	27
B.53.1	VKR 100x100x10	Real	32	ULS 2	32	-	-	1	1	-	2
B.54.1	VKR 100x100x10	Real	5	ULS 1	3	4	1	1	1	-	5
B.55.1	VKR 100x100x10	Real	5	ULS 1	2	4	1	1	1	-	5
B.56.1	VKR 100x100x10	Real	4	ULS 1	2	3	1	1	1	-	4
B.57.1	VKR 100x100x10	Real	11	ULS 2	4	9	3	2	1	-	11
B.58.1	VKR 100x100x10	Real	5	ULS 2	5	-	-	2	1	-	2
B.59.1	VKR 100x100x10	Real	11	ULS 2	4	9	3	2	1	-	11
B.60.1	VKR 100x100x10	Real	4	ULS 1	2	3	1	1	1	-	4
B.61.1	VKR 100x100x10	Real	5	ULS 1	2	4	1	1	1	-	5
B.62.1	VKR 100x100x10	Real	5	ULS 1	3	4	1	1	1	-	5
B.63.1	VKR 100x100x10	Real	32	ULS 2	32	-	-	1	1	-	2
B.64.1	HE-B 1000	Real	3	ULS 2	3	-	-	3	1	1	3
B.65.1	HE-B 1000	Real	11	ULS 2	11	-	-	5	-	1	5
B.66.1	HE-B 1000	Real	17	ULS 2	17	-	-	8	-	1	8
B.67.1	HE-B 1000	Real	21	ULS 2	21	-	-	10	-	1	10
B.68.1	HE-B 1000	Real	32	ULS 2	32	-	-	22	-	2	22
B.69.1	HE-B 1000	Real	32	ULS 2	32	-	-	22	-	2	22
B.70.1	HE-B 1000	Real	21	ULS 2	21	-	-	10	-	1	10
B.71.1	HE-B 1000	Real	17	ULS 2	17	-	-	8	-	1	8
B.72.1	HE-B 1000	Real	11	ULS 2	11	-	-	5	-	1	5
B.73.1	HE-B 1000	Real	3	ULS 2	3	-	-	3	1	1	3
B.74.1	HE-B 1000	Real	3	ULS 2	3	-	-	3	1	1	3
B.75.1	HE-B 1000	Real	11	ULS 2	11	-	-	5	-	1	5
B.76.1	HE-B 1000	Real	17	ULS 2	17	-	-	8	-	1	8

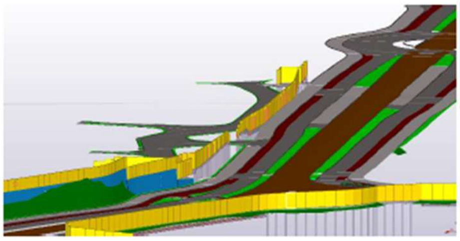
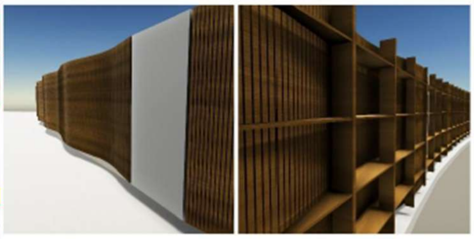
Member	Section	Status	Maximum	Combination	RCS	FB	TFB	LTB,t	LTB,b	SB	IA
[-]	[-]	[-]	[%]	[-]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
B.77.1	HE-B 1000	Real	21	ULS 2	21	-	-	10	-	1	10
B.78.1	HE-B 1000	Real	32	ULS 2	32	-	-	22	-	2	22
B.79.1	HE-B 1000	Real	32	ULS 2	32	-	-	22	-	2	22
B.80.1	HE-B 1000	Real	21	ULS 2	21	-	-	10	-	1	10
B.81.1	HE-B 1000	Real	17	ULS 2	17	-	-	8	-	1	8
B.82.1	HE-B 1000	Real	11	ULS 2	11	-	-	5	-	1	5
B.83.1	HE-B 1000	Real	3	ULS 2	3	-	-	3	1	1	3

9.3 Appendix C – Questionnaire – Parametric BIM-Modelling

Evaluering av Parametrisk Design

Bussveien v/Hans og Grete Stien

Støyskjerm og spilevegg

For å modellere BIM-modellene til støyskjerm og spilevegg ved Bussveien ble det anvendt parametrisk design. Parametrisk design ble blant annet brukt til å plassere ut støyskjerm mellom gitte kotehøyder og terreng, sette ut spilevegg langs en buet betongvegg med varierende offset(sinuskurve), samt tilegne alle elementene riktig BIM-Informasjon. I min masteroppgave prøver jeg å kartlegge hvilke oppgaver parametrisk design egner seg til å løse. I den forbindelse vil jeg svært gjerne høre hvordan du opplevde bruken av parametrisk design og eventuelt om du ser for deg å jobbe på en likende måte i fremtiden.

Hvilke fordeler/ulemper opplevde du ved bruk av parametrisk design i dette prosjektet?

Pros:

- Kan legge ut geometri nøyaktig og effektivt
- Raskt å skrive metadata til modell
- Friere tøyler til å modelere langs kurver

Cons:

- Blir veldig avhengig av originator på script for å oppdatere modell. (Dette er et generelt problem, en klarer omtrent aldri å scripte noe helt vanntett/robust som løser alle problemer, så det blir en balansesak.) Kanskje holde geometri «levende» med parametere inntil et punkt «design frys» der en begynner å detaljere, og så «kutter» link mellom parameterstyrt og modell.
- Når en først begynner å «jukse» med manuell oppdatering av geometri, så er en i farlig vann og ødelegger for parametrisk tankegang
-

Har du inntrykk av at parametrisk design økte effektiviteten av modelleringsarbeidet? Hvis ja, kan du gi et estimat på hvor mye tid som ble spart?

- Ikke på dette prosjektet. Men ikke parametrisk design sin feil, har vært så mye frem og tilbake med støyskjermer og interfaces. Gjenbruk av tankegang på neste støyskjerm vil gjøre den mer effektiv. Må ha en lesson learned på hva en ønsker å ha i modell, og hva parametrisk design skal skrive ut til modell av metadata.

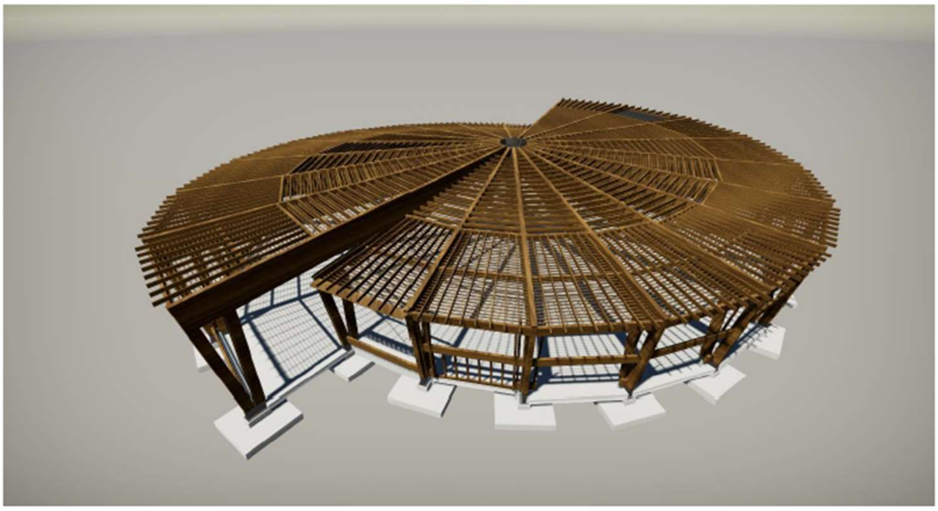
Kunne du tenke deg å anvende parametrisk design i fremtiden?

- Absolutt. Må brukes riktig. Tror det er nødvendig å bruke for å øke effektivitet. Har noen tanker på hvordan det skal kunne brukes. Må ha fokus på planlagt input/output fra start så blir det bra.

Evaluering av Parametrisk Design

Klepp Aktivitetspark

Paviljong



For å modellere BIM-modellen til Klepp Paviljong ble det anvendt parametrisk design. Parametrisk design ble brukt til å modellere store deler av takkonstruksjonen, tilegne alle elementene riktig BIM-Informasjon, og kutte elementene mot hverandre. I min masteroppgave prøver jeg å kartlegge hvilke oppgaver parametrisk design egner seg til å løse. I den forbindelse vil jeg svært gjerne høre hvordan du opplevde bruken av parametrisk design og eventuelt om du ser for deg å jobbe på en likende måte i fremtiden.

Hvilke fordeler/ulemper opplevde du ved bruk av parametrisk design i dette prosjektet?

Utelukkende fordeler ved å bruke parametrisk design i dette prosjektet. Her hadde vi ingen gjentagende vinkler, avstander eller kopieringsmuligheter for selve taket. Alle tak hadde ulik helning mot ulike punkt og alle bjelkene hadde ulik OK og UK i topp og bunn.

Bruk av normale modelleringsmetoder ville ikke vært hensiktsmessig pga. mengden på antall objekter og ulike kutt for omtrent hver eneste bjelke. Normalt ville man da holdt seg til et typisk snitt og tegnet ut dette.

Dersom man skulle valgt å gjøre dette ved vanlig modellering ville det også vært svært kritisk dersom det kom endringer. Med parametrisk modellering var en liten endring en smal sak og spart utallige timer.

Har du inntrykk av at parametrisk design økte effektiviteten av modelleringsarbeidet? Hvis ja, kan du gi et estimat på hvor mye tid som ble spart?

Usikker på hva som ble brukt fra begynnelsen av, men når vi måtte utføre endringer tok dette tilnærmet ingen tid enn hva en måtte gjort med normal modellering.

Hvis en skal anta, vil jeg tro at selve første modelleringen av taket kunne blitt utført på relativ lik tid, men da må alt være rett første gangen og har ikke rom for modelleringsfeil.

Etter hva jeg har forstått er det å utarbeide skript det som tar tid, men siden man har skriptet vil evt. endringer/justeringer/tilpasninger være lett å forholde seg til og noe man til en viss grad kan tilby kunde og ikke noe man ønsker å unngå.

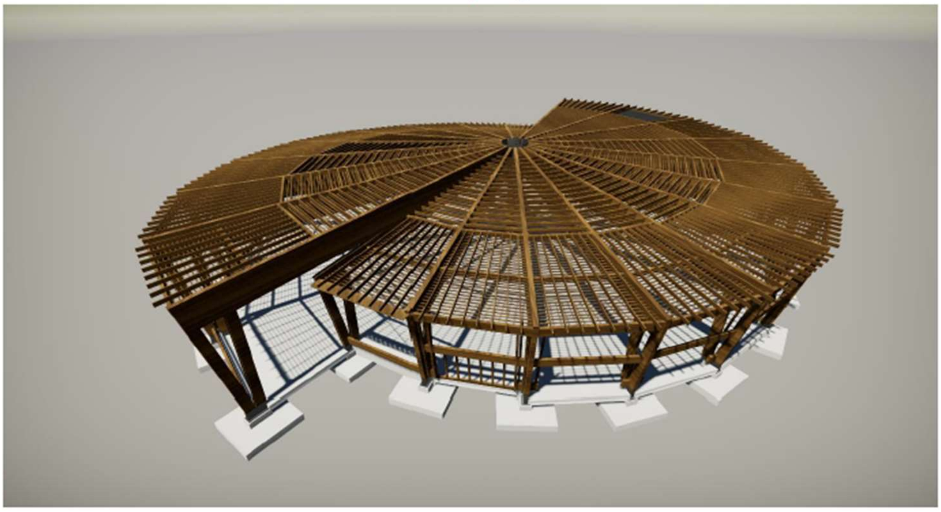
Kunne du tenke deg å anvende parametrisk design i fremtiden?

