

## **Structural Evaluation Assistant (SEA)**

Decision-making support for conceptual structural design

by

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# Affirmation

I, Lukáš Kurilla, hereby confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.



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# Abstract

The goal of this research is to raise interest of architects in structural behaviour of design in its conceptual phase. Therefore, this research deals with the development of a middleware – a bridging tool between the finite element (FE) solver (OOFEM) and the architectural modeller (Rhino3D), which will provide architects with an interactive FE analysis directly in the architectural modeller.

However, architects are not typically trained to use expert FE analysis software directly. FE analysis is too complex and professional for users without sufficient structural knowledge. Thus, there is a problem of correct modelling and interpretation of analytical results. Therefore, it is important to deal with methods of FE analysis simplification for conceptual structural design, that will make FE analysis more accessible for architects.

In this research, three methods of possible FE analysis simplification were developed. The first one – *Rating system*, evaluates the design as a whole with two scalar values, and thus informs architects about structural efficiency and identifies potential structural problems. Then, to uncover the identified structural problem in more detail, the second method – *Levelling system*, defines three levels of results simplification. This enables architects to extend their structural knowledge and understand the problems. The last method – *Design tracker*, allows architects to store and compare design alternatives created during the design process. Comparing alternatives supports architects' decision-making and allows them to understand the impact of a change in the design on its structural behaviour.

The results of this research can be used to teach architects at universities as well as in practice for interdisciplinary cooperation between architects and structural engineers, especially in the conceptual design phase.





# Abstrakt

Cieľom tohto výskumu je vzbudiť záujem architektov o statické pôsobenie návrhu už v jeho koncepcnej fáze. Preto sa tento výskum zaoberá vývojom middlewéru – digitálneho nástroja, ktorý premostuje statickú analýzu (OOFEM) s architektonickým modelárom (Rhino3D), a ktorý má zabezpečiť vytvorenie interaktívnej statickej analýzy v prostredí architektonického modelára.

Architekti však nie sú bežne vyškolení na priame použitie statickej analýzy, ktorá je príliš komplexná a odborná na to, aby ju užívateľ bez expertných vedomostí dokázal správne nastaviť a interpretovať jej výsledky. Preto je dôležité zaoberať sa metódami, ktoré by statickú analýzu pre potreby koncepcného statického návrhu zjednodušili, aby bola dostupnejšia pre architektov.

V tomto výskume boli vyvinuté tri metódy predstavujúce možné zjednodušenie statickej analýzy. Prvá metóda – *Rating system* (hodnotiaci systém) hodnotí celkový návrh dvojicou skalárnych veličín informujúcich architekta o efektívite a potencionálnych statických problémoch v návrhu. Druhá metóda – *Levelling system* (systém levelovania) s cieľom detailnejšie spoznať identifikovaný statický problém definuje tri stupne zjednodušenia výsledkov statickej analýzy, čím umožní architektovi dodatočne si prehĺbiť vedomosti zo statiky. Tretia metóda – *Design tracker* (sledovač návrhu) umožňuje vzájomné porovnávanie alternatív návrhu, čím podporuje rozhodnutia architekta a umožňuje mu uvedomiť si dopad vykonaných zmien na statické vlastnosti návrhu.

Výsledky tohto výskumu je možné použiť pri výučbe na architektonických školách ako i v praxi pre zlepšenie medziodborovej spolupráce architekta a statika predovšetkým v koncepcnej fáze návrhu.



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## **Part I**

# **Introduction**





# Chapter 1

## Problem statement

*"This Pritzker prize-winning architect promotes an architectural process which is disconnected from structures, and purposefully ignores any structural input. The structural engineer comes in at the end of his process to make his creations (cf. his "sketch" in Figure 1.1a) stand. This unidirectional process results in heavy structures, waste of material and awkward details (Figure 1.1c)."*<sup>1</sup>

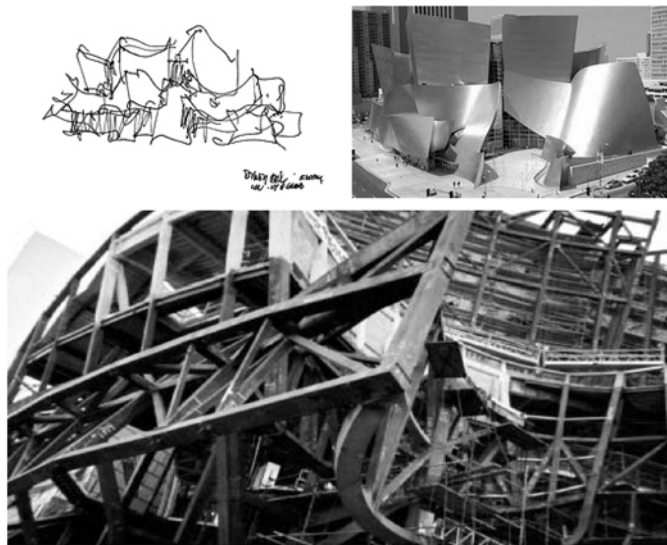


FIGURE 1.1: (a) Conceptual sketch by Frank Gehry for the Walt Disney Concert Hall in Los Angeles, CA, 1999-2003; (b) aerial view; and (c) the structure before receiving cladding. (Philippe Block, 2009)

<sup>1</sup>Philippe Block. "Thrust Network Analysis: Exploring Three-dimensional Equilibrium". PhD thesis. Massachusetts Institute of Technology, June 2009.

## 1.1 Interdisciplinary cooperation

In many cases the reason of over-dimensioned (heavy) structures, or more serious structural collapses, is that architectural design in its early stages does not follow physical laws. Nowadays architects form innovative designs based on their aesthetics and spatial needs without thinking structurally during the design process. To achieve structural safety and material efficiency architects cooperate with structural engineers. However, in current common practice, a structural engineer comes into the design process in a later phase when it is too late to make changes for optimal structural solutions. To avoid collapses or over-dimensioned structures especially in more innovative designs, it is important to establish a good interdisciplinary cooperation between architects and engineers already in the early design phase.

### Interconnected hands

Le Corbusier was also aware of importance of this interdisciplinary cooperation in the conceptual phase. In his work *Relation between architect and engineer* he drew a pair of interconnected hands that were to represent the relationship between engineers and architects (Figure 1.2).

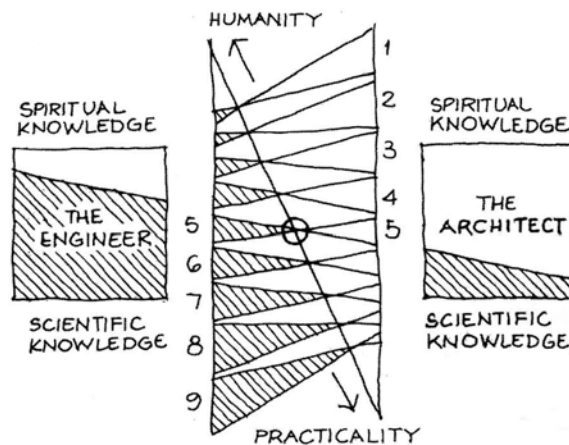


FIGURE 1.2: An interpretation of Le Corbusier's view of the Engineer-Architect relationship. (Millais, 2005)

*"In my drawing, the engineer's sphere casts a reflection on that of the architect - the reflection of the knowledge of physical laws. Similarly, the architect's understanding of human problems is reflected in the sphere of the engineer."*<sup>2</sup>

A good example of cooperation between architects and engineers is the design of Eiffel Tower (Figure 1.3). On the left you can see the conceptual design representing engineer's technical idea of the tower. Its aesthetics is based on the moment diagram, which should ensure sufficient stiffness of the tower. The sketch in the middle shows the architectural visions of the tower. It is noticeable that the aesthetics of the tower is based on archetypes established

<sup>2</sup>Le Corbusier. "Relation between architect and engineer". In: *Science et Vie* (1960).

in that period (victory arch etc.). The Eiffel tower as we know it today is the result of the interconnection of both ideas (Figure 1.3 on the right).

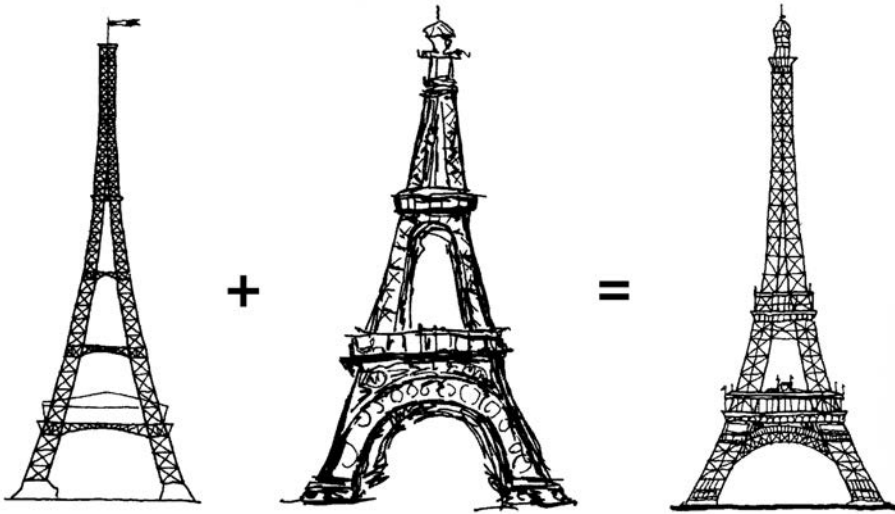


FIGURE 1.3: Eiffel tower, the initial concepts of the engineer (left) idea from the architect (middle) and the final design (right). (Millais, 2005)

## History of professions

Interconnection between architects and engineers has its roots in history as both professions arose from one profession, namely from Master Builder.

*"In the past, at the time of the construction of the great cathedrals, the Master Builder was the person who dealt with all the design issues to do with a building, from the very artistic to the very technical. He was the "architect" and the "engineer" for the project. However, since the Industrial Revolution with the great development in the field of sciences and materials, a clear distinction between the two professions became more evident: the architect came to be in charge of the architectural issues, whereas the engineer was concerned with the more technical issues."*<sup>3</sup>

In the past the builder performed both the role of an architect and engineer in one person. In the conceptual design he focused mainly on the form, which is evidenced by form-finding methods that were developed (graphic statics). The shape of the structure was designed to follow the forces acting on it.

At the time of modernism, with the arrival of steel and reinforced concrete, the shape of structure became prescribed – uniform in character. The emphasis on the proper form receded into the background and engineers began to focus more on streamlining the element profiles and their dimensions rather than on the form itself (see Figure 1.5). The architect becomes the main form-maker; the structural engineer only makes the design stand.

GOTHIC

MODERN

<sup>3</sup>Olga Popovic Larsen and Andy Tyas. *Conceptual Structural Design*. Thomas Telford, 2003. ISBN: 0-7277-3235-8.

Advances in the design process gradually brought a clear distinction between the two professions. Digital tools developed in a later era also copied this distinction. Two different digital tools were developed: the analytical one for engineers to assist them in designing materials and dimensions of the structures and the modelling tool that allows architects to deal with geometry and visualizations.

## 1.2 Conceptual and structural design

The analysis of the conceptual and structural design also proves that cooperation between architects and engineers in the conceptual design phase is of great importance. Schlaich in his conference paper Challenges in Education – Conceptual and Structural Design defines four steps: conceiving, modelling, dimensioning and detail (see Figure 1.4 and a citation below).