Ja. Mye av dagens tilleggprogrammer til modelleringsverktøy er basert på parametrisk modellering så antar at det blir lettere å bruke etter hvert.

Evaluering av Parametrisk Design

Klepp Aktivitetspark

Paviljong



For å modellere BIM-modellen til Klepp Paviljong ble det anvendt parametrisk design. Parametrisk design ble brukt til å modellere store deler av takkonstruksjonen, tilegne alle elementene riktig BIM-Informasjon, og kutte elementene mot hverandre. I min masteroppgave prøver jeg å kartlegge hvilke oppgaver parametrisk design egner seg til å løse. I den forbindelse vil jeg svært gjerne høre hvordan du opplevde bruken av parametrisk design og eventuelt om du ser for deg å jobbe på en likende måte i fremtiden.

Hvilke fordeler/ulemper opplevde du ved bruk av parametrisk design i dette prosjektet?

It reduced the amount of repetitive drawing/modeling operations due to the geometry of the structure.

Not really any disadvantage.

Har du inntrykk av at parametrisk design økte effektiviteten av modelleringsarbeidet? Hvis ja, kan du gi et estimat på hvor mye tid som ble spart?

In this case, I am sure it saved 4 days (32hours) in the first design but more importantly, it allowed to modify the structure fast when changes in the design was made after the first design was released. So, it is probably difficult to estimate the total saving in the project.

Note that the design of all the elements of the roof, was never in the scope of the project. So, we decided to apply this technique as an innovation. We did it as well to support the architect design.

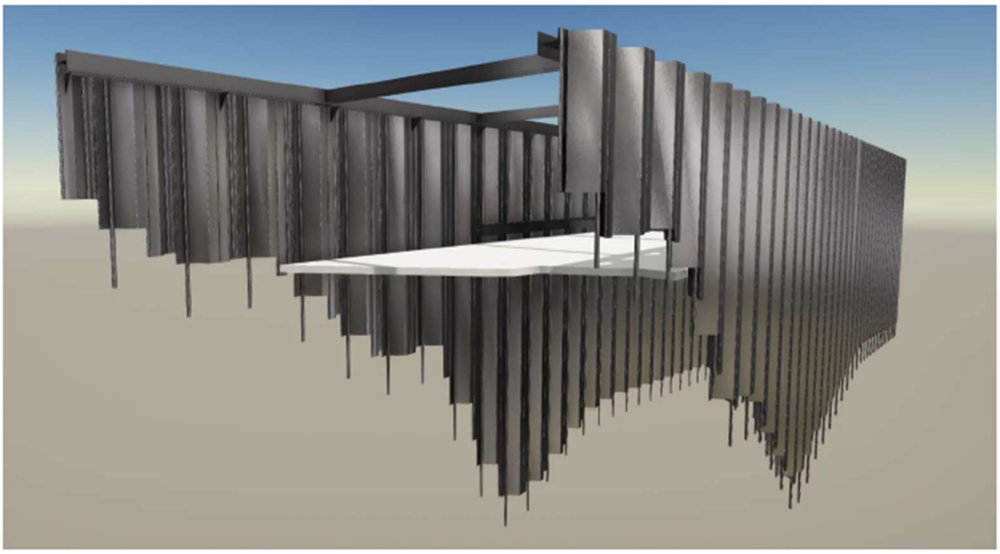
Kunne du tenke deg å anvende parametrisk design i fremtiden?

Yes. Specially in demanding geometries or repetitive operations.

Evaluering av Parametrisk Design

Bussveien v/Hans og Grete Stien

Spuntkonstruksjoner



For å modellere BIM-modellen til spuntkonstruksjon ved lokasjon 4 ble det anvendt parametrisk design. Parametrisk design ble blant annet brukt til å plassere ut spunt mellom en gitt kote og berg, samt tilegne alle elementene riktig BIM-Informasjon. I min masteroppgave prøver jeg å kartlegge hvilke oppgaver parametrisk design egner seg til å løse. I den forbindelse vil jeg svært gjerne høre hvordan du opplevde bruken av parametrisk design og eventuelt om du ser for deg å jobbe på en likende måte i fremtiden.

Hvilke fordeler/ulemper opplevde du ved bruk av parametrisk design i dette prosjektet?

Svært effektivt. Enkelt å gjøre endringer underveis. Enkelte endringer må likevel gjøres manuelt, f.eks tilpasning av stagvinkel for å unngå eksisterende konstruksjoner i grunn. Mitt inntrykk er likevel at parametrisk design gir et godt grunnlag for en modell.

Har du inntrykk av at parametrisk design økte effektiviteten av modelleringsarbeidet? Hvis ja, kan du gi et estimat på hvor mye tid som ble spart? Ja. Jeg har ikke modellert noe særlig selv, så utfordrende å angi tidsbesparelse. Jeg vil anta at besparelsen er vesentlig i prosjekter som Bussveien hvor det har vært mye endringer underveis.

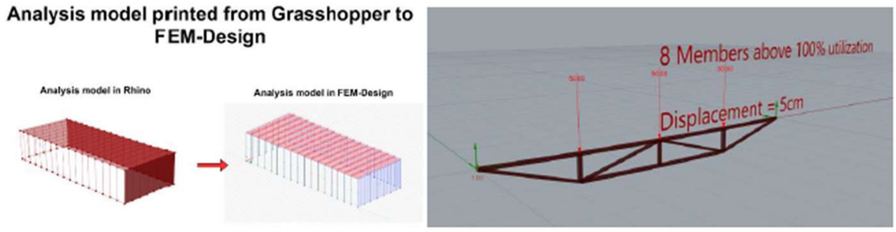
Kunne du tenke deg å anvende parametrisk design i fremtiden?

Ja. Jeg tror det vil være nyttig å anvende til modellering av blant annet spunt og peler.

9.4 Appendix D – Questionnaire – Parametric Analysis Model

Parametric Analysis Model

Grasshopper – Karmaba3D/FEM-Design



With the use of plug-ins like FEM-Design and Karamba3D, Grasshopper is empowered with the ability to construct and analyze structural analysis models. In my thesis, two cases have been explored to assess the capabilities of these plug-ins. One showcase a workflow for generating FEM-Design analysis models (Ecofisk). The other is a more conceptual case constructed to evaluate Karamba3D (Truss). As Karamba is imbedded into Grasshopper, real-time feedback from the structural analysis is enabled and the results can instantly be viewed in the Rhino viewport.

Do you think similar workflows will see more frequent use in the future?

- Yes, setting up the analysis model with loads, levels, etc as a first edition for later manipulation for details is valuable.

What do you see as the greatest hurdle preventing further adoption of such workflows?

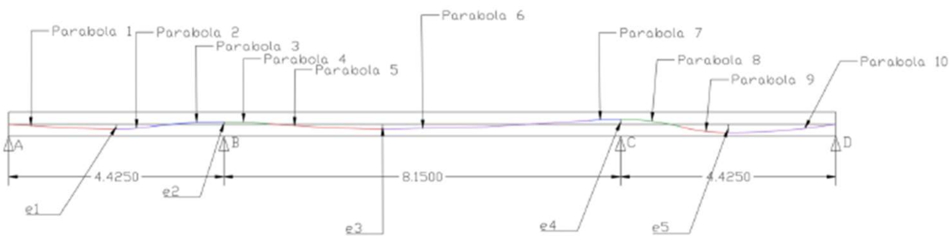
- We have had little repeating geometry, so making a scrip that can automize can be hard

- Software providers, Noise, Autodesk will try to commercialize and adopt the methods used in grasshopper.

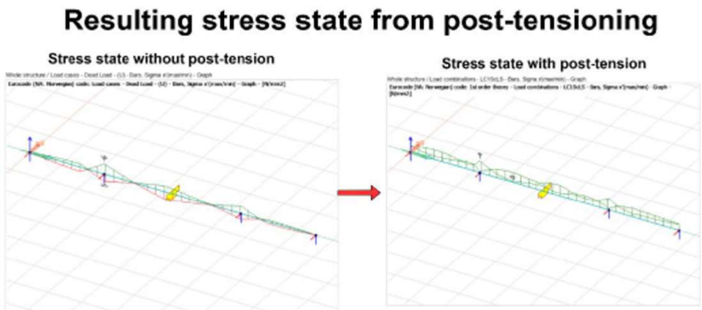
9.5 Appendix E – Questionnaire – Generative Design of Structures

Generative Design

Optimization of post-tension tendon profile



To investigate the potential of Generative Design algorithms like Galapagos, a case was constructed. This case draws inspiration from a real world structure and aims to optimize the profile of the post-tensioned tendon in response to a set of imposed loads. The results show that it is possible to find reasonable solutions that satisfy the given constraints e.g. compression throughout the cross-section of the beam (Has been validated in FEM-Design).



Do you think similar optimization routines will be used more frequently in the future?

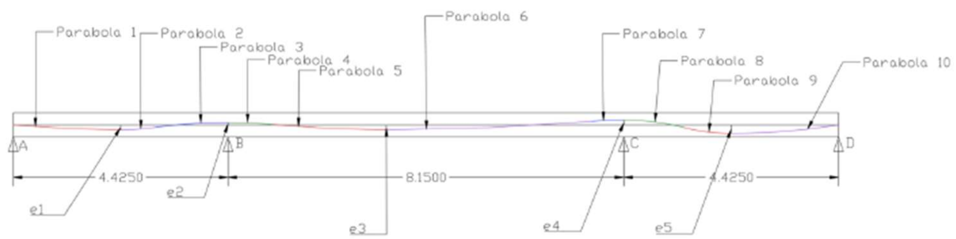
Yes. For special cases. Situations where optimizing is worth the cost. (Cost hours spent optimizing/cost material saved < 1). I could see this being the method of choice for tasks I had in my previous line of business, where weight, extent of structure and robustness were more focused upon, and cost were more tied up to installation vessel size etc. Could also be connected to probability densities for resistance parameters and other input variables.

What do you see as the greatest hurdle standing in the way for using such algorithms in the structural engineering workflow?

Time available for analysis in typical building project. Should be a team doing the scripting, so that there are several that now the method.

Generative Design

Optimization of post-tension tendon profile



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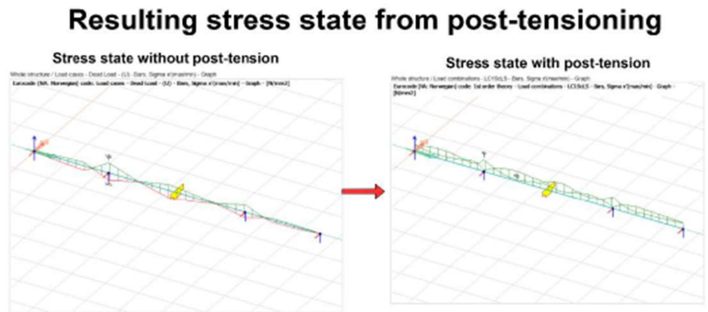

Do you think similar optimization routines will be used more frequently in the future?

When it comes to optimization routines, there is a big discussion in the scientific community. Some engineers think that these types of tools should be applied when there is a big benefit in reducing use of materials or cost. It should be then applied to industrialized processes. However in my opinion it has also a big potential in the future in several types of problems, for example in early phases or with designs where the optimization of sections or structural elements has an important role. For example section in post-tension long beams or bridges.