### Four design steps

*"In reality the design process is never a straight forward procedure. Rather, we reach our solutions in an iterative, cyclic, hopefully concentric and sometimes even slightly chaotic manner. Always bearing in mind fabrication and erection, this process of Conceptual and Structural Design, the daily work of civil and structural engineering, is defined by the following steps: conceiving, modelling, dimensioning, detailing."*<sup>4</sup>

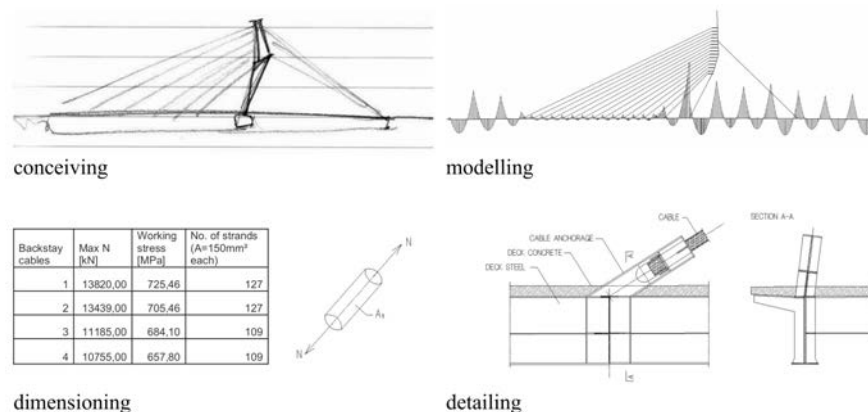


FIGURE 1.4: The process of Conceptual and Structural Design. (Schlaich, 2006)

The first step (Figure 1.4 conceiving) requires skills that are rather the domain of architects than engineers, but the other three steps (Figure 1.4 modelling, dimensioning and detailing) cannot be managed without an engineer's knowledge and experience. In fact conceptual and structural design is divided between this pair of professions.

<sup>4</sup>Mike Schlaich. "Challenges in Education – Conceptual and Structural Design". In: *IABSE Symposium Report 92* (2006), pp. 20–26. ISSN: 22213783. DOI: 10.2749/222137806796168840.

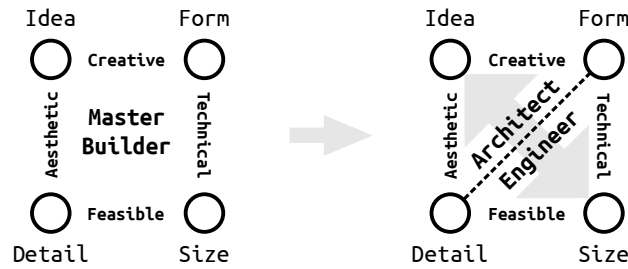


FIGURE 1.5: Division of Master Builder profession into Architects and Engineers.

## Interaction

It seems possible that all four steps can be done in a linear order. First, the architect designs a form, then the structural engineer designs dimensions and details. But it is not true. The linear process works only in the later design phases, where only one or few design alternatives have to be analysed. But for the purpose of the conceptual design a non-linear design process is needed. Schlaich highlights the non-linearity of the design process caused by mutual influence of individual steps between one another, when a change made in one-step affects all the other steps.

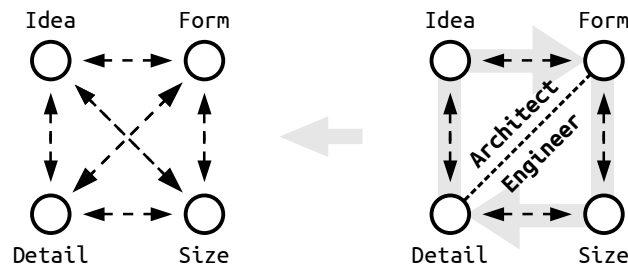


FIGURE 1.6: Non-linear (left) and linear (right) design process.

## 1.3 Rapid communication

The need for interaction between individual design steps brings the demand for rapid communication between professions. Despite the potential of information technologies, it is a problem to establish a communication platform for the rapid communication between architects and structural engineers.

In the design work-flow, the architect sends a design model to the structural engineer, and the engineer needs to convert it into an analytical model. Then the structural engineer analyses the converted model and proposes changes in the design. The architect evaluates the proposed changes and based on his/her decision they are implemented into the design model. In case of disagreement or the need to evaluate another design alternative, the process starts over again.

Data incompatibility between the architect's design model and engineer's analytical model creates a time consuming process on the engineer's side, and prevents necessary rapid communication in the practice (Figure 1.7). The main

DESIGN WORK-FLOW

THE PROBLEM

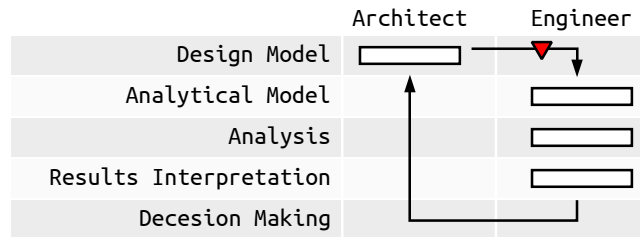


FIGURE 1.7: A work-flow of a common interdisciplinary cooperation in the structural design.

cause of this incompatibility is the reduction of one dimension in the analytical model, as well as the necessity to define supplementary information required for the analytical model, such as structural supports or loading cases.

## 1.4 Conclusion

This chapter shows the importance of interconnecting architectural and engineering approaches in the conceptual and structural design. Four design steps in the conceptual and structural design were introduced and the non-linearity of the design process was stressed. The problem this chapter highlights is the lack of rapid communication (free steps interaction) in the current interdisciplinary work-flow, which does not allow architects to analyse the necessary number of design alternatives in the conceptual design.

## Chapter 2

# Motivation

"Conceptual design is the thought process of generating and implementing the fundamental ideas that characterize a product or system. This process significantly affects the product novelty, performance, robustness, development time, value, and cost."<sup>1</sup>

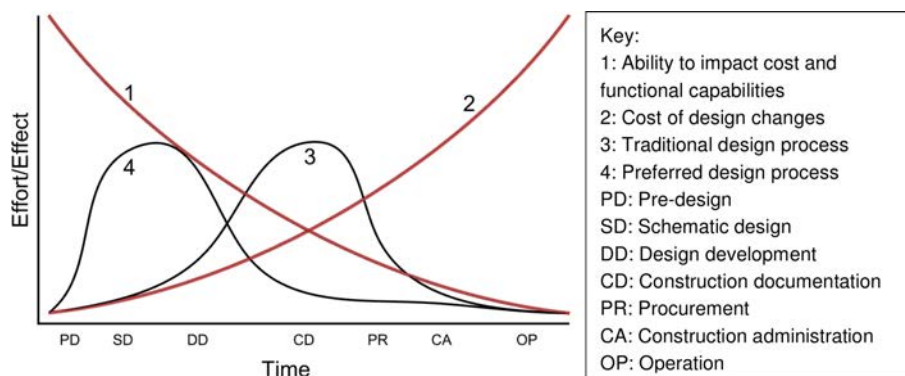


FIGURE 2.1: The MacLeamy Curve. (Ramsden et al., 2015)

<sup>1</sup>Ehud Kroll, Sridhar S. Condoor, and David G. Jansson. *Innovative Conceptual Design*. Cambridge Books Online. Cambridge University Press, 2001. ISBN: 9780511612923.

## 2.1 Structurally informed design

The previous chapter examines the problem of interdisciplinary work-flow (lack of rapid communication), which makes it impossible to model and analyse the necessary number of design alternatives in the conceptual design phase. This problem also causes that the structural analysis in fact is performed in the later design phase, where the cost of a design change is too high. This is represented in the graph in Figure 2.1 (3) as a traditional design process. To prevent unwanted costly changes in a later phase of the design process, it is necessary to be informed about structural behaviour earlier – in the conceptual design phase, when the price of a design change is still low. This is how to achieve the preferred design process showed in Figure 2.1 (4).

### Possible approaches

Structurally informed conceptual design is a broad topic and there has been a lot of research on this issue. Some research focuses on interdisciplinary cooperation and model incompatibility the other studies focus on analysis and design supporting methods.

#### SMART MODEL

One approach is to create "smart model"<sup>2</sup>, which combines both models and allows the user to switch between them (Figure 2.2). In this approach the analytical model is automatically generated in the background while the design model is created. However, when applied in practice, it does not work very well. The smart model approach needs a correction to the created analytical model, especially when it was created by an architect. After each change in the model it is necessary to perform the correction again. This shows that it is a more time consuming process than to create a new analytical model from scratch.

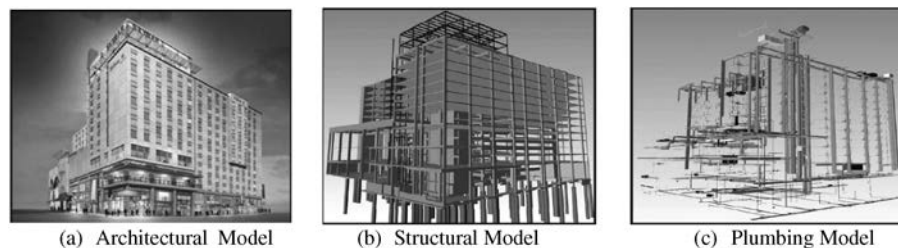


FIGURE 2.2: Building information models of the Aquarium Hilton Garden Inn Project (Courtesy of Holder Construction Company, Atlanta, GA). (Azhar, 2011)

#### SIMPLIFIED MODEL

Laurens Luyten<sup>3</sup> approaches this problem in a different way. His research focuses on the development of a simplified analytical model as the language for better collaboration between architects and structural engineers in the con-

<sup>2</sup>Salman Azhar. "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry". In: *Leadership and Management in Engineering* 11.3 (2011), pp. 241–252. DOI: 10.1061/(ASCE)LM.1943-5630.0000127.

<sup>3</sup>Laurens Luyten. "CAAD and Conceptual Design Collaboration between Architects and Structural Engineers". In: *Real Time-Proceedings of the 33rd eCAADe Conference*. Vol. 2. Vienna University of Technology. 2015, pp. 215–224.



ceptual design phase (Figure 2.3). In this approach, the architect depends on engineer consultations. The research does not show how the architect could independently analyse design. The architect can earn structural knowledge from the engineer, but cannot train his/her structural intuition directly by exploring design alternatives.

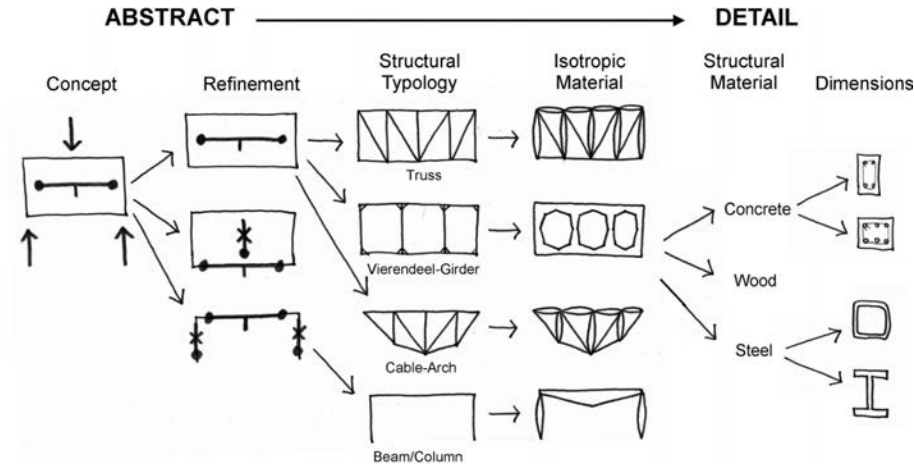


FIGURE 2.3: Application of developed language for concept creation and refinement. (Luyten, 2015)

Another solution to establish a structurally informed design in its early stage is to use software tools based on the optimization of form-finding methods. Caitlin Mueller<sup>4</sup> in her PhD thesis developed an interactive evolutionary algorithm which helps the user to find a structurally better solution. The disadvantage of this approach is that the user cannot directly control the modelling process, and thus he/she lacks action and reaction feedback which is important for human-learning. Furthermore, a less experienced user can blindly believe in a wrong optimal solution which is proposed by the incorrectly initialized algorithm.

SIMULATION  
AND OPTIMIZATION

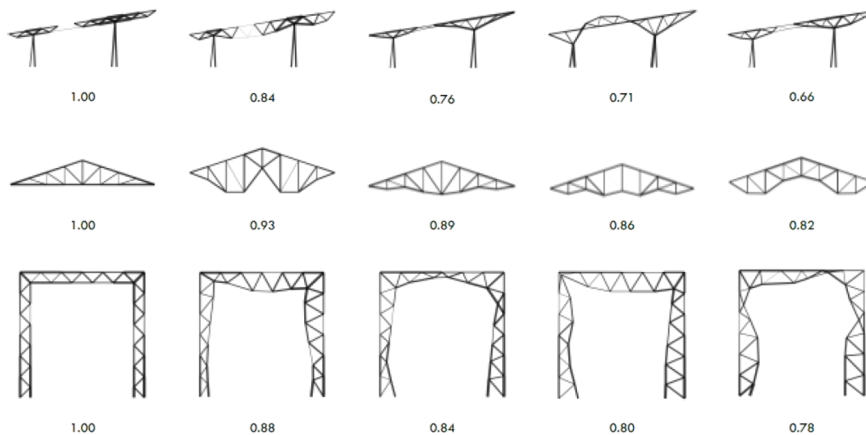


FIGURE 2.4: Example of optimization used by genetic algorithms. (Mueller, 2014b)

<sup>4</sup>Caitlin T Mueller. "Computational Exploration of the Structural Design Space". PhD thesis. Massachusetts Institute of Technology, June 2014.