What do you see as the greatest hurdle standing in the way for using such algorithms in the structural engineering workflow?

It is probably the economy of the project. These types of tools are not yet really implemented in the industry.

,

There is also a risk in the design of really optimize structures, is the fact of they can be sensitive to local instability of really slender elements.

In my opinion, as these optimization techniques become more efficient, easier to implement in the analysis routines and developed with the design programs, they will become more reliable and common to use.

Another issue, is that these methodologies relies on a really advance design of structural elements.

9.6 Appendix F – Conference paper – First draft

Application of Generative Design for structural optimization at the conceptual design phase

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Abstract

Optimization of structural components can lead to higher performing designs by reducing unnecessary cost and increasing the efficient use of material. The structural optimization process is a rigorous iterative time-consuming process of achieving an optimal solution by satisfying design requirements, objectives and constrains. Recently, development within Algorithmic Aided Design tools have made it easier for structural engineers to achieve automation of optimization routines. AAD methods like Parametric Design has already seen noticeable adoption and has provided possibilities to generate precise and highly customizable BIM-Models. Furthermore, as part of the structural design is to analyze structures, Analysis Models for Finite Element Analysis(FEA) is needed. in similar fashion to BIM-Models, Analysis Models can be produced parametrically. By doing so, additional innovative technologies are enabled. Generative Design which is one of them, provide optimization routines which can aid in the pursuit of optimal solutions given a set of criteria. The use of Generative Design in combination with FEA to optimize structural design has yet to see noticeable adoption within the structural engineering community. This paper discusses two illustrative cases to demonstrate how generative design tools has been applied to optimize structures at the conceptual phase. The results has been validated with a commonly used FEA software: FEM-Design. Finally, a workflow has been proposed based on the learnings gained from the cases. This workflow inherits characteristics that when followed yielded consistent and reliable results.

1. Introduction

With the advent of new and more powerful technologies, designers and architects are facing lower thresholds while trying to realize increasingly complex structures (Banfi, F. et al. 2017). Structural engineers are often tasked with taking such concepts from an idea to a product which is buildable and structurally sound, while adhering to the initial design. As structural engineers, the final delivery will often be in the form of a highly detailed and information rich 3D-model (Model based delivery), traditional 2D-drawings, or a combination of the two. The purpose of such deliverables is to serve as the reference for the builders at the building site. Naturally, these references need to be of high quality and free of errors while precisely mimicking the physical and functional characteristics of the building. To achieve this, all the aforementioned deliveries are regularly generated in some form of BIM software such as Tekla or Revit (Kovacic, I., & Filzmoser, M. 2014, July). These software' offer easy collaboration between project team members and enables thorough quality control procedures. Consequently, proficiency in such tools is fast becoming a necessity to keep up in an environment where the bar is raised continuously (Russell, D. et al. 2014). As a result, efficient modelling methodologies such as parametric design has seen increasing presence in the typical structural engineering workflow. Furthermore, as this methodology is seeing more use, new and inventive workflows are proving to alter the ways structural engineers work on daily basis. Furthermore, structural engineers regularly use FEA tools to evaluate the structural integrity of structures. To be able to do so, analytical models must be generated. In much the same manner as with BIM-models, such analytical models can be made parametrically. In addition, by having an algorithmically defined structure, additional benefits are enabled. Since the position of all elements are governed by the logic described by the script, optimization algorithms can be deployed which in turn can manipulate the geometry to achieve certain objectives. Structural engineers aim to optimize structures in terms of the amount of material needed while maintaining the structural integrity of the building. To analyze and design structures, structural engineers commonly use FEA software. In other words, for the optimization algorithm to properly asses each iteration of the structure, FEM-analyses needs to be incorporated into the automated workflow. With the use of Grasshopper plug-in Karamba3D, such capabilities are enabled. With the power of Grasshopper, Karamba3D and optimization algorithms such as Simulated Annealing and Evolutionary Solver, structural engineers can let the algorithms turn out solutions in the conceptual design phase. Furthermore, being able to deploy algorithms which can aid in the finding of optimal solutions can provide significant yields both in terms of the overall price of the structure, as well as the time-savings related to the conceptual design phase. Subsequently, having integrated structural analysis within the parametric modelling routine will enable high levels of interoperability between the BIM-model and analysis model.

Through case studies, this paper aims to illustrate workflows structural engineers might adopt in the future. Although the applications shown are limited, the fundamental purpose is to highlight the possibilities that exist in the employment of optimization algorithms in structural design. Finally, a general workflow will be suggested that describe how to attack a problem, with the aforementioned algorithms.

As this paper mainly conducts research through case studies, the qualitative research method will be the overarching method, this also falls in line with use of surveys to obtain feedback from industry professionals on the different topics. However, to evaluate the accuracy of the case studies, quantitative methods are needed to compare the numerical results from various different sources. In other words, the quantitative research method will be used to validate the outcome of certain cases to be able to evaluate the cases as a whole qualitatively.

2. Generative design vs traditional methods

Traditionally, optimizing structures is done iteratively, with a more trial-and-error approach. Obviously, an experienced engineer will have through his previous projects found solutions to problems that might strike resemblance to the task at hand. Their previous experience will then serve as a foundation for how to proceed in the pursuit of solving said task. This approach is tried and proven and with the collective experience of the project team will reliably produce adequate results. However, past solutions does not necessarily mean that it is the most optimal way of solving the particular problem. In addition, it is next to impossible to rule out biases based on past experiences. Consequently, the exploration of other and possibly superior alternatives might be neglected on the sole base that a deemed preferred solution has already been used. Generative Design refers to the process of deploying optimization algorithms that aids in the search for optimal solutions given a set of inputs and constraints as shown in Figure xx. Then, the optimization algorithms explore the possible solution space through iteration of generational genome populations. A common method used in Generative Design are Evolutionary solvers. There various generative design tools have been developed as discussed in the following section and the general approach can be seen in Figure 1.

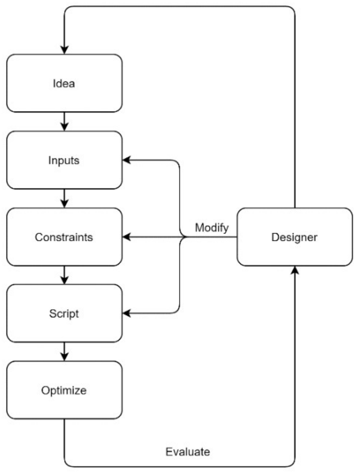


Figure 1 Generative Design approach

2.1 Rhinoceros 3D

Rhinoceros is a 3D-CAD software developed by McNeel. The geometry is defined by NURBS(Non-uniform rational basis spline) that the user can manipulate to freeform the wanted shape of the object being modelled. Rhinoceros is widely used in the industry, and has long been a favorite among designers. In later years, with the inclusion of visual programming capabilities provided by the imbedded application Grasshopper, Rhinoceros has seen noticeable adoption among architects and civil engineers who seek to enhance their efficiency in modelling BIM-models. In addition, FEA software providers has also seen the potential, and are now providing plug-ins that enable bi-directional interoperability between their respective software and the modelling capabilities that Rhinoceros bring.

2.2 Grasshopper

Grasshopper is a visual programming language developed by David Rutten that enables scripting of the geometry within Rhinoceros. With the use of grasshopper, the user can with a high degree of precision and efficiency develop scripts that produce complex geometry that would be cumbersome to do manually. It could be argued that Grasshopper is the go-to tool in terms of AAD and has by far the largest community support compared to its competitors.

2.3 Galapagos

Galapagos is an optimization routine, also developed by David Rutten(Rutten D. 2013), which is embedded within Grasshopper. Galapagos enables the user to define a set of input parameters which the algorithm can manipulate. Furthermore, these parameter are usually inputs to a problem which needs optimization. For Galapagos to learn which combination of the parameters that yields the best solution, a fitness criteria needs to be defined. The fitness criteria says something about the performance of that particular iteration given the associated parameter values. Subsequently, when the algorithm is set up as described, the routine can be set in motion. Before starting, Galapagos asks if the fitness score should be minimized or maximized. Finally, the user can choose from two different optimization techniques, Evolutionary Solver and Simulated Annealing. The Evolutionary Solver is by far the most common method as is also the one applied to the relevant cases in this paper.

2.4 Karamba3D

Karamba3D is a FEA plug-in for Grasshopper (Preisinger, C. 2013) which enables scripting of structural analysis in the same manner as is regularly done with geometry within Rhinoceros. It is very “light-weight”, providing fast solutions to structural analysis problems defined by geometry and information programmed in a Grasshopper script. This capability makes it a prime candidate to be paired with Generative Design routines like Galapagos. Exploiting this capability will be further studied in this paper.

2.5 Software for different Algorithmic Aided Design methods

The software used for the different AAD methods can be seen in Figure 2.

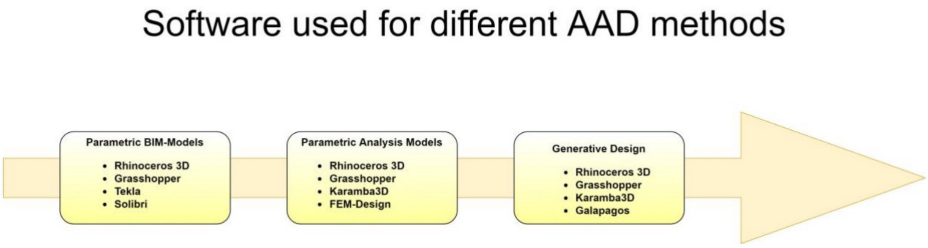


Figure 2 Software used for different AAD methods

2.5 Collaboration of BIM models with digital tools at conceptual design phase

BIM based structural design has been widely-adopted in construction practice. Use of BIM during structural design results in systematic modelling processes, powerful interactive visualization platform, and standardized data exchange interfaces during the life cycle of the construction. During the conceptual design phase, as given in Figure 3, structural optimization can be performed while collaborating with BIM models.

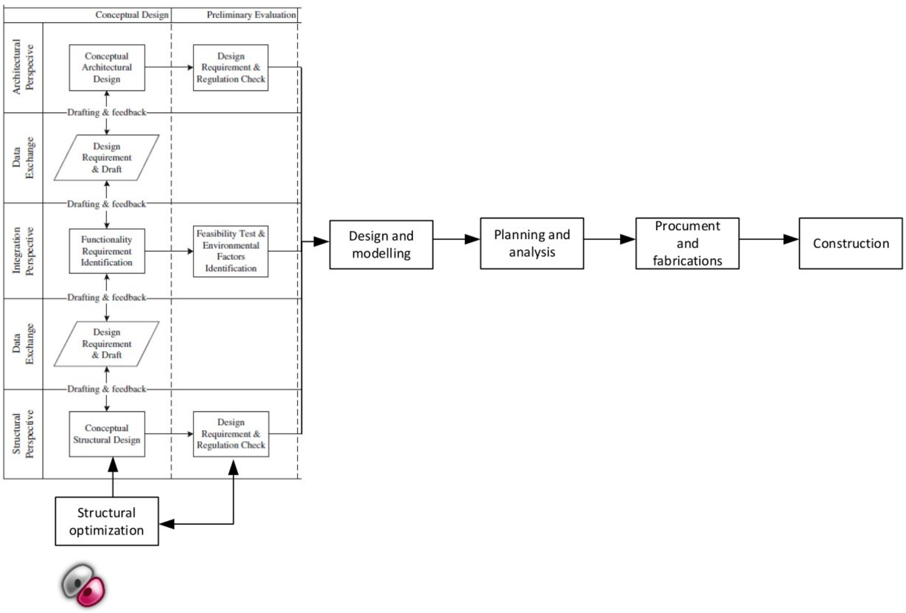


Figure 3 BIM-enabled Structural Design in Construction (modified from Chi et al. (2015)

3. ILLUSTRATIVE CASES

To study the potential of structural optimization algorithms a set of cases has been constructed. These cases was developed with input and guidance from industry professionals and stem from real cases they have experienced in their work. To study these cases a template of has been established, this template describes the problem and the workflow followed to solve it.

3.1 TEMPLATE

To study these cases a template of has been established, this template describes the problem and the workflow followed to solve it(Figure 4).

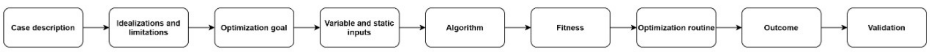


Figure 4 Template flowchart

Case description:

Brief description of the problem at hand which includes an explanation of the structure, why the problem is suitable for optimization.

Idealizations and limitations

Commonly, structural engineers idealize the structure when performing the structural analysis, the case specific idealizations that has been made in addition to the limitations of the procedure will be described here.

Optimization goal

Describe the wanted outcome of the optimization.

Variable and static inputs

To optimize a structure the algorithm needs a set of inputs. Furthermore, these inputs have been segregated into either static or variable. The static inputs are parameters that remains unaltered through optimization process effectively functioning as the constraints to the given problem. The variable inputs however, are the parameters the optimization algorithm can alter in the pursuit of finding the most optimal solution. Which inputs are static and variable will depend on the optimization goal and are therefore case specific.

Algorithm

In short terms elaborate on the workings of the algorithm.

Fitness

The performance of the structure will be a sum of parameters deemed important for the value of the given iteration. Parameters such as passing the preliminary SLS check as well as the total weight of the structures are examples of ways to measure the performance of the iteration.

Optimization routine

Describe how the optimization routine is set up.

Outcome

After the algorithm has run its course, the best solution with its accompanying genes and fitness is presented.

Validation

To validate the result, stand-alone FEA software such as FEM-Design are used. The top solution proposed by the optimization algorithm will be exported through automated workflows enabled in Grasshopper and more thorough analyses can be undertaken.

4. CASE 1 – STRUCTURAL OPTIMIZATION OF 65M STEEL TRUSS WITH RESPECT TO SELF-WEIGHT

4.1.1 Case description

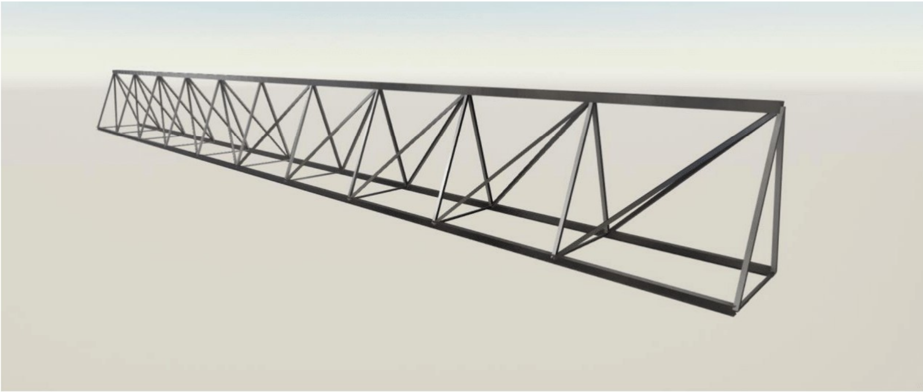


Figure 5 Case 1 - Truss Render

In this case, a structure being demanded a specially built truss spanning a gap of 65m. The truss can be seen in Figure 5.

4.2 IDEALIZATIONS AND LIMITATIONS

Only one load combination is included, the top and bottom chords have continuous cross-sections. i.e. will have same cross-section for the entire span. The middle web members all have same cross-section. Exactly how Karamba3D goes about selecting the optimal cross-sections is somewhat of a black box.

4.3 OPTIMIZATION GOAL

In this case, the goal of the optimization was to find the lightest structure that still satisfied the constraint of 100mm maximal displacement given the applied loads.

4.4 STATIC INPUTS

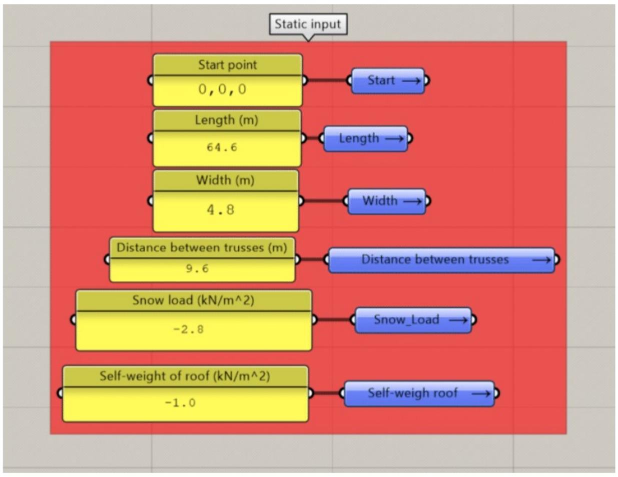


Figure 6 Case 1 - Static inputs

As seen in Figure 6, although these inputs remain static throughout the optimization, they could easily be changed to suit a new and differently sized truss with alternative imposed loads.

4.4.1 Geometry

In terms of geometry, the width, length and distance between trusses were given (Table 1).

Table 1 Case 1 - Static input - Geometry

Dimension	**Value**
Length	64.6m
Width	4.8m
Distance between trusses	9.6m

4.4.2 Supports

The structure was to be constrained from movement by the following supports(Table 2Table 7).

Table 2 Case 1 - Static input - Supports

Point	**Translation**	**Rotation**
Point 1	X-Direction = Restrained Y-Direction = Restrained Z-Direction = Restrained	X-Axis = Free Y-Axis = Free Z-Axis = Free
Point 2	X-Direction = Restrained Y-Direction = Free Z-Direction = Restrained	X-Axis = Free Y-Axis = Free Z-Axis = Free
Point 3	X-Direction = Free Y-Direction = Free Z-Direction = Restrained	X-Axis = Free Y-Axis = Free Z-Axis = Free
Point 4	X-Direction = Free Y-Direction = Free Z-Direction = Restrained	X-Axis = Free Y-Axis = Free Z-Axis = Free

4.4.3 Loading

The truss was to be imposed with loading from both the roof and the snow that could accumulate on it(Table 3).

Table 3 Case 1 – Static input - Loading

Load	**Value**
Snow load	2.8 kN/m^2
Self-weight of roof	1.0 kN/m^2

4.4.4 Safety factors

As the SLS criteria of max 100mm displacement will be the governing parameter in designing this truss, the safety factors for SLS will be used for the load-combination in the optimization routine(Table 4)

Table 4 Case 1 - Static input - Safety factors

Safety factor	**Value**
γ_G	1.0
γ_Q	1.0

4.4.5 Maximum displacement

A maximum value of displacement was also given(Table 5). *Table 5 Case 1 – Static input - Maximum displacement*

Dimension	**Value**
Maximum displacement	100mm

4.4.6 Material properties

Material property for the steel used in the truss members(Table 6).

Table 6 Case 1 - Static input - Material properties

Material	**Value**
Steel	S355

4.5 Variable inputs

To be able to optimize the structure, the variable inputs need to be defined.

4.5.1 Geometry

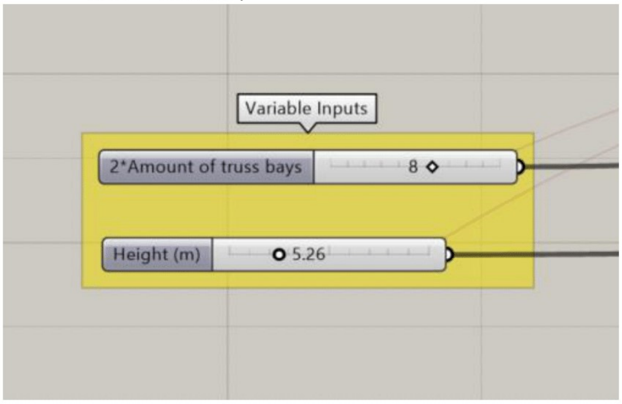


Figure 7 Case 1 – Variable input - Geometry

The algorithm got two genes to alter in order to find the most optimal solution, the total amount of truss bays, and the height of the truss. These can be seen in Figure 7 and Table 7.

Table 7 Case 1 - Variable input - Geometry

Dimensions	**Span of values**
Height	[4.80 , 6.64]m
Amount of truss bays	[10 , 20] Number of bays

4.5.2 Cross sections

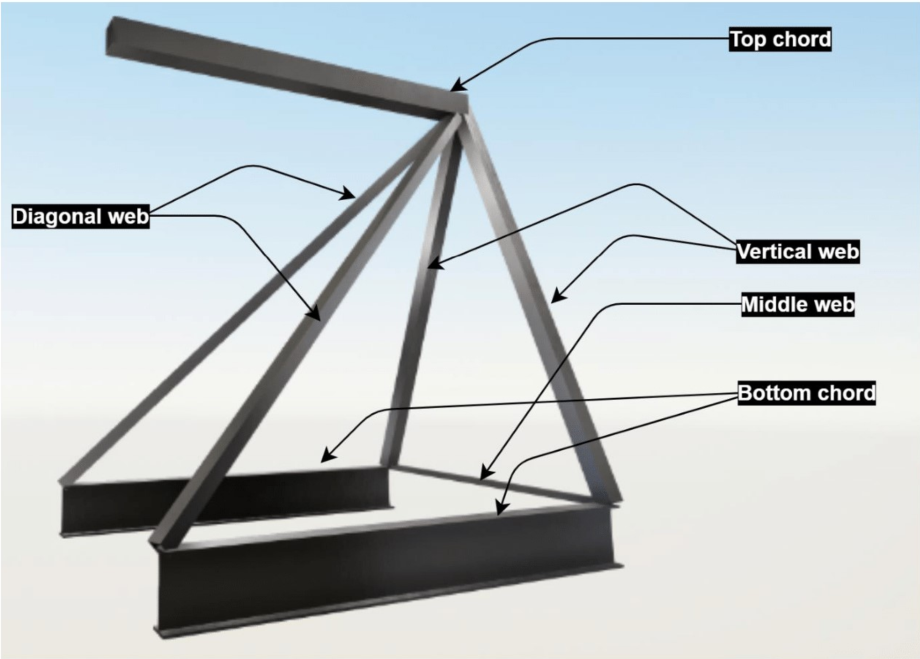


Figure 8 Case1 – Variable input – Cross sections

To optimize the structure, the algorithm could use a pool of different cross-sections, the diagonal web members, vertical web members, middle web members and top chord could pick from a list of rectangular hollow sections (RHS), while the bottom chord picked from a pool of HEB sections. The different structural members as well as the span of possible cross-sections can be seen in Figure 8 and Table 8.