## Chosen approach

### ANALYSIS DIRECT USE

The chosen approach for this research is to provide the architect with an interactive structural – finite element (FE) analysis which will enable him/her to independently analyse a large number of design alternatives in the conceptual design process.

The direct use of FE analysis allows the architect to earn structural knowledge by learning how to create an analytical model and by understanding the analysis results. Furthermore, the interactive feedback gives the architect opportunity to train his/her structural intuition during the design process. However, one problem is that architects are not typically trained to use the expert structural analysis software directly. Therefore, the simplification of direct FE analysis use is necessary for beginner users.

### IDENTIFIED PROBLEMS

There are two basic problems structurally that untrained users encounter when using FE analysis directly. The first essential problem is to create a proper analytical model corresponding to the real behaviour of the structure, especially in cases of complex structural systems and geometry. The second problem includes interpretation of the structural analysis results and identification of possible structural problems (see red triangles in Figure 2.5).

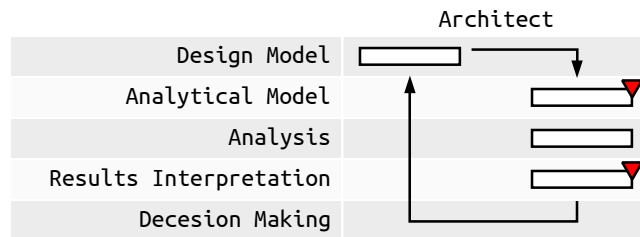


FIGURE 2.5: Problems of direct use of structural analysis by the architect.

## 2.2 Research objectives

### LEVEL OF SIMPLIFICATION

The first goal of this research is to develop a method of simplification of FE analysis use. What is important is that this method should allow users to change the level of simplification, similar to games where the player chooses the difficulty. This will later enable architects to extend their structural knowledge.

### RESULTS INTERPRETATION

The second goal of this research is related to the first one. It is the development of the most simplified level of analytical results to support less trained users' interpretation (see yellow star in Figure 2.6 results interpretation). This should allow a structurally untrained user to be able to compare two different design alternatives and decide which is structurally more efficient. It is also important, that a simplified interpretation of the results should allow the user to identify possible structural problems which can guide him/her towards structurally better solutions.

### DECISION-MAKING SUPPORT

The third goal is focused more on the design process, especially on the decision-making support (see yellow star in Figure 2.6 decision-making). The

developed method should guide architects during the design process, and based on their deduction, help them avoid the identified structural problems.

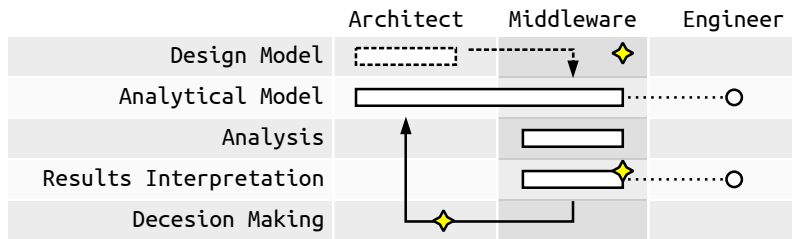


FIGURE 2.6: Proposed solution based on middleware development; yellow stars represents goals of this research, white circles represents engineer’s support by consultation.

The last goal of this research is the implementation of all the developed methods into a software tool which will establish interactive analysis in the common architectural modeller (see yellow star in Figure 2.6 middleware). Thus it will be possible to get feedback from users, which is important for research evaluation. The developed software tool can be also used at architectural schools and in common practice, which will have a positive impact on interdisciplinary cooperation.

SOFTWARE TOOL

The development of a support method for the creation of a correct analytical model goes beyond the scope of this research. It is a broad topic for an entire thesis, therefore only marginal attention will be given to this subject. For research purposes, it is assumed that the creation of an analytical model is discussed with the structural engineer (see Figure 2.6 analytical model). That way, there is no limitation on the required rapid design exploration. After correcting the analytical model in the initial phase, architects can independently analyse its different modifications (see arrows in the loop in Figure 2.6).

ANALYTICAL MODEL

COOPERATION

Furthermore, consultations with the structural engineer are occasionally also expected in the results interpretation step. All this will contribute to broadening architect’s structural knowledge and improving interdisciplinary cooperation.

### 2.3 Methodology and chapters overview

To develop the means of a decision-making supporting method the natural design process was reviewed in the first chapter of the Literature review – Part II (see Chapter 3). The review focused on design stages, process and requirements of decision-making. Knowledge earned in this review was used to design a Design tracker – the decision-making supporting method described in Section 7.1.

DESIGN TRACKER

To support decision-making, each design alternative needs to be evaluated. Therefore, a review of existing optimization and form-finding methods and tools was carried out in Chapter 4. In focus were the scoring systems and evaluation criteria that guide designs towards an optimal solution. Based on this review the first level of FE analysis results simplification was developed – a Rating system method (see Section 6.2). Knowledge learned in this review

LEVELLING AND RATING SYSTEMS

about different strategies of the structural design and the use of different dominant structural properties helped to define a Levelling system introduced in Section 6.1.

**MIDDLEWARE**

The first chapter in the Part III – Structural Evaluation Assistant (see Chapter 5) describes the development of a software tool – a middleware. The development of the middleware was necessary to get feedback from users and thus to prove the found methods. The middleware was developed also to impact the current state of interdisciplinary cooperation. The chapter describes the selection of existing software tools which were bridged by the middleware, and also the design of software architecture and graphical user interface (GUI) of the middleware. More information about middleware interface is in the Appendix A.

**IMPLEMENTATION**

Further chapters of the Part III describe the implementation of each developed method into the middleware. Calculation and data visualization of the Rating system is presented in Chapter 6. The design of user experience interface of the Design tracker is presented in Chapter 7.

**APPLICATION**

The application of the developed middleware and supporting methods is presented in Part IV. The first chapter (see Chapter 8) introduces ability of the middleware to support decision-making in the interactive design and also in the design exploration processes. The last chapter (see Chapter 9) of Part IV shows a practical application of the middleware at school and in practice.

## **Part II**

# **Literature Review**



## Chapter 3

# Design as searching process

"If design is search, then design problems have a structure and the act of designing is a process on that structure. Informally and as shown in Figure 3.1, design problems consist of a set of information states, divided into initial, intermediate, and goal states, and a set of operators that move between those states. Each of the states represents some design, possibly incomplete. Designing in its simplest form consists of finding a set of operator sequences (or paths) between initial and goal states."<sup>1</sup>

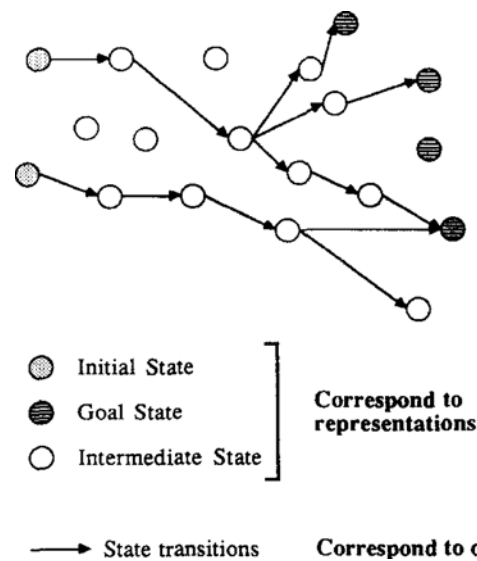


FIGURE 3.1: A generic diagram for search. (Woodbury, 1991, p. 62)

<sup>1</sup>Robert F Woodbury. "Searching for designs: Paradigm and practice". In: *Build. Environ.* 26.1 (Jan. 1991), pp. 61–73. ISSN: 03601323. DOI: 10.1016/0360-1323(91)90040-I, p. 62.

### 3.1 Variables define design goals

Woodbury in the aforementioned quote likened the design process to finding a set of paths between the initial and goal states. Before dealing with the course of finding the paths themselves, it is necessary to clarify what is meant by the concepts of initial and goal states in static design. Both the initial and goal states are closely interconnected.

#### INITIAL STATES

In the context of optimization and digital design, fixed and variable parameters of the design – variables of the parametric model, can be considered the initial state. They define the requirements and limits of the design, and so they clearly determine the goal where the path – the design process is to go.

#### GOAL STATES

In structural design it is possible to define three types of goals: finding topology optimization, shaping and sizing. In finding topology optimization only supports, boundary conditions, and external loads are defined as fixed design parameters. The number and position of nodes, as well as their connectivity – elements of the design – result from a design process and are not specified at the initial state of designing. (they are variable design parameters). For shaping, the topology of the design is already known, and only node positions remain variable design parameters. For sizing, the node positions are also fixed (the overall shape of the design is therefore determined). Only dimensions (shapes and areas of the profiles) of individual elements of the structure change during the design process.

#### Structure systems

To understand a possible structural design goal it is important to know possible structure systems and their properties. In his book *Structure Systems*<sup>2</sup>, Heino Engel defines five basic types of structure systems, divided on the basis of their specific structural properties, see Figure 3.2. In this work we will deal with the first three of them.

#### FORM ACTIVE

The first system includes *Form active structures* (Figure 3.2 (1)). These are pure-compression or pure-tension structures for which the dominant component are normal forces. The shape (shape and geometry) of the design itself has the greatest influence on the design efficiency. Therefore, this structure system uses a form-finding method.

#### VECTOR ACTIVE

The second system contains *Vector active structures* (Figure 3.2 (2)). Similarly to Form active structures, this system lacks the bending moment component, so the dominant components are again normal forces. However, the efficiency in this system is influenced by the topology of the structure. Therefore, special topological optimizations are used for this system more than form-finding methods.

#### SECTION ACTIVE

The third system includes *Section active structures* (Figure 3.2 (3)). The efficiency of the structure in this system is affected by changing the dimensions and shape of the structure's profile. To optimize this system, searching algorithms are mostly used.

<sup>2</sup>Heino Engel. *Structure systems (Tragsysteme)*. Ostfildern : Hatje Cantz, 2013, p. 352.