Table 8 Case 1 – Variable input – Cross sections

Member	**Span of values**
Diagonal web	[RHS20x20x2 , RHS400x400x16]
Vertical web	[RHS20x20x2 , RHS400x400x16]
Middle web	[RHS20x20x2 , RHS400x400x16]
Top chord	[RHS20x20x2 , RHS400x400x16]
Bottom chords	[HEB100 , HEB1000]

4.6 ALGORITHM

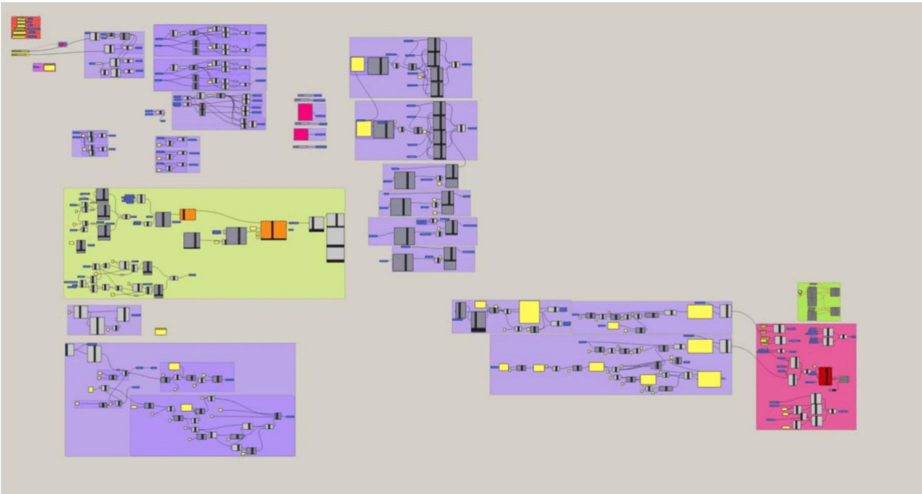


Figure 9 Case 1 - Algorithm

After setting all inputs, the algorithm which can be seen in Figure 9 is set in motion, first the lines which will later represent truss members are drawn up and all the top points where the diagonals intersect the top chord is gathered. Furthermore, all lines are then assigned a random cross-section picked from a pool of predefined sections. Subsequently, self-weight and snow load is applied as point loads to the previously gathered top points of the truss. Depending on the amount of truss bays, the magnitude of the loads will vary. The location of the support points is set and supports are made with the appropriate degrees of freedom. Now Karamba3D has enough information to evaluate the structure, when it is finished, Karamba determined the best combination of cross-section for each member to meet the constraint of maximum displacement while not exceeding the utilization of each member. When all members has been given a new cross-section, the total mass of the structure is calculated. The total mass will be the fitness of that particular iteration and is sent back to Galapagos. This is repeated until it finds the lightest structure that still fulfills the requirements. Once Galapagos has found a suitable solution it is sent to FEM-Design for validation. In addition, if needed, the structure can also be sent to Tekla to populate a BIM-model.

4.7 Fitness

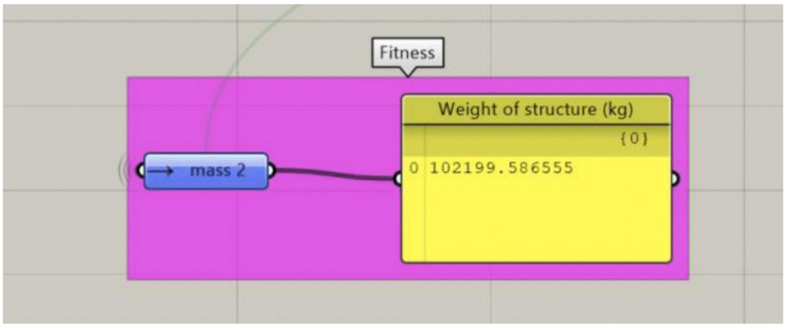


Figure 10 Case 1 – Fitness

The fitness was solely based on the total weight of the structure as can be seen in Figure 10.

4.8 Optimization routine

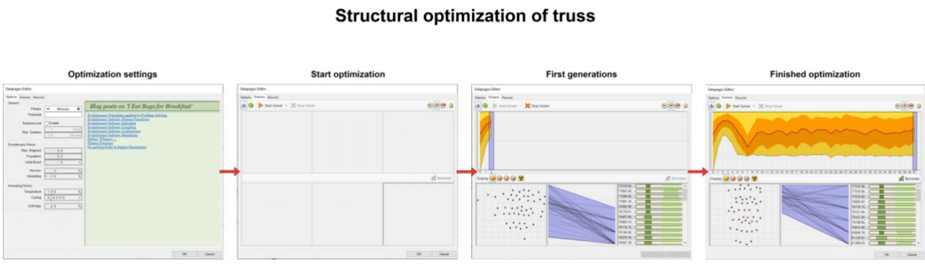


Figure 11 Case 1 - Structural optimization of truss

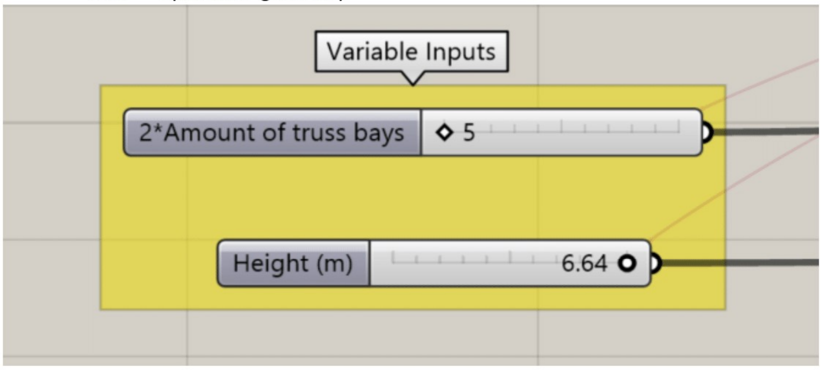
The optimization routine make use of the evolutionary solver within Galapagos(Figure 11). We want the lightest structure that still satisfies the given constraints, i.e. algorithm was set to minimize the fitness value. The total population of each generation was bound by maximum of 50 genomes, this should be sufficient to properly explore the fitness landscape while keeping the runtime of the optimization routine within reasonable limits. The initial boost was set to 4, i.e. generation 0 will have 4 times as many genomes than the following generations. This was done to thoroughly cover the fitness landscape such that the following generations did not colonize local optima's instead of the best global one. With a total runtime of 15 minutes, the evolutionary solver converged towards a solution after 41 generations yielding a total weight of 77516.56 kg.

	Weight	**Generation**	**Runtime**
Optimized solution	77516.56 kg	41	15:20 minutes

4.9 Outcome

After running the optimization routine the following conditions were present in the fittest genome.

4.9.1 Optimized geometry



The genome that yielded the best results had genes with the following value(Table 9).

Table 9 Case 1 - Fittest genome

Gene	**Value**
Height	6.64m
Amount of truss bays	10

4.9.2 Loads

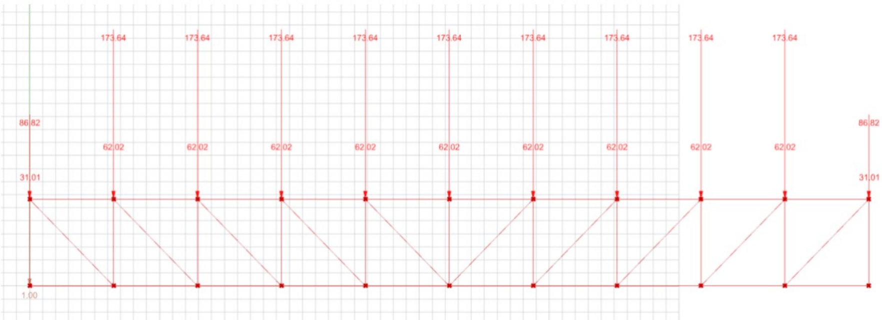


Figure 12 Case 1 - Distribution of loads for optimized genome

With 10 truss bays there are 11 top points, the following table shows the load applied at each point. As shown in Figure 12 and Table 10 the loads on the start and end points are half of the others due to the influence area being 50% smaller than the rest.

Table 10 Case 1 - Magnitude of applied laods

Point number	**Roof dead load**	**Snow load**
1	31.01 kN	86.82 kN
2	62.02 kN	173.64 kN
3	62.02 kN	173.64 kN
4	62.02 kN	173.64 kN

5	62.02 kN	173.64 kN
6	62.02 kN	173.64 kN
7	62.02 kN	173.64 kN
8	62.02 kN	173.64 kN
9	62.02 kN	173.64 kN
10	62.02 kN	173.64 kN
11	31.01 kN	86.82 kN

4.9.3 Optimized cross-sections

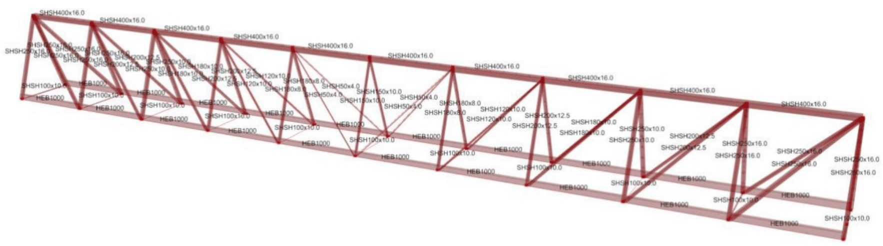


Figure 13 Case 1 - Optimized Cross-sections

Given these parameters, Karamba3D had assigned the following cross-sections to the different structural members(Figure 13, Table 11, Table 12, Table 13,Table 14, Table 15)

Diagonal web members

Table 11 Case 1 - Optimized Diagonal web members

Member id	Profile
Diagonal 1	**SHS250x250x16**
Diagonal 2	**SHS200x200x12.5**
Diagonal 3	**SHS180x180x10**
Diagonal 4	**SHS120x120x10**
Diagonal 5	**SHS50x50x4**
Diagonal 6	**SHS50x50x4**
Diagonal 7	**SHS120x120x10**
Diagonal 8	**SHS180x180x10**
Diagonal 9	**SHS200x200x12.5**
Diagonal 10	**SHS250x250x16**

Vertical web members

Table 12 Case 8 - Optimized Vertical web members

Member id	Profile
Vertical 1	**SHS250x250x16**
Vertical 2	**SHS250x250x16**
Vertical 3	**SHS250x250x10**
Vertical 4	**SHS200x200x12.5**

Vertical 5	**SHS180x180x8**
Vertical 6	**SHS150x150x10**
Vertical 7	**SHS180x180x8**
Vertical 8	**SHS200x200x12.5**
Vertical 9	**SHS250x250x10**
Vertical 10	**SHS250x250x16**
Vertical 11	**SHS250x250x16**

Middle web members

Table 13 Case 1 - Optimized Middle web members

Member id	Profile
Middle	**100x100x10**

Top chord

Table 14 Case 1 - Optimized Top chord

Member id	Profile
Top chord	**400x400x16**

Bottom chords

Table 15 Case 1 - Optimized Bottom chords

Member id	Profile
Bottom chords	**HEB1000**

4.10 VALIDATION

To validate the results, the geometry, loads, cross-sections and supports was sent to FEM-Design. The process of doing so was automated through the FEM-Design plug-in for grasshopper.

4.10.1 Results

A thorough description of the analysis can be viewed in appendix B. The following are the outcome validating the results from the optimization routine.

Maximum displacement

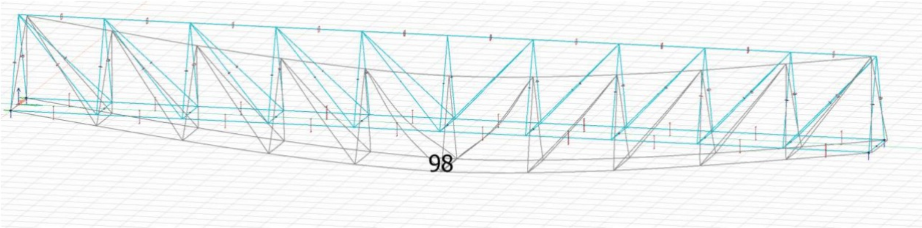


Figure 14 Case 1 - Validated result - Displacement

The results from the SLS load-combination yielded a maximum vertical displacement of 98mm(Figure 14).