Einteilung der Tragsysteme im Bauen

Classification of structure systems in building

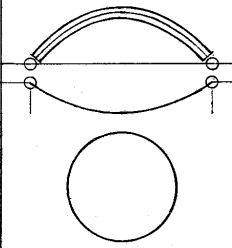
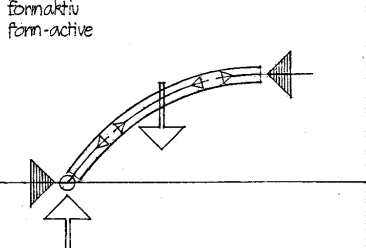
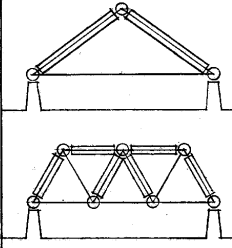
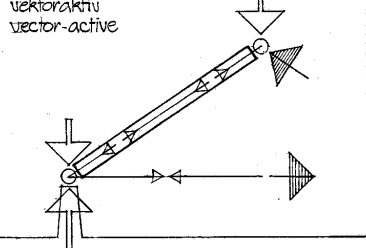
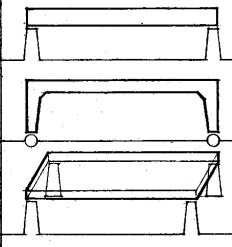
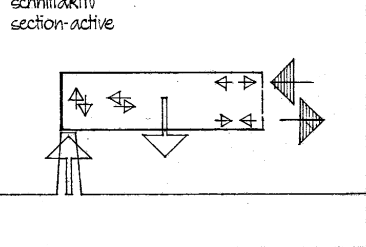
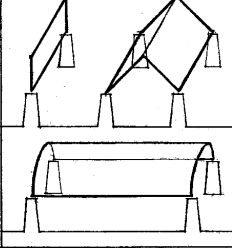
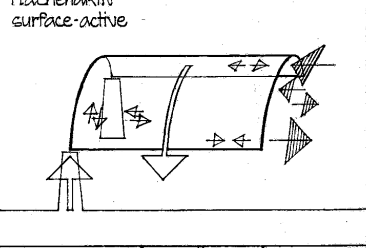
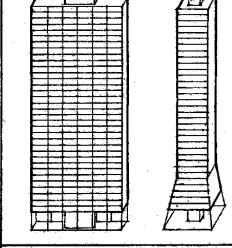
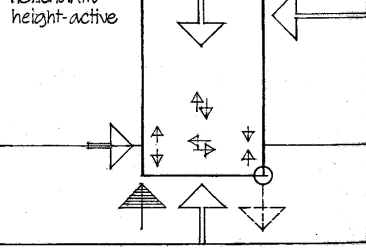
Kriterium Criterion	Prototyp prototype	Kräfte forces	Merkmal feature	Mechanik der Kraftumlenkung mechanics of redirection of forces
1 FORM	 <p>Stützboogen funicular arch Hängeseil suspension cable Kreisring circular ring Ballon balloon</p>	Druck oder Zug  compression or tension	Stützlinie thrust line  Kettenlinie catenary  Kreis circle	formaktiv form-active  
2 VEKTOR VECTOR	 <p>Dreieckverbund triangular truss  Fachwerkträger trussed beam</p>	Druck und Zug  compression and tension	Dreieck- verbund  triangu- lation	vektoraktiv vector-active  
3 QUER- SCHNITT CROSS SECTION	 <p>Balken beam Rahmen frame Platte flat slab</p>	Biegung Schnittkräfte  bending section forces	Querschnitt- profil  sectional profile	schnittaktiv section-active  
4 FLÄCHE SURFACE	 <p>Scheibe plate gefaltete Platte folded slab Zylinderschale cylindrical shell</p>	Membran- kräfte  membrane stresses	Flächen- form  surface shape	flächenaktiv surface-active  
5 HÖHE HEIGHT	 <p>Scheibe slab Turm tower</p>	(Komplexe Be- dingungen)  (complex conditions)	Lasten- Erdung Stabili- sierung  load grounding stabili- zation	höhenaktiv height-active  

FIGURE 3.2: Classification of structure systems in building (Engel, 2013)

### 3.2 Intermediate states and actions

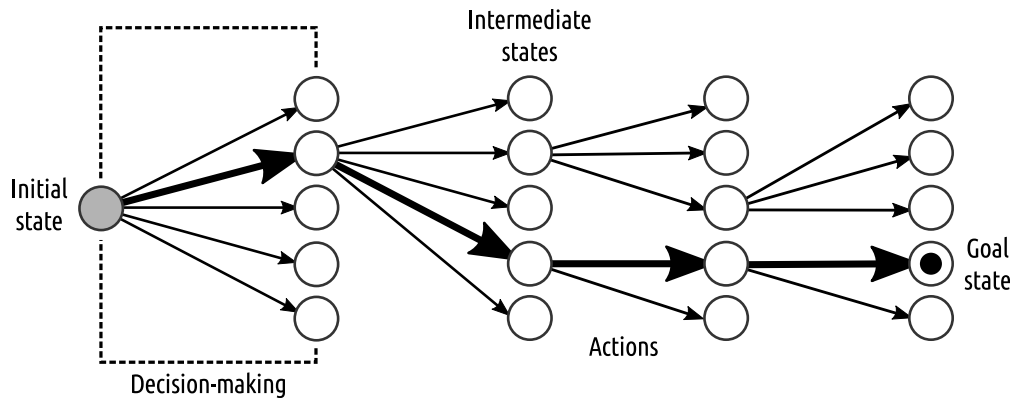


FIGURE 3.3: Design process scheme

On the paths between the initial and goal states there are several intermediate states. Individual intermediate states are sequentially created on the basis of actions (the arrows in the Fig.3.3) Actions represent various changes made in the design, such as geometry adjustment (point shift) and so on. Actions always have an initial state, before making a change in the design, and the resulting state after the change. In the design process they can either continuously continue (thick arrows in Figure 3.3) or they can diverge (Figure 3.3, thin arrows that share the same initial state).

#### Path as design method

In the simplest case, the design process may be linear, that is, the actions performed have a clear direction (rule) to achieve the desired goal. Later, methods such as form-finding with a linear design process will be shown. However, more common and more natural for people is a design process in which the path leading to achieving the desired result is unclear. The path structure between the initial and goal state is similar to that shown in Figure 3.3. The design path is divided into individual sections (decision-making in Figure 3.3), and the designer decides which direction to go, what action to take – what changes to make in the model.

#### Decision-making

*"Decision theory is not a substitute for the fortune teller. It is rather a procedure that takes account of all available information to give us the best possible logical decision."*<sup>3</sup>

The example in Figure 3.4 shows a common decision-making tree diagram. This diagram is often used in practice, especially in economics for risk analysis. Branches of the tree represent possible actions (to buy, not to buy flowers). For

<sup>3</sup>D Warner North. "A Tutorial Introduction to Decision Theory". In: *IEEE Trans. Syst. Sci. Cybern.* SSC-4.3 (1968), pp. 200–210. ISSN: 0536-1567. DOI: 10.1109/TSSC.1968.300114.

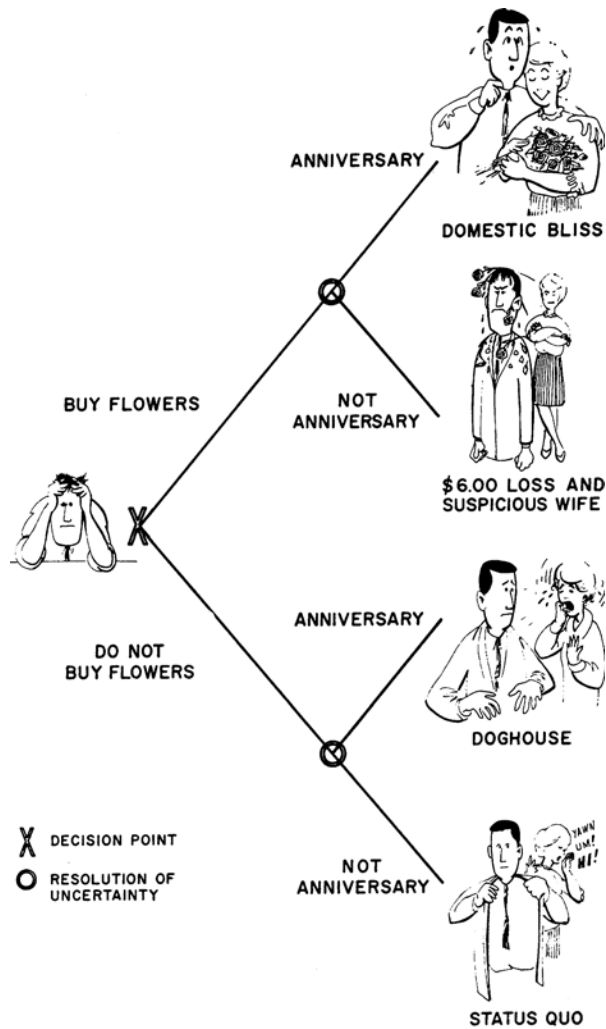


FIGURE 3.4: Diagram of anniversary decision. (North, 1968, p. 201)

each action its overall impacts are evaluated. Based on this, one can evaluate different actions and choose the most advantageous one.

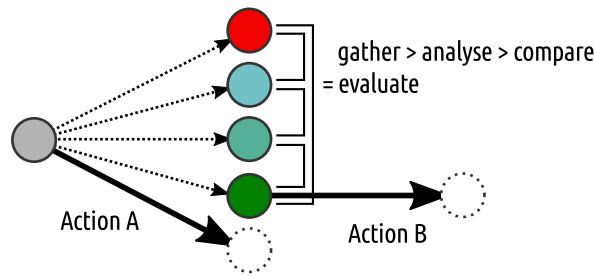


FIGURE 3.5: Design process: decision-making scheme.

Similarly, this is also the case for decision-making in a design process. Designer cyclically verifies various actions creating a field of new design alternatives from which he chooses one (Figure 3.5). As in the diagram with flowers, the evaluation of each design alternative serves to support the decision-making. In order to evaluate the alternatives, they must be analysed and compared (Figure 3.5). Based on the results of the evaluation, the designer decides either for action A – creating a new alternative (insufficient results) or action B – further development of the selected, the most successful alternative.

### 3.3 Conclusion: Research focus

This research focuses on the structural design process, structural analysis and decision-making. The next chapter explores the design process in more detail, using structural methods such as form-finding, genetic algorithms, and evolutionary structural optimization. These methods will be compared in terms of design objectives, a sequence of steps to follow, decision making and design evaluation. This comparison and examination serve to find a way to simplify structural analysis, which is the main objective of this research.

## Chapter 4

# Structural performance based design approaches

*In the fields of architecture and engineering, the requirements of design tools are somewhat different from those of analysis tools. The analysis process can usually be executed in a regular, predetermined sequence of steps. ... In contrast, the design process is not expected to consistently yield the same result. Although a designer may follow a sequence of steps, the steps are not self contained, but influenced by factors outside the process itself (the unique background of the designer, stimuli of the environment, Zeitgeist, etc.). (Bülow 2007, p.58)*

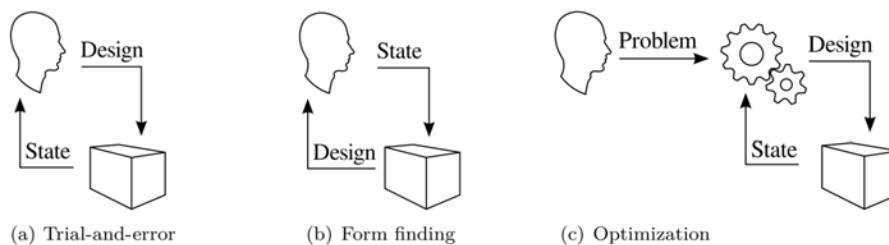


FIGURE 4.1: Different kinds of design process with (a) the conventional trial-and-error process, (b) the structural form-finding process, (c) the structural optimization process. (Descamps, 2013)

Descamps in his PhD Thesis entitled Optimal shaping of lightweight structures<sup>1</sup> states three approaches to the process of structural design: conventional trial-and-error, structural form-finding and structural optimization (see Figure 4.1). Descamps' scheme has led me to divide processes not only according to the method used, but also based on their input and output.

DESIGN APPROACHES

Three different approaches to the structural design are introduced in this chapter. In the course of my research I have named them: *Design to performance*, *Conditions to design* and *Problem to solutions*.

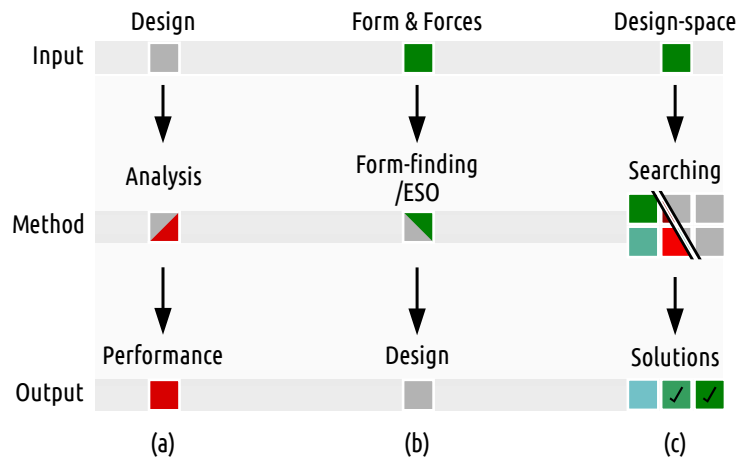


FIGURE 4.2: Different kinds of design process: (a) design-to-performance (b) forces-to-design (c) design-to-solutions.

FEEDBACK

In addition to the inputs and outputs of each method, from the user's point of view, it is important to deal how the user interacts with the algorithm and its benefits to the user. Therefore, for each of these design approaches I present a graph that represents the progress of the design process and its connection with the user's feedback. At the end of the chapter, after comparing the approaches, a proposed design process is presented. The following chapters (main part) of this work are devoted to its detailed presentation.

## 4.1 Design to performance

Design to performance is the only one of the analysed approaches that is associated with manual modelling on the user side (human base modelling). The structural analysis method gives the user feedback in the form of a design evaluation (Figure 4.3). Feedback neither includes direct support to decision-making, nor guides the user to find a better solution.

### Input

ANALYTICAL MODEL

The input for FE analysis is an analytical model. It is similar to a design model (commonly created by architects) but it differs in geometric representation of the model (in an analytical model geometry is cut by one dimension –

<sup>1</sup>Benoit Descamps. "Optimal shaping of lightweight structures". PhD thesis. Brussels School of Engineering, Nov. 2013.

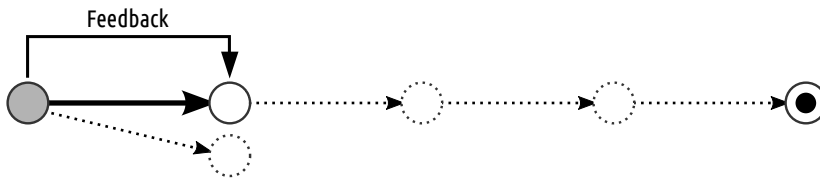


FIGURE 4.3: Design to performance, feedback represents results form FE analysis.

eg. from 3D to 2D) and in the required additional information such as specific material properties, and boundary loading conditions.

### Method

In common application of the FE method, the method does not change any geometry of the design. It only calculates deformation and stress in the structure (usually in one iteration step) and returns the result to the user. This information is the only feedback for a user.

ANALYSIS ONLY

### Existing tools

One plugin of interactive FE analysis that is available in the architectural modeller Rhino3D-Grasshopper is Karamba3D<sup>2</sup>. It allows one to create an analytical model and carry out its analytical results. But, Karamba3D is designed for structural engineers more than architects. It is a full-fledged analytical tool with a broad field of applications. This is why its interface is complex and requires structural experience to setup analysis correctly.

KARAMBA3D

### Conclusion

The main advantage of this approach is that it trains the designer's intuition by making the user directly involved in the design process and decision-making about the next step. Disadvantage are that it is time consuming and there is a high probability of failure that is directly related to the user's experience. The method is often chaotic (associated with the trial and error method) and normally provides no decision-making assistance.

TRIAL-AND-ERROR

The user receives direct feedback from the analysis and needs to correctly interpret it, in order to know if a change leads to an improvement or a deterioration in the design. Another problem is the creation of a proper structural model that corresponds with the real behaviour of the structure, and does not distort the analysis results.

CORRECT MODELLING AND INTERPRETATION

## 4.2 Conditions to design

Unlike the previous Design to performance approach, which was based on a user-natural approach (to design first and then evaluate the shape of a structure), this set of methods is the opposite. The user first defines design proper-

<sup>2</sup>Clemens Preisinger. *Karamba3D*. version 1.2.2. [software]. 2014. URL: <http://www.karamba3d.com/> (visited on 09/20/2017).

ties and the result - feedback is represented as a changed shape or topology of the design. The first of the methods I deal with are form-finding methods. Axel Kilian called this design process a Force driven design.

"While constraints may initially prove to be a limitation, over the course of the design process they can evolve to become a driver for innovative design solutions."<sup>3</sup>

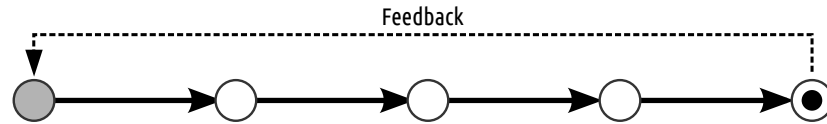


FIGURE 4.4: Conditions to design, feedback represents found design.

## Form-finding

"Form-finding is a forward process in which parameters are explicitly/directly controlled to find an 'optimal' geometry of a structure which is in static equilibrium with a design loading."<sup>4</sup>

The aim of the form-finding method is to find the equilibrium state of the external and internal forces that can affect the structure, thus also eliminating any bending moments in the structure. This method is used to design form active structures (Figure 3.2 (1)) which include, for example, cable or light-weight structures for which it is characteristic that there are pure tension or compression only structures.

## Input

### TOPOLOGY AND BOUNDARY CONDITIONS

Unlike design to performance methods, in which the user directly at the initiation (on input) determines a particular shape for a design (design for its subsequent evaluation), the particular shape of the structure is the output in this method. The input for the calculation is only the defined topology of the structure containing information about its fixed and free points (boundary conditions) as well as their interconnection (an element of structure). In addition to the topology, the input also includes information about the proposed external and internal forces. They directly affect the structure points and their shifting also changes the resulting shape of the structure.

## Method

The form can be found either in one calculation step or in a series of calculations, depending on the method used.

<sup>3</sup>Axel Kilian and John Ochsendorf. "Particle-spring systems for structural form finding". In: ... Assoc. SHELL ... 2005.

<sup>4</sup>Sigrid Adriaenssens et al. *Shell structures for architecture : form finding and optimization*. Abingdon : Routledge, 2014. ISBN: 978-0-415-84059-0, p. 2.



Geometric stiffness methods, such as Force density or Graphic Statics, allow one to solve a matrix system in one iteration, or to organize form and forces diagrams to find the resulting form (see Figure 4.5).

GEOMETRIC STIFFNESS

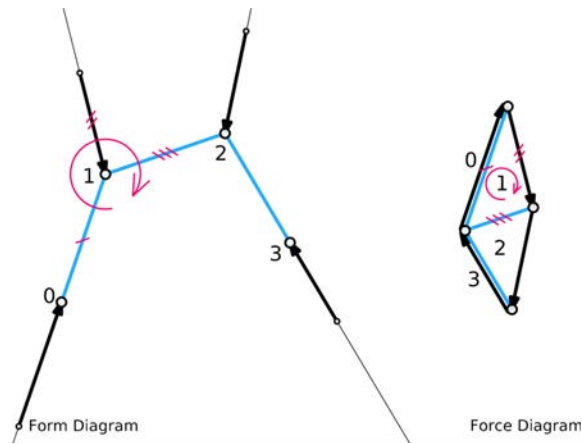


FIGURE 4.5: Forces applied on point 1 in the form diagram are read in the same order as in the force diagram (Fivet and Zastavni, 2015)

Dynamic equilibrium methods – such as Particle spring system – calculate residual forces for each free point of the structure in each iteration step. Based on the found residual forces, the point is shifted by the proportional part of the residual force vector. That way the geometry of the structure changes during each iteration until the residual forces disappear and an equilibrium state is established.

DYNAMIC EQUILIBRIUM

### Existing tools

There are many accessible digital tools for form-finding these days. Of all the Geometric stiffness design tools the most worthwhile is probably RhinoVault which implements the method TNA (Matthias Rippmann and Philippe Block, 2014). Without any expert knowledge it is hard to use this tool, but after a short introduction into the TNA method or Graphic Statics the tool is intuitive and allows users to clearly understand relationship between form and forces.

RHINOVAULT

One of the most popular digital tool for Particle spring system these days is Kangaroo3d (Piker, 2017). It is also ported in Rhino3D-Grasshopper. Its use is intuitive and requires no expertise. The model used in this tool resembles a common physical model consisting of spring elements, so it is easy to predict its behaviour and check the correctness of the result. A better understanding of model behaviour is also aided by an animation which visualizes the gradual deformation of the structure.

KANGAROO3D

### Conclusion

One of the frequently mentioned drawbacks of using form-finding methods in design is the lack of variability of shapes that can be achieved. These are limited to pure tension or compression structures – form active structures. On

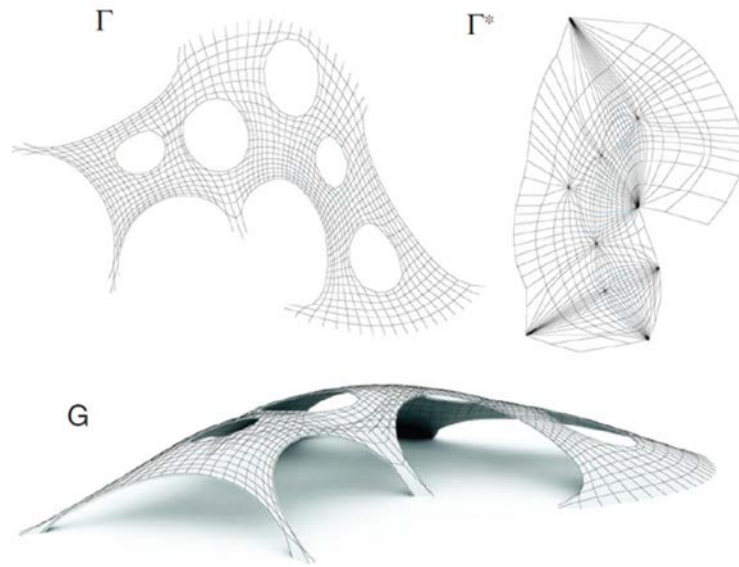


FIGURE 4.6: Thrust Network Analysis: form diagram  $T$ , force diagram  $T^*$  with given scale, the reciprocal relation between one node in the form diagram and corresponding space in the force diagram, and the thrust network  $G$  for given supports  $VF$  and loading  $P$ . (Matthias Rippmann, Lachauer, and Philippe Block, 2012)

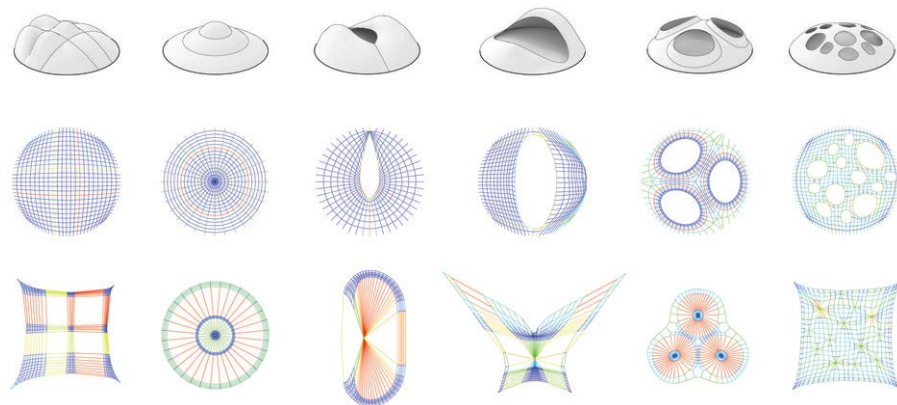


FIGURE 4.7: RhinoVAULT, an implementation of Thrust Network Analysis (TNA), allows exploration of an infinite number of compression-only solutions, for example how to span a circular space using geometrically linked form and force diagrams. (P. Block, M. Rippmann, and Van Mele, 2015)

the other hand, these shapes are structurally perfect and it would be hard to find them in a manual design process (see Figure 4.7). In manual shaping, the visualization of residual forces can guide the user forward to better, structurally more efficient design forms.

### Topology optimization

The goal of this method is to reduce the weight of a structure by removing structurally less stressed parts from the structure. The result is a new topology that follows forces distribution in the structure (similar to the form-finding method). A good example is the project of Florence bridge by Arata Isozaki in Figure 4.8.