Utilization

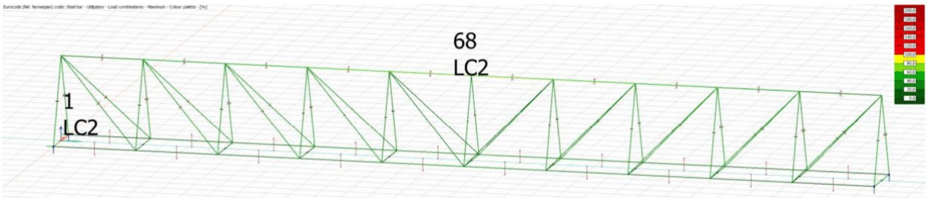


Figure 15 Case 1 - Validated result - Utilization

The results from the maximum load-combination yielded a maximum utilization of 68%(Figure 15)

4.11 PRINT TO TEKLA

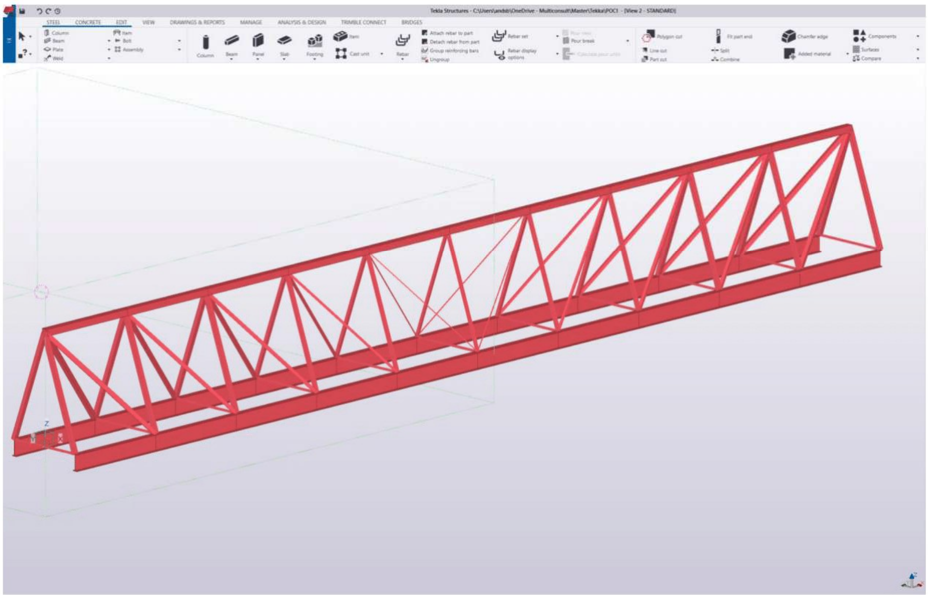


Figure 16 Case 1 - Optimized truss printed to Tekla

With the structural integrity validated within FEM-Design, the truss was printed to Tekla(Figure 16).

5. CASE 2 – OPTIMIZATION OF TENDON PROFILE FOR A MULTI-SPAN POST-TENSIONED BEAM

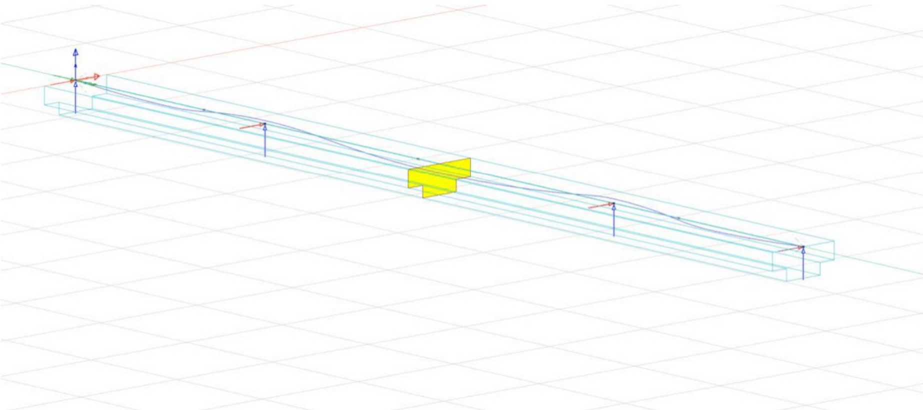


Figure 17 Case 2 - Post-Tensioned multi-span beam

5.1 CASE DESCRIPTION

To accommodate larger open areas within buildings, columns needs to be placed further apart. Consequently, longer spanning beams are needed. At these spans, regular reinforced concrete solutions are no longer feasible. Subsequently, structural engineers often turn to post-tensioned systems to solve this problem. These systems offer the engineer options to achieve structural integrity while keeping the beams relatively slender. The process of designing post-tensioned beams is done iteratively where the main outcome is to determine the necessary cross-sectional area of the beam, the tendon profile and finally the required tendon force. Initially, some assumptions regarding losses, trial cross-section and tendon profile is made. Furthermore, the necessary tendon force is calculated to balance the loads vs. the applied forces. Finally, as the geometry of the tendon and the needed force is known, the actual losses can be calculated. Compared to the initial assumptions, the engineer can now go back and re-iterate to optimize the structure further. This process continues until the performance of the solution is deemed acceptable. The following case will present an automated approach to designing a post-tensioned system. The case draws inspiration from a real structure.

5.2 IDEALIZATIONS AND LIMITATIONS

In reality the distributed load acting on the beam by the post-tensioned tendon is not uniform i.e. it varies with the slope. In other words, the idealizations that has been made in this case is that the distributed loads are uniform within each parabola section. Furthermore, the optimization routine does not include losses in tendon force due to friction, relaxation and alike. In addition the beam is only subjected to one load-combination(SLS) during the optimization.

5.3 OPTIMIZATION GOAL

For this case the optimization goal was to find a tendon profile that needed the least amount of jacking force while still maintaining compression throughout the beam.

5.4 STATIC INPUTS

5.4.1 Geometry

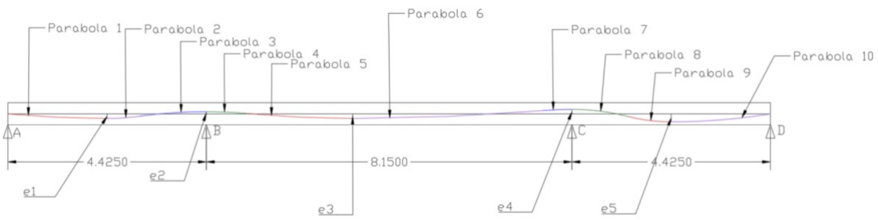


Figure 18 Case 2 – Post-Tensioned beam (Dimensions in meter)

Supports

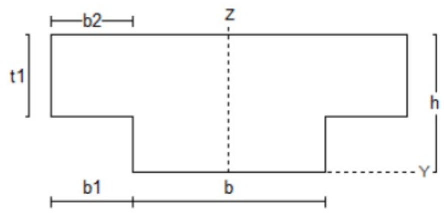
The structure(Figure 18) was to be constrained from movement by the following supports(Table 16).

Table 16 Case 2 - Static inputs - Supports

Point id.	**Coordinate**	**Translation**	**Rotation**
Point A	X = 0	X-Direction = Restrained	X-Axis = Free
	Y = 0	Y-Direction = Restrained	Y-Axis = Free
	Z = 0	Z-Direction = Restrained	Z-Axis = Free
Point B	X = 4.425m	X-Direction = Free	X-Axis = Free
	Y = 0	Y-Direction = Restrained	Y-Axis = Free
	Z = 0	Z-Direction = Restrained	Z-Axis = Free
Point C	X = 12.575m	X-Direction = Free	X-Axis = Free
	Y = 0	Y-Direction = Restrained	Y-Axis = Free
	Z = 0	Z-Direction = Restrained	Z-Axis = Free
Point D	X = 17m	X-Direction = Free	X-Axis = Free
	Y = 0	Y-Direction = Restrained	Y-Axis = Free
	Z = 0	Z-Direction = Restrained	Z-Axis = Free

Cross-section

The cross-section that was chosen has the dimensions as shown in Figure 19.



b	700	mm
b1	300	mm
b2	300	mm
h	500	mm
t1	300	mm
t2	0	mm
Zt	284	mm
Areal	5,30E+05	mm2
Iy	9,83E+09	mm4

Figure 19 Case 2 - Static Inputs - Cross-Section

5.4.2 Loading

In addition to the self-weight of the beam, three point is placed, one on each span with the following coordinates and magnitude(Table 17)

Table 17 Case 2 - Static inputs - Loading

Point	**Coordinates**	**Magnitude**
Point load 1	X = 3m Y = 0 Z = 0	X = 0 Y = 0 Z = -210kN
Point load 2	X = 8 Y = 0 Z = 0	X = 0 Y = 0 Z = -115kN
Point load 3	X = 14.095 Y = 0 Z = 0	X = 0 Y = 0 Z = -115kN

5.4.3 Material properties

Concrete

The concrete characteristics are set to C35

5.4.4 Safety factors

As the SLS crack criteria of no tension in the cross-section will be the governing parameter in designing this post-tensioned beam, the safety factors for SLS will be used for the load-combination in the optimization routine(Table 18).

Table 18 Case 2 - Static input - Safety factors

Safety factor	**Value**
γ_G	1.0
γ_Q	1.0

5.5 VARIABLE INPUTS

To be able to optimize the structure, the algorithm can alter a set of variables. In this case, the variables are the following.

5.5.1 Tendon profile

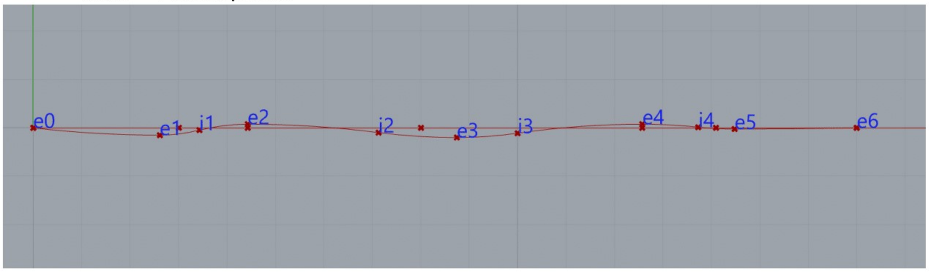


Figure 20 Case 2 - Tendon profile point of interest

To define the shape of the tendon profile the algorithm can alter the location of a set point of interest(Figure 20). The variable inputs for the algorithm was set up in such a way that they alter the locations of the given point of interest by a fraction of the dimensions of the given structure e.g. span length and cross-sectional height. By doing so, it would be a trivial task optimize a different beam with altering span length and cross-section.

Eccentricities

One parameter that controls the magnitude of the equivalent loads generated from the tendon is the maximum eccentricities at each span and support(Table 19).

Table 19 Case 2 - Variable inputs - Eccentricities

Eccentricity id.	**Span of values**	**Description**
e_1	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity in span 1
e_2	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity at support B
e_3	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity in span 2
e_4	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity at support C
e_5	[0.1 , 0.9]% of half cross-section height.	Maximum eccentricity in span 3

X-coordinate of eccentricities and inflection point

In addition to manipulating the magnitude of the eccentricities, the algorithm was also able to alter the position at which the eccentricity was located. In addition, it could also alter the location of the inflection points(Table 20).