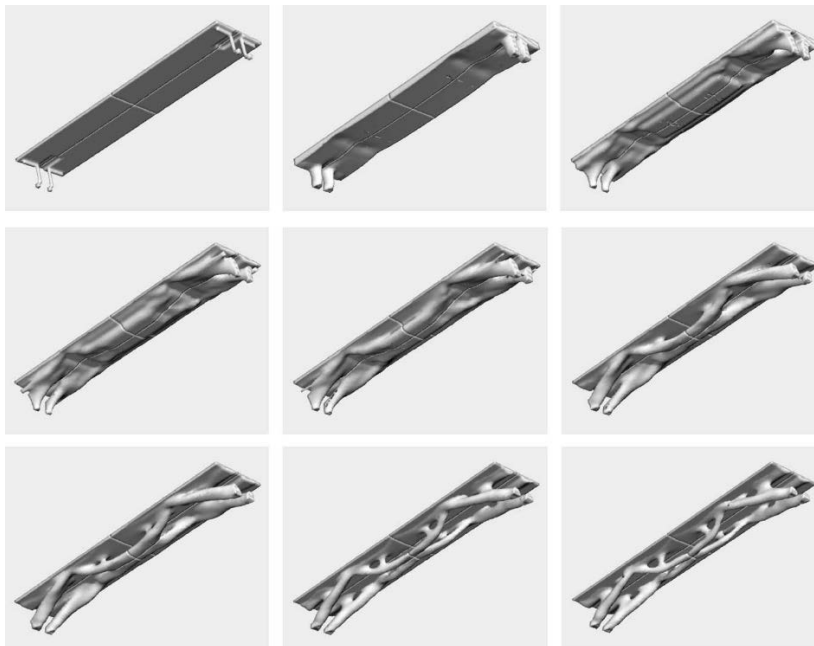


FIGURE 4.8: The evolutionary design process of the design entry by Arata Isozaki & Associates for the station project in Florence, Italy. (Cui, Ohmori, and Sasaki, 2003)

### Input

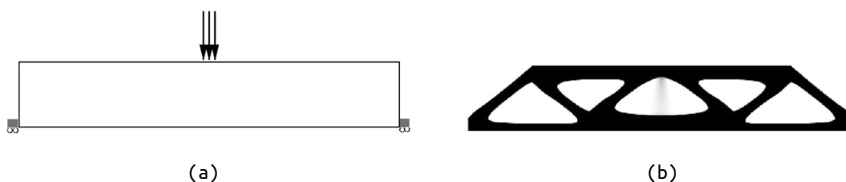


FIGURE 4.9: Two-dimensional topology optimization. The box is to be filled to 50% by material. Where the material should be placed for optimal performance under loads and boundary conditions is shown in the left picture. (Christensen and Klarbring, 2008)

The input for this method is the boundary volume from which an unstressed material is removed (see Figure 4.9). For stress calculation it is necessary

to specify the supports as well as the external loads (see Figure 4.9(a)).

### Method

ESO The basic method of topological optimization is Evolutionary Structural Optimization method (ESO). It is an iterative method, where stress in the structure is evaluated at the beginning of the iteration. Based on stress calculation, the less stressed parts of the structure are identified and removed at the end of each iteration step. This process is repeated until the number of iterations set by the user is reached.

BESO The rules of this method have been extended in BESO method (Bi-directional ESO), which has the capability of not only removing but also randomly adding previously removed material. This method reacts to force redistribution in the structure when the topology changes. BESO this way allows you to generate a more varied field of solutions.

The methods are more detailed in the publication Evolutionary Optimization of Fabric Formed Structural Elements<sup>5</sup>.

### Existing tools

MILLIPEDE Interesting research on the use of ESO optimization in design was carried out by Kajjima Sawako and Michalatos Panagiotis. They have jointly developed Millipede, a tool which enables topological optimization in Rhino3D-Grasshopper environment<sup>6</sup>. For an average user it might be difficult in the beginning to set and control the design process, but after a while spent with the tool, it begins to be intuitive and the optimization result can be predicted.

### Conclusion

Similar to the form-finding method, the shape options of the resulting design are limited – the result produces vector active structures only. Even though the shape options of the resulting design are limited to vector active structures, this method is widely applied in interesting designs. However, the constant problem that persists presently is the manufacturability of the resulting geometry. With the advent of 3D printing, there is a chance that several such structures will be realized.

The lesson learned from this method is the evaluation of the used and unused parts of the structure which can be removed. A similar principle became an inspiration for the Catastrophe project<sup>7</sup>, where the user trains his/her intuition in trying to identify unnecessary elements of the truss system or other structures such as the Eiffel tower. The user who removes the most elements until the structure collapsed is the winner.

<sup>5</sup>Diederik Veenendaal. "Evolutionary Optimization of Fabric Formed Structural Elements". Master's thesis of Civil Engineering, the Netherlands: Delft University of Technology, June 2008.

<sup>6</sup>Michalatos Sawako Kajjima a Panagiotis. *Millipede*. Version 1.0. [software]. 2014. URL: <http://www.grasshopper3d.com/group/millipede> (visited on 02/11/2017).

<sup>7</sup>Gennaro Senatore and Daniel Piker. *Simulators Archives - Expedition Workshed*.

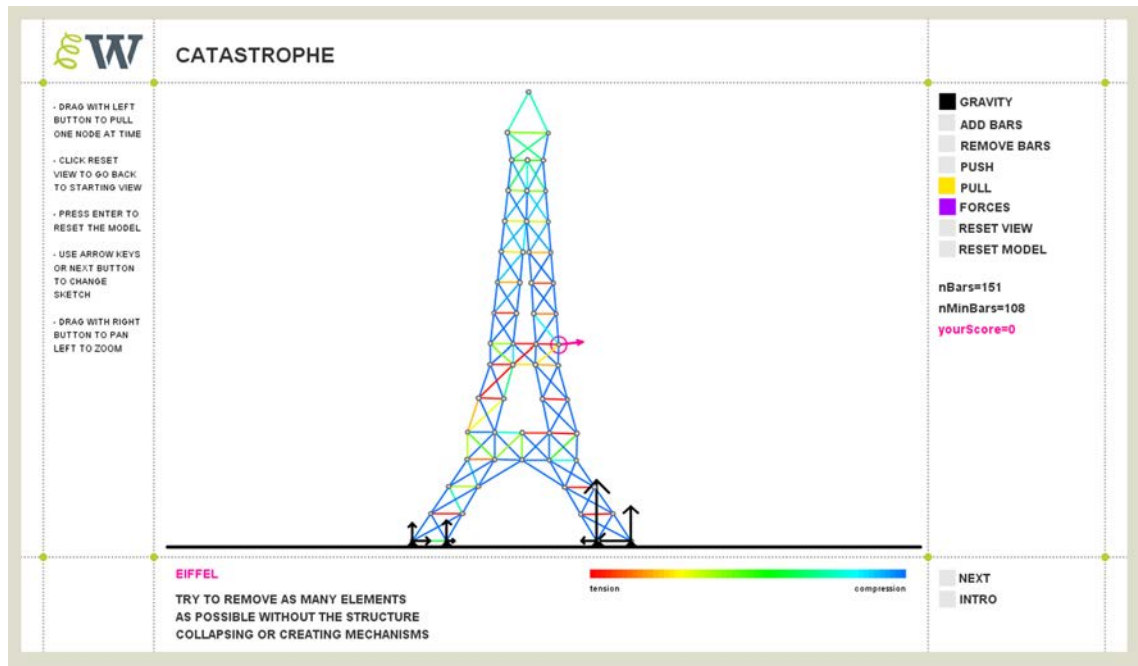


FIGURE 4.10: Catastrophe, understanding structural behaviour by interactive model and forces visualization.

### 4.3 Problem to solutions

"Structural optimization is an inverse process in which parameters are implicitly/indirectly optimized to find the geometry of a structure such that an objective function of fitness criterion is minimized."<sup>8</sup>

Similarly to the design to solution method, this process is very close to the natural design method and the trial and error method. In this case, however, this is a fully automated process of finding ways to achieve the desired goal. The algorithm itself generates different design alternatives and evaluates them with respect to the target design goal. As a result of this process, there are usually several alternative solutions that meet the predetermined requirements.

#### Input

The task (in some literature also called problem) that needs to be solved is defined by the user with a parametric model. In the model, fixed and variable parameters are specified, where fixed parameters usually define design limits and variables define the degree of design freedom.

PARAMETRIC MODEL

The goal of the design is specified through a fitness function. The fitness function is modified based on property requirements of the design. The result of function – the fitness value is always a one digit number evaluating the design as a whole. In the optimization process, the goal can be either to minimize the fitness value – for example minimization of material and weight

GOAL

<sup>8</sup>Sigrid Adriaenssens et al. *Shell structures for architecture : form finding and optimization*. Abingdon : Routledge, 2014. ISBN: 978-0-415-84059-0, p. 4.

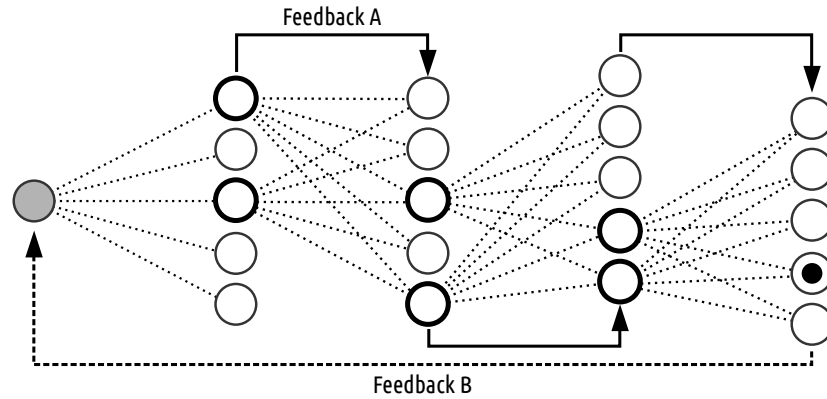


FIGURE 4.11: Problem to solutions approach, Feedback A – selection, Feedback B – input driven modelling.

in a structure (aiming for material economy), or to maximize the fitness value – for example maximization of stiffness (aiming for efficient load-bearing structures).

### Method

#### MUTATION AND Crossover

Optimization methods, namely Evolutionary Algorithms (EA), generate a population of new individuals (possible solutions) in each iteration that are evaluated by the fitness function. The best of them are chosen to become parents for the next population in the next iteration step. A new generation of individuals (solutions) arises from the parents using mutation and crossover methods. To ensure diversity, some algorithms also include the option of selecting a weaker individual (low rated solutions) as a parent for the next generation. The algorithm stops when a targeting fitness value is achieved or the selected number of iterations has been reached.

### Existing tools

#### GALAPAGOS

Galapagos<sup>9</sup> is an implicit evolutionary solver for Rhino3D/Grasshopper developed by the Grasshopper plugin developer David Rutten. With Galapagos, users can define a simple fitness function and connect it to their parametric model created in Grasshopper. During optimization the solver changes variables of parametric model. When optimization stops the user can explore the field of solutions generated during optimization and select the most preferable ones.

#### IEA

Not all criteria can be coded into the fitness function (so-called hard to program criteria, such as aesthetics). This is why Peter von Buelow used an interactive version of EA in the design process. In this method, each created generation of solutions interacts with the user and engage him/her in the evaluation process (see Figure 4.11 – Feedback A). Thus, the users can influence selection of parents based on their subjective preference. In the Figure 4.12, the same algorithm is used by users. However, it is driven by three different

<sup>9</sup>David Rutten. “Galapagos: On the Logic and Limitations of Generic Solvers”. In: *Architectural Design* 83.2 (2013), pp. 132–135. ISSN: 1554-2769. DOI: 10.1002/ad.1568.

users' preferences. This is why the results of the optimization process are different.

*“In looking particularly at the non-computational tools, it is interesting to notice that the goal of the tool is not so much to provide the solution, as to provide the stimulus that leads the user to discover the solution.” (Bülow 2007, p.47)*

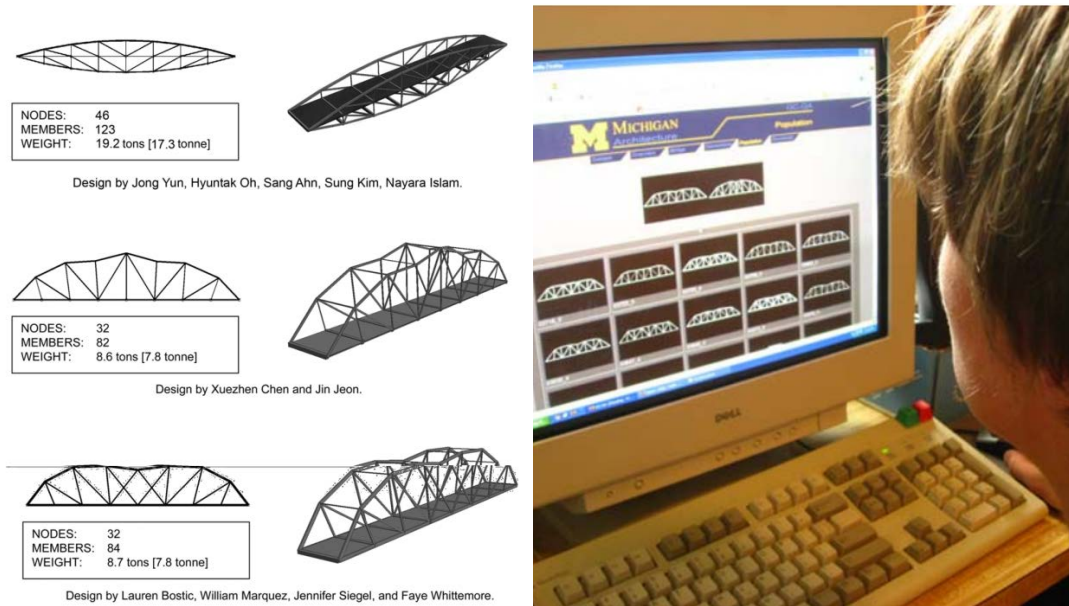


FIGURE 4.12: Interactive EA, example of bridge design. (Von Buelow, 2008)

Another problem that mainly affects creativity is a parametric model as an input for the optimization. It is hard and time-consuming to create a parametric model to be as flexible as possible. A less flexible parametric model also limits variety of solutions which can be explored during the optimization process. Caitlin T. Mueller deals with this problem in her PhD thesis<sup>10</sup>. She uses the Shape grammar algorithm which extends flexibility of a parametric model to cover a wider exploration space. The tool developed during her PhD studies is called Structure FIT<sup>11</sup>. It was originally written for the web interface (in silverlight). However, its extended version is currently being worked out so that it will be ported into Rhino3D/Grasshopper environment.

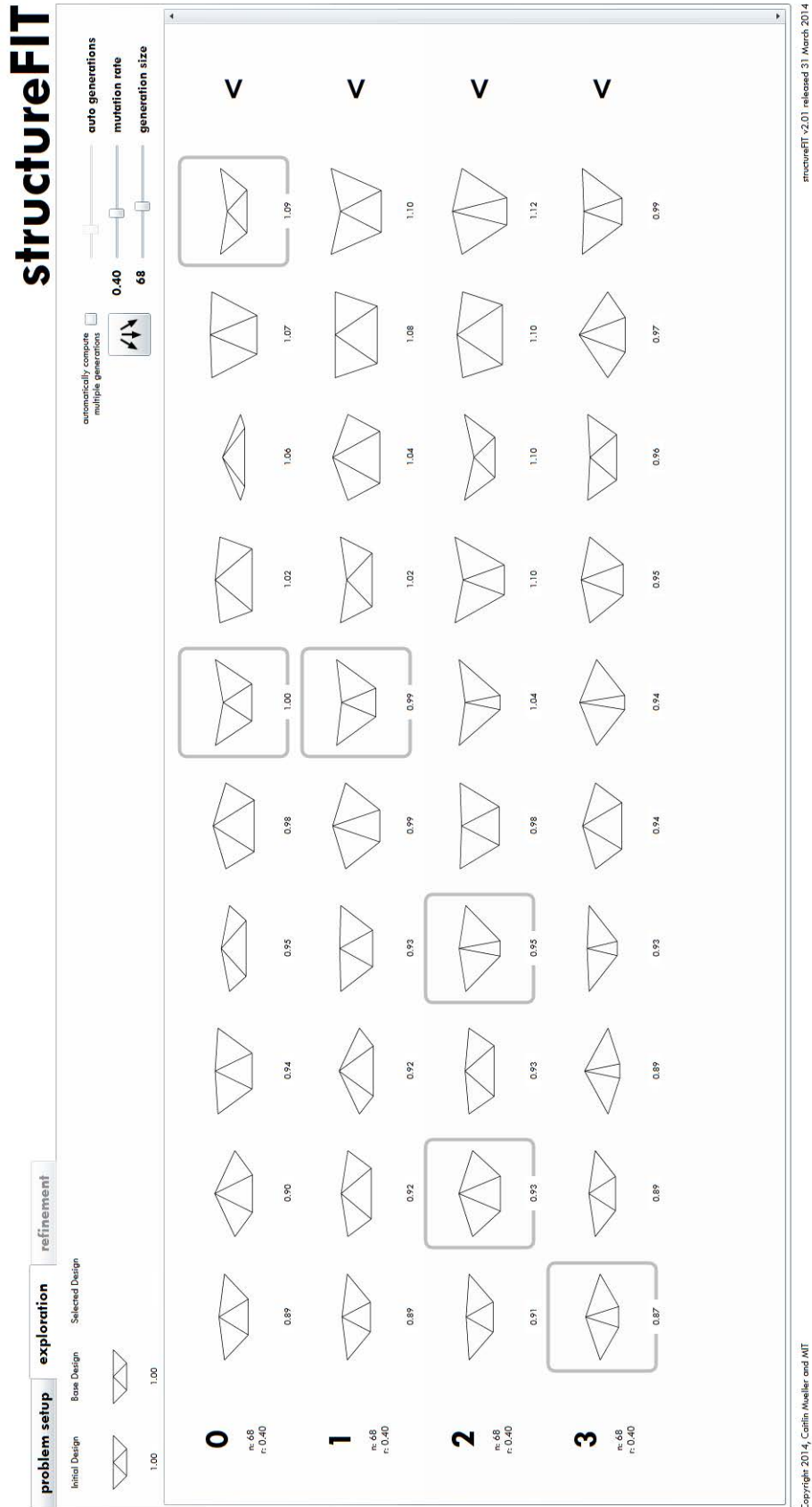
STRUCTURE FIT

## Conclusion

The advantage of this approach compared to the Design to performance approach is a clear direction of the design to reach the goal. Nevertheless, the success of this process depends on the correct definition of the problem (parametric model) and the goal (fitness function). If the optimization task is incorrectly defined, there is a risk that a common user will blindly believe in

<sup>10</sup>Caitlin T Mueller. “Computational Exploration of the Structural Design Space”. PhD thesis. Massachusetts Institute of Technology, June 2014.

<sup>11</sup>Caitlin T Mueller. *Structure FIT DesignTool*. Version 2.01. [software]. 2014. URL: <http://www.caitlinmueller.com/structurefit/> (visited on 01/11/2016).



Copyright 2014, Caitlin Mueller and MIT structureFIT v2.01 released 31 March 2014

FIGURE 4.13: StructureFIT: selection of preferred solutions based on their visual and structural performance. (Mueller, 2014b)



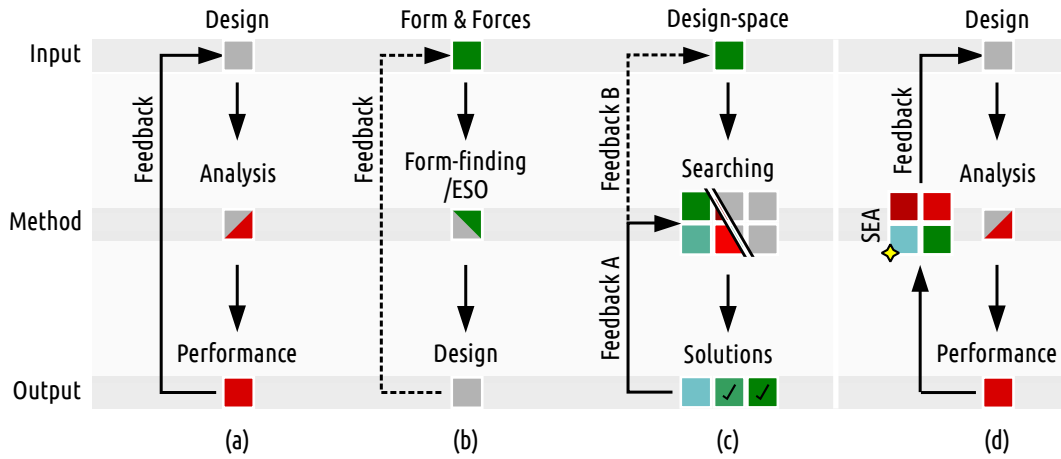


FIGURE 4.14: Different kinds of design process with feedback: (a) design-to-performance (b) forces-to-design (c) design-to-solutions (d) proposed approach.

the correctness of an incorrect result. In this process, the user also lacks direct control over modelling process. The selection of parents in Interactive EA is not sufficient and usually is more black-box than a controlled process. The user is missing direct feedback from his/her action which would otherwise give him/her an opportunity to learn from it.

### 4.4 Conclusion: Proposed design approach

The previous sections show that each of the researched design approaches has different inputs, ways of coming to a goal (actions), as well as different outputs and interactions with the user (feedback), see Figure 4.14.

This research focuses on user based modelling, which represents a design approach called Design to performance (Figure 4.14(a)). The problem in this design method is the decision-making process, which is often based on the trial and error method. Based on the knowledge gained in this work from the analysis of the two other approaches to structural design – Conditions to form and Task to solutions, see Figure 4.14(b)(c) I propose a method supporting users’ decision-making that should help structurally less experienced users to

DESIGN TO PERFORMANCE  
WITH DECISION MAKING  
SUPPORT

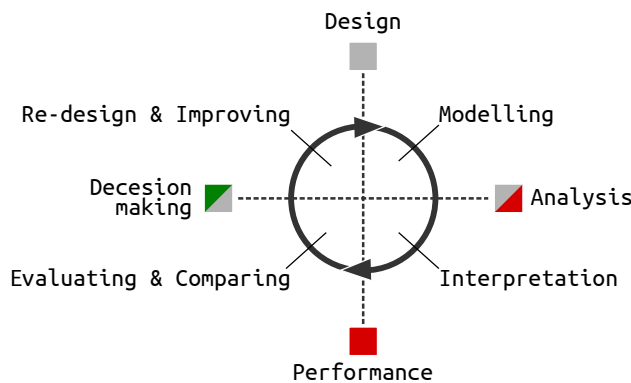


FIGURE 4.15: Stages of the interactive design process.

independently find more effective structural solutions.

By integrating decision-making support into the Design to performance approach (Figure 4.14(d)), two new stages are added in the design process circle: the interpretation support stage and evaluation stage, see Figure 10.1.

#### EXTENDED FEEDBACK

This should enable the user to get feedback not only from interactive analysis (Figure 4.16 – Feedback A) but should also allow him/her to evaluate the current solution and compare it with the previous solutions (Figure 4.16 – Feedback B). This way, the user should get support in deciding on the next step in the design process, which also allows him/her to train his/her structural intuition.

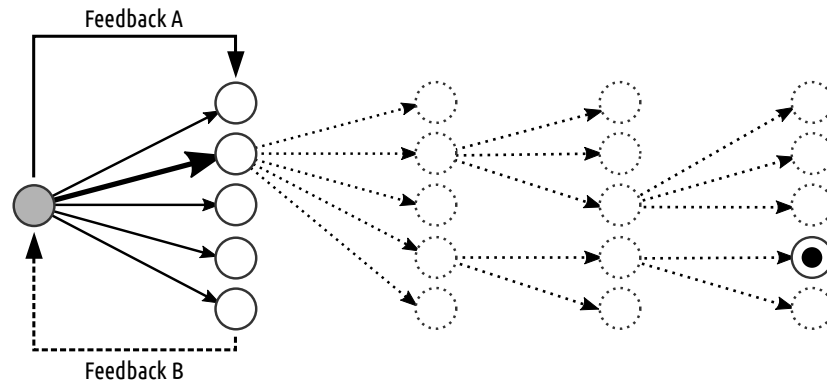


FIGURE 4.16: Proposed design process, Feedback A – analytical feedback, Feedback B – decision-making support.

#### INTERACTIVE ANALYSIS

The primary goal of this research work is to develop and implement a decision-making support method for conceptual structural design. To implement a developed method into a digital tool, it was necessary to establish an interactive analysis by developing a middleware tool, which is the secondary goal of this research. More about the development of this middleware is introduced in the next chapter.