Table 20 Case 2 - Variable inputs - Position of eccentricities and inflection point

Location id.	**Span of values**	**Description**
a_1	[0.4 , 0.6]% of span 1 length	Controls the x-coordinate of eccentricity e_1
a_2	[0.1 , 0.9]% of distance between e_1 and support B	Controls the x-coordinate of inflection point i_1
a_3	[0.4 , 0.6]% of span 2 length	Controls the x-coordinate of eccentricity e_3
a_4	[0.1 , 0.9]% of distance between e_3 and support B	Controls the x-coordinate of inflection point i_2
a_5	[0.1 , 0.9]% of distance between e_3 and support C	Controls the x-coordinate of inflection point i_3
a_6	[0.4 , 0.6]% of span 3 length	Controls the x-coordinate of eccentricity e_5
a_7	[0.1 , 0.9]% of distance between e_5 and support C	Controls the x-coordinate of inflection point i_4

5.5.2 Tendon force

The magnitude of the force applied to the post-tensioned tendon is the last of the variable inputs(Table 21).

Table 21 Case 2 - Variable inputs - Tendon force

	Span of values	**Description**
Tendon force	[200 , 2000] kN	Directly correlated with the equivalent uniformly distributed loads acting on the beam from the post-tensioned tendon

5.6 ALGORITHM

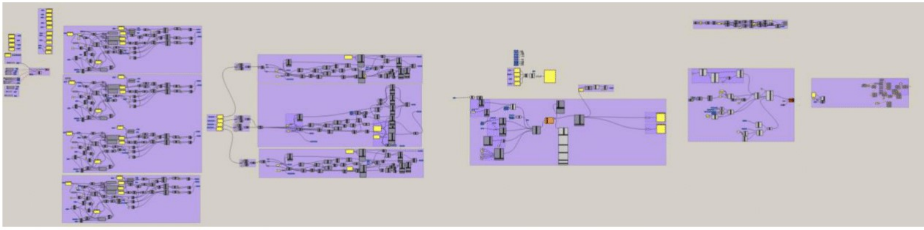


Figure 21 Case 2 - Algorithm

To determine the tendon profile the algorithm(Figure 21) draws inspiration from the procedure described in Gilbert(2017). It describes how it is possible to idealize the tendon profile as parabolas with a given radius of curvature. Subsequently, the radius of curvature is curvature, together with the applied tendon force is directly related to the equivalent uniformly distributed load acting on the beam from the tendon. The algorithm uses the equations making up the approach and automates it. Initially, after all variable and static inputs have been set, the algorithm is set in motion. The following is a description of the steps the algorithm takes to arrive at an optimized tendon profile.

5.6.1 Span 1

Location of inflection point

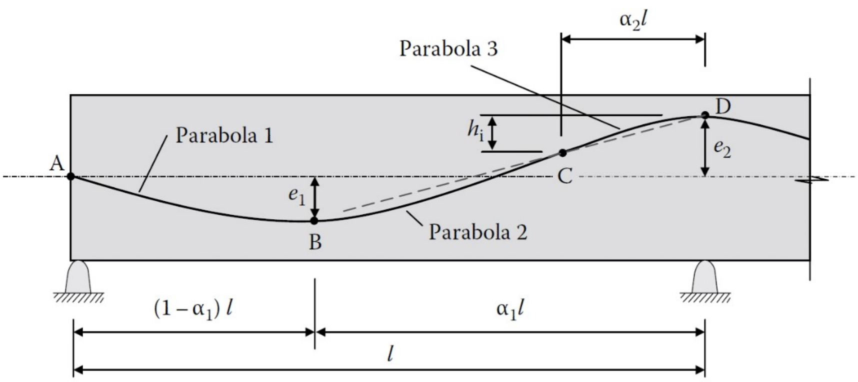


Figure 22 Case 2 - Illustration of tendon profile parabolas(Gilbert, 2017)

First the distance which inflection point i_i is offset e_2 is calculated.

$$h_{i_1} = \frac{\alpha_2}{\alpha_1}(e_1 + e_2)$$

Radius of curvature for parabolas

Now the algorithm has all the variable it needs to calculate the radius of curvature for the three parabolas in span 1.

$$r_1 = \frac{l^2(1-\alpha_1)^2}{2e_1}$$

$$r_2 = \frac{l^2(\alpha_1-\alpha_2)^2}{2(e_1+e_2-h_{i_1})}$$

$$r_3 = \frac{\alpha_1\alpha_2 l^2}{2(e_1+e_2)}$$

Equivalent loads

When the radius of curvature is known the equivalent uniformly distributed loads can be calculated using the following formula.

$$q_i = Pk_{P_i} \; where \; P = Force \; in \; post - tensioned \; tendon \; and \; k_{P_i} = \frac{1}{r_i}$$

This yields the following formula for the three equivalent loads for span 1.

$$q_1 = Pk_{P_1}$$

$$q_2 = Pk_{P_2}$$

$$q_3 = Pk_{P_3}$$

5.6.2 Span 2

Location of inflection point

Offset for i_2 and i_3 is calculated

$$h_{i_2} = \frac{\alpha_4}{\alpha_3}(e_2+e_3)$$

$$h_{i_3} = \frac{\alpha_5}{\alpha_3}(e_3+e_4)$$

Radius of curvature for parabolas

Radius of the four parabolas in span 2 can then be found.

$$r_4 = \frac{\alpha_3\alpha_4 l^2}{2(e_2+e_3)}$$

$$r_5 = \frac{l^2(\alpha_3-\alpha_4)^2}{2(e_2+e_3-h_{i_2})}$$

$$r_6 = \frac{l^2(\alpha_3-\alpha_5)^2}{2(e_3+e_4-h_{i_3})}$$

$$r_7 = \frac{\alpha_3\alpha_5 l^2}{2(e_3+e_4)}$$

Equivalent loads

With the radius of curvature, the four equivalent uniformly distributed loads can be calculated.

$$q_4 = Pk_{P_4}$$

$$q_5 = Pk_{P_5}$$

$$q_6 = Pk_{P_6}$$

$$q_7 = Pk_{P_7}$$

5.6.3 Span 3

Location of inflection point

Offset for i_4 is calculated.

$$h_{i_4} = \frac{\alpha_7}{\alpha_6}(e_4 + e_5)$$

Radius of curvature for parabolas

Radius of the three parabolas in span 3 can then be found.

$$r_8 = \frac{\alpha_6 \alpha_7 l^2}{2(e_4 + e_5)}$$

$$r_9 = \frac{l^2(\alpha_6 - \alpha_7)^2}{2(e_4 + e_5 - h_{i_4})}$$

$$r_{10} = \frac{l^2(1 - \alpha_6)^2}{2e_1}$$

Equivalent loads

With the radius of curvature, the three equivalent uniformly distributed loads can be calculated.

$$q_8 = Pk_{P_8}$$

$$q_9 = Pk_{P_9}$$

$$q_{10} = Pk_{P_{10}}$$

Drawing tendon profile

Using the coordinates of the eccentricities and inflection points together with the now known radius of curvature for each parabola, all parabolas can be drawn in rhino as curves(Table 22). These curves will later be used to print the tendon shape to Tekla.

Table 22 Case 2 - Parabola start and end points

Parabola id.	Start point	End point
Parabola 1	e_0	e_1
Parabola 2	e_1	i_1
Parabola 3	i_1	e_2
Parabola 4	e_2	i_2
Parabola 5	i_2	e_3

Parabola 6	e_3	i_3
Parabola 7	i_3	e_4
Parabola 8	e_4	i_4
Parabola 9	i_4	e_5
Parabola 10	e_5	e_6

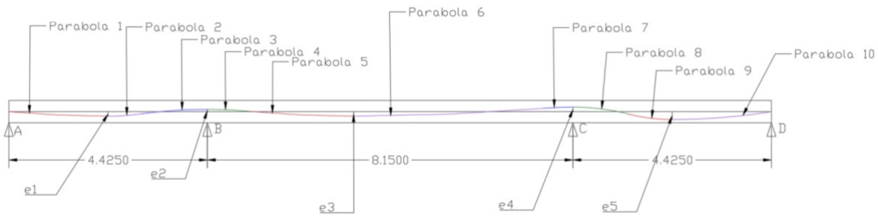


Figure 23 Case 2 - Parabolas

5.6.4 Karamba

Now that the coordiantes for each parabola and equivalent loads are calculated, it is time to build the FEA model. Individual beam elements are modelled between each of the parabolas, 10 in total(Figure 23). Futhermore, the equivalent loads and point loads are applied. The outcome of the analysis is the stress state at predefined points of interest. These stress states are finally used to evaluate the performance of the structure and enables Galapagos to find the most optimal solutions. Furthermore, the equivalent uniformly distributed loads are now made available to the FEA nodes in the Karamba plug-in. Together with the predefined beam elements and boundary conditions, the Karamba structural analysis node evaluates stresses in the cross-section at 12 points of interest. The stress conditions together with the applied tendon force is fed to Galapagos as the fitness for the optimization

5.7 Fitness

To measure the performance of each iteration a fitness condition is constructed. In this case, the fitness conditions depend on two different inputs. The first input is the applied force to the post-tensioned tendon, the second is a sum of a condition-based equation determined by the stress-condition at the 12 points of interest. For every point with stress above 0 MPa i.e. tensile stress, a penalty value of 2000 is added, e.g. if all 12 points are in tension a penalty of 24000 will be added. On the other hand, if all points are in compression, no penalty is added.

5.8 Optimization routine

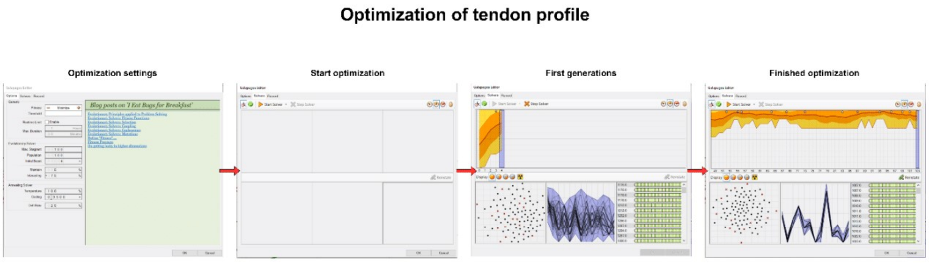


Figure 24 Case 2 - Optimization of tendon profile

Now that the function of the algorithm is explained, the variable inputs has been set up and a way to assess the performance of each iteration has been added, Galapagos has enough information to start the optimization routine(Figure 24). Galapagos has control of all the variable inputs is given instant feedback on the performance through the fitness condition. By doing so it gradually learns which combination of the variables yields the best performance and after a set amount of time it presents the best solutions it could find. After a runtime of 45 minutes and 103 generations, Galapagos converged towards a solution only requiring 1007 kN of force.

5.9 Outcome

The best genome had the following combination of input variables(Table 23).

Table 23 Case 2 - Genes of fittest genome

Input variables	**Value**
a_1	0.41
a_2	0.226
a_3	0.47
a_4	0.331
a_5	0.316
a_6	0.43
a_7	0.261
e_1	0.6
e_2	0.3
e_3	0.8
e_4	0.3
e_5	0.1

5.9.1 Optimized tendon profile

The input variables produced a tendon profile intersection the different point of interest at the following coordinates(Table 24).

Table 24 Case 2 - Point of interest coordinates

Point of interest	**Coordinate**
e_0	(0 , 0 , 0)mm
e_1	(2611 , 0 , -150)mm
i_1	(3425 , 0 , -49)mm
e_2	(4425 , 0 , 75)mm
i_2	(7123 , 0 , -97)mm
e_3	(8745 , 0 , -200)mm
i_3	(10000 , 0 , -110)mm
e_4	(12575 , 0 , 75)mm
i_4	(13730 , 0 , 14)mm
e_5	(14478 , 0 , -25)mm
e_6	(17000 , 0 , 0)mm

5.9.2 Optimized tendon force and equivalent loads

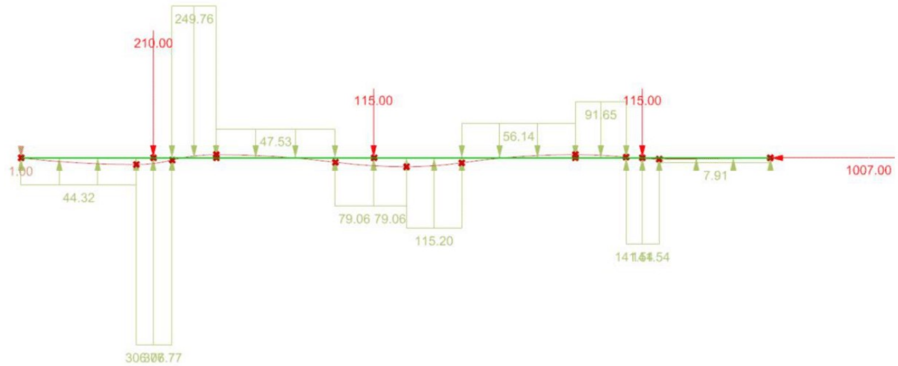


Figure 25 Case 2 - Illustration of loads

The magnitude and position of each equivalent load can be viewed in Figure 25 and Table 25.

Table 25 Case 2 - Magnitude of equivalent loads and tendon force

Load	**Coordinate**	**Description**
P	1007 kN	Tendon force
q_1	44.32 kN/m	Equivalent loads from parabola 1
q_2	306.77 kN/m	Equivalent loads from parabola 2
q_3	-249.76 kN/m	Equivalent loads from parabola 3

q_4	-47.53 kN/m	Equivalent loads from parabola 4
q_5	79.05 kN/m	Equivalent loads from parabola 5
q_6	115.2 kN/m	Equivalent loads from parabola 6
q_7	-56.14 kN/m	Equivalent loads from parabola 7
q_8	-91.64 kN/m	Equivalent loads from parabola 8
q_9	141.53 kN/m	Equivalent loads from parabola 9
q_{10}	7.91 kN/m	Equivalent loads from parabola 10

5.10 VALIDATION

To validate the result the beam was also analyzed in FEM-Design. All geometry the geometry, loads, and load cases were sent automatically through the FEM-Design Grasshopper plug-in. However, as of now it is not possible to model post-tensioned cables through the plug-in. The tendon profile and applied force was therefore manually generated inside FEM-Design(Figure 26) with the known locations for the point of interest.

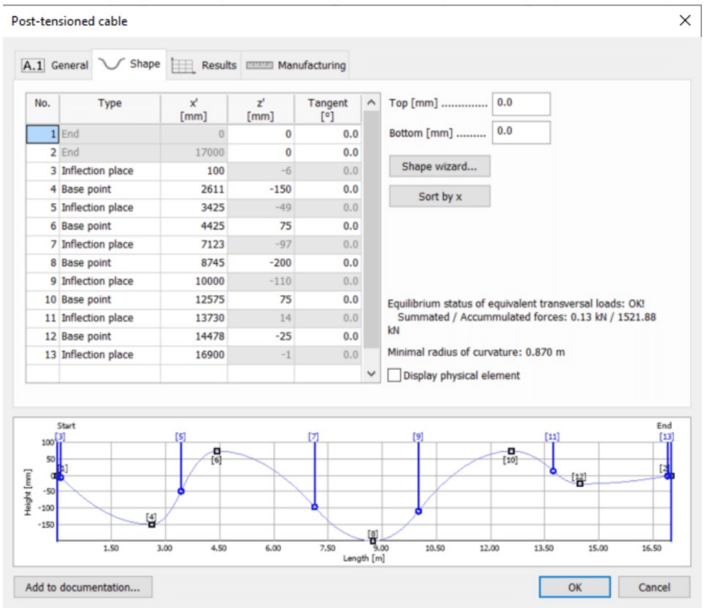


Figure 26 Case 2 - Tendon point of interest manually inserted into FEM-Design

5.10.1 Results

After running the analysis the following results was found(Figure 27).

Figure 27 Case 2 - Validation of results

With the post-tensioning applied, the following stress state was observed(Table 26).

Table 26 Case 2 - Stress results from FEM-Design

Observations	**Value**
Max stress	4 MPa (Compression)
Min stress	0 MPa

Not only is the entirety of the beam in compression as was intended, the minimum stress is 0 MPa indicating a well optimized profile and tendon force.

5.11 PRINTING TO TEKLA

Finally the geometry was automatically printed to Tekla to populate a BIM-model as can be seen in Figure 28.

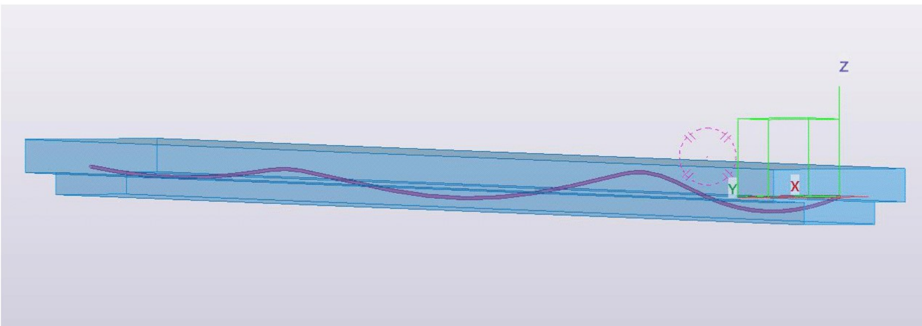


Figure 28 Case 2 – Beam and optimized tendon profile printed to Tekla

6. Discussion

In the pursuit of exploring the capabilities of Algorithmic Aided Design this paper has presented two cases where Generative Design of structures has been executed. As the author was the developer of the scripts and algorithm, his views together with feedback from industry professionals will serve as input to the following discussion regarding the potential of AAD.

6.1 Case 1 – Structural optimization of 65m steel truss with respect to self-weight

The process of setting up this script provided great insight in into the intricacies of using optimization routines. Not only was the script set up to optimize the structure with the Karamba3D-Grasshopper-Galapagos interoperability, It also had to find an efficient way of gather the optimized structure and export it to FEM-Design for validation. Lastly, the possibility for Karamba to pick cross-sections for each iteration was not discovered before late in the writing of this paper. Initially, the given cross-section for all structural members was a variable input to Galapagos. By having so many inputs, the optimization routine was very slow to converge towards a reasonable solution.

6.2 Case 2 – Optimization of tendon profile for a multi-span post-tensioned beam

Building the script to run this optimization algorithm was quite time consuming, in fact, doing it the traditional way would probably be faster. However, since the script is set up in such a way that it is trivial to change the loadings, dimensions, and span lengths, it is not farfetched to think that the next time there is a use for a similar optimization routine, significantly less time is needed to set it up. Furthermore, the results show that there is a satisfying correlation between the stress evaluation in Karamba and FEM-Design.

6.3 Questionnaire

A questionnaire was sent out to get feedback on how structural engineers view using optimization routines similar to the ones presented in this paper. They came back saying that it could be used as a good tool in the early phase or in cases where slimming down on material costs is of significant priority. When asked mention some hurdles standing in the way of using such algorithms they mentioned the complexity of the scripts and the time needed to define them. Overall, they are positive and agree that it could see use in the future.

6.4 Summary

Both case 1 and 2 show that it is indeed possible to set up routines to find reasonably good solutions to a problem, given a set of variables and some hard constraints. Whether the solutions presented is the very best possible is not known. However, the point of these cases was not necessarily to solve the presented problems, but to illustrate the degree of automation a structural engineer can enable with the technology currently available. With the ever growing prevalence of Machine Learning and AI, automation has and will affect all industries, it is therefore naïve to think that structural engineering will somehow escape this. Consequently, to stay competitive, similar workflows should be explored to harvest the benefits once the technology has reached adequate maturity. The cases described here can be considered stepping stones for fully atomized Machine Learning algorithms solving structural engineering problems autonomously. A video demonstrating case 1 and 2 can be seen here https://youtu.be/wIo5PulGBrM

6.5 PROPOSED WORKFLOW

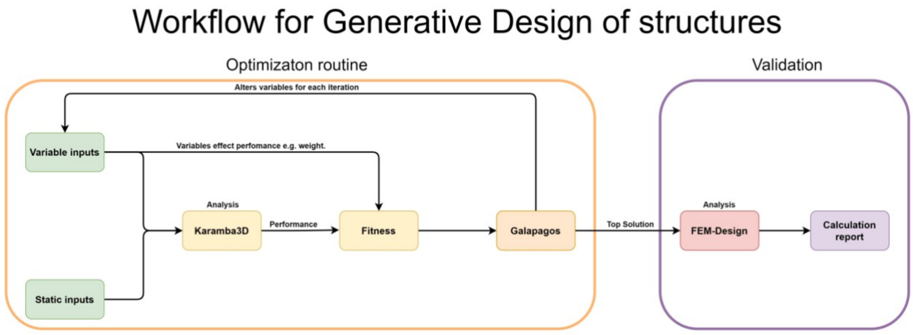


Figure 29 Proposed Workflow for Generative Design of structures

1. Static inputs are defined
2. Variable inputs(Genes) and the range of their values are defined
3. Said inputs define the structural problem which is furthermore fed into Karamba3D
4. Karamba3D analyses the structure outputs performance parameters in real-time
5. Together with the performance parameters, some of the variable inputs(Genes) will often make up the fitness of a given genome
6. The Fitness and Variable inputs(Genes) are made available to the optimization routine Galapagos
7. The optimization routine is run with a given optimization goal, either maximize or minimize
8. After the optimization routine has finished, the top solution is sent to FEM-Design for validation
9. After validating the structure, calculation reports can be generated

7. CONCLUSION

The objective of this paper has been to explore cases to get an understanding for how AAD is currently used, which possibilities it brings and lastly, investigate what the future might hold. By having the analysis model defined parametrically, new and innovative technologies are enabled. Generative Design, which is one of them was explored in case 1 and 2. The main objective of this chapter was to verify whether such optimization routines could produce reasonable solution, and as the verified results indicate both cases highlights structures that satisfy the given criteria. As Machine Learning and AI will affect all industries in the future(Wang, W., & Siau, K. 2019), the cases described in this paper give a taste for how structural engineers might deploy computers to tackle the problems of tomorrow. Lastly, as an outcome of this paper, a proposed workflows has been presented. The workflow has been developed through trial and error when working on the different cases and inherit characteristics that when followed yielded consistent results. Consequently, this workflow can serve as user guide for newcomers looking to make use of the technologies studied in this paper.

7.1 FUTURE RECOMMENDATIONS

7.1.1 Automatic modelling of reinforcement

Modelling reinforcement is a cumbersome task in any concrete structure, although placing rebar can be done parametrically in grasshopper, you still have to refer the calculation documentation to get the exact positions of all elements. However, with use of FEM-Design plug-in for grasshopper, it is possible to import the result from its auto-generated reinforcement placing back to grasshopper, this could in turn be used to automatically place the rebar in a BIM-model. By doing so, a lot of time could be saved.

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