**Part III**

**Structural Evaluation  
Assistant**



## Chapter 5

# Interactive analysis

"Scripting Cultures considers the implications of lower-level computer programming (scripting) as it becomes more widely taken up and more confidently embedded into the 'design process' ...scripting affords a significantly deeper engagement between the computer and user by automating routine aspects and repetitive activities, thus facilitating a far greater range of potential outcomes for the same investment in time."<sup>1</sup>

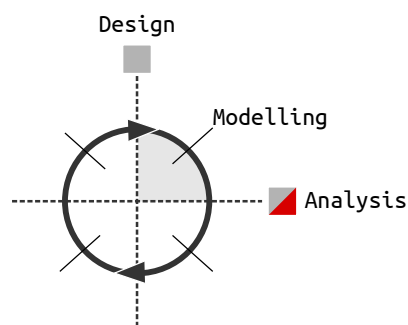


FIGURE 5.1: From design to analysis.

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<sup>1</sup>M Burry. *Scripting Cultures: Architectural Design and Programming*. Ed. by M Burry. 1st ed. AD Primer. Wiley, Aug. 2011. ISBN: 978-0470746417, p. 8.

## 5.1 Middleware

BRIDGING EXISTING TOOLS

The middleware created for this research consists of two software tools: MIDAS and DONKEY. Thanks to the MPO grant programme the tools were designed in interdisciplinary cooperation. MIDAS was developed on the structural engineering side by Ladislav Svoboda and DONKEY on the architectural side by the author. Both tools communicate through VTK file format, implemented on both sides (see Appendix).

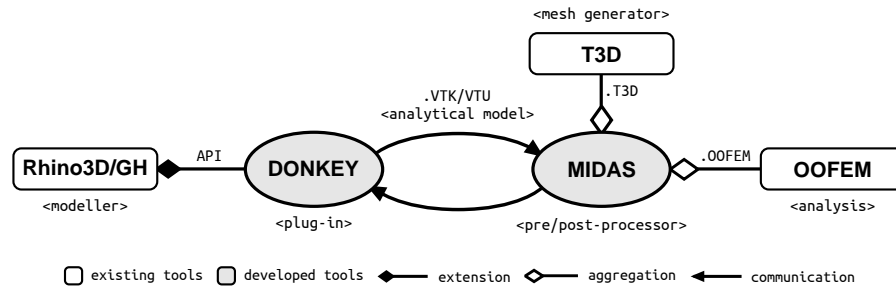


FIGURE 5.2: Middleware, the software architecture graph.

### Midas

The MIDAS (Multifunctional Interface Between Design and Mechanical Response Solver) is a console based application without GUI written in C++ and released under GPLv3 license. The aim of this software is to create a widely applicable tool improving the cooperation between two professions - designers and structural engineers. This is why this tool can work with different file formats used by different CAD or analysis tools like: unv, vtk, vtu (vtk xml version) as well as oofem, sifel, t3d and ansys.<sup>2</sup>

MESH GENERATOR

T3D

To create a correct mesh geometry for the finite element method, MIDAS uses T3D mesh generator. It is a powerful mesh generator capable to discretize complex three-dimensional domains into triangular and tetrahedral meshes of high quality. Although T3D is not public domain software, it is freely available for non-commercial purposes (education, research, etc).<sup>3</sup>

FINITE ELEMENT SOLVER

OOFEM

As a solver for structural analysis, OOFEM is used. It is a console based finite element solver with object oriented architecture. The aim of OOFEM is to develop an efficient and robust tool for finite element method computations, as well as to provide a modular and extensible environment for future development. This tool can solve mechanical, transport and fluid mechanics problems. It is written in C++ and released under a GNU Lesser General Public License (LGPL).<sup>4</sup>

<sup>2</sup>Ladislav Svoboda et al. "A simple framework for integrated design of complex architectural forms". In: *CoRR* abs/1203.2499, <http://arxiv.org/abs/1203.2499> (2012).

<sup>3</sup>Daniel Rypl. *T3D*. [software]. 2005. URL: <http://mech.fsv.cvut.cz/~dr/t3d.html> (visited on 01/11/2016).

<sup>4</sup>Borek Patzak. *OOFEM*. version 2.3. [software]. 2014. URL: <http://www.oofem.org/en/oofem.html> (visited on 01/11/2016).

Later, OOFEM and T3D were directly linked and used by MIDAS as dynamic libraries. Because the T3D licence policy, the executable binary version of MIDAS is limited to non-commercial use only.<sup>5</sup>

## Donkey

The purpose of the DONKEY<sup>6</sup> is to allow a user to create an analytical model and visualize its analytical results directly in a CAD modeller. As a modeller Rhino3D and its plug-in for algorithmic modelling Grasshopper (GH) were chosen. DONKEY is developed as custom GH components written in C#. The source code is licensed under GNU licence and shared on GitHub server.



FIGURE 5.3: Developed DONKEY components in the Grasshopper interface.

The developed components are arranged into four groups of GH's menu: structural elements, boundary conditions (loads and supports), analysis and visualization of analytical results (Figure 5.3).

The components from the first group are used to define structural elements' geometry and properties. There are two types of elements: shells and beams. Each element type requires a different type of geometry. The beam elements work with line and polyline geometry, the shell elements with triangle, polygon and mesh geometry.

## 5.2 Modelling

The chosen analytical finite element method requires the information about material and profile properties, except the geometry. Those needs usually guide a user to focus on materialization and dimensions instead of finding an efficient form in the conceptual design. This is a common mistake in the practice. The problem is that the materialization and profile definition lock degrees of design freedom, which can hide important form solutions. This is why, for the developed structural elements, inputting the geometry is only obligatory. The other material and profile properties are optional; there are default pre-defined value inside elements' components (Figure 5.4 (b, d)).

In order to change dimensions of a beam element, it is possible to use a PROFILE component (Figure 5.4 (a)). In addition to dimensions the component also defines the shape of the profile. There are many types of profiles in practice, but with the aim to focus on the form exploration rather than sizing,

EXCESSIVE DEMANDS  
OF FE ANALYSIS

SIZING

<sup>5</sup>Ladislav Svoboda. *MIDAS*. version 0.82. [software]. 2015. URL: <http://mech.fsv.cvut.cz/~da/MIDAS/en/> (visited on 01/11/2016).

<sup>6</sup>Lukas Kurilla. *DONKEY*. version 0.84. [software]. 2017. URL: <http://donkey.kurilluk.net/> (visited on 09/15/2017).

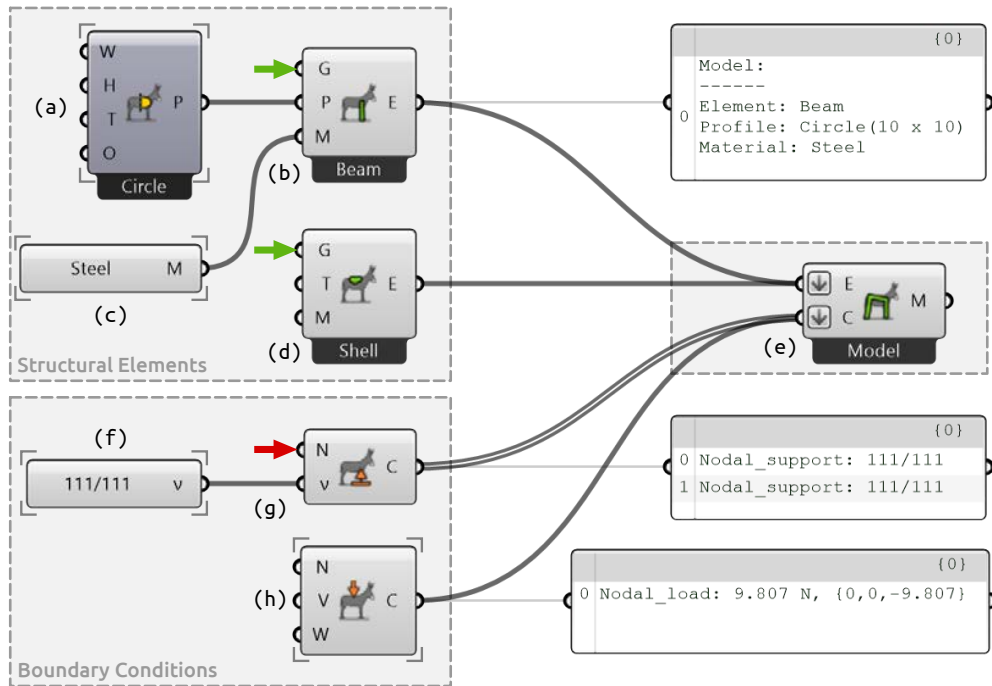


FIGURE 5.4: Analytical model definition using the developed DONKEY components.

there are only two basic shapes defined in the component: rectangular and circular.

To define a profile for a shell element, only the thickness property is needed (input "T" on Figure 5.4 (d)), therefore there is no specific profile component for shell elements. The beam's profile component also consists of the thickness value. Here, the value defines the thickness of a pipe profile. If the thickness is zero the profile is full.

#### MATERIALIZATION

The MATERIAL component (Figure 5.4 (c)) is designed to be a preliminary property which allows one to explore the basic stiffness of different materials, but not their anisotropic behaviour. For simplification in the early stage all anisotropic materials (like timber or concrete) are considered to be a continuous homogeneous isotropic material (like steel). The different types of material can be chosen from pre-defined list or customized through a pop-up window defining density, modulus, Poisson's ratio, thermal alpha and yield stress values (Figure 5.5).

All the created elements are connected into the MODEL component. It merges elements into one analytical model (Figure 5.4 (e)). The common mistake in creating such model is the geometry dualities. They cause that connections between elements are unwelded for an analysis and the model breaks apart. To avoid dualities, points of each elements' geometry are registered as structural nodes in the model. If the node already exists, the point of the element merges with it<sup>7</sup>. Thus the geometry dualities are removed, and a clearly defined connection between elements is secured.

#### STRUCTURAL SUPPORTS

The first difficulty is supporting a model. The analysis will fail if there is no support in the model. If that happens, the component warns a user and

<sup>7</sup>The geometrical dualities identification depends on a tolerance value stored in Rhino3D.



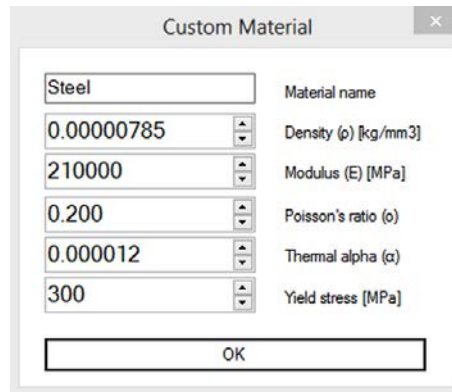


FIGURE 5.5: Custom material implemented in pop-up window.

asks him to add the required support into the model. Supports can be added to NODE or ELEMENT, which means that support is added to all the nodes of the elements. For each support its degrees-of-freedom (DOF) has to be defined. The DOF consists of six variables defining movement and rotation in three axes  $x$ ,  $y$ ,  $z$ . Freedom of the axes can be set using radio buttons in a pop-up window (Figure 5.6).

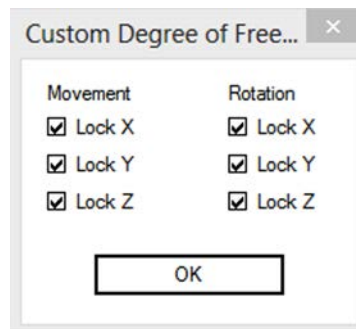


FIGURE 5.6: Custom degree of freedom implemented in pop-up window.

The second difficulty are loading conditions. Without the correct loading conditions the analytical results might not be suitable for real world situation. In practice, there are many advanced rules and safety factors in order to correctly load a model. However, for the conceptual phase and form comparison it should be enough to use dead loads at the beginning and later add basic live loads to test different loading scenarios.

Loading the model with dead loads can be set in the model component option. It is turned on in a newly created component. Therefore, compared with supports, there are no required loads to be connected into the component to run analysis. The additional live loads can be applied on a NODE or a whole ELEMENT, and so add a point load or line or area loads (depending on the element type) in the model. For each load it is necessary to specify a vector determining the force direction and the magnitude of the force, which for the simplification is defined in kilograms and it is automatically converted into Newtons.

### 5.3 Data work-flow

Connecting the MODEL component output with an ANALYSIS component, an analytical model is created on hard-drive in VTK file format<sup>8</sup> and sent to MIDAS. MIDAS reads this model input data and prepares the elements' geometry for the finite element method subdividing and re-meshing it. This can, for instance, change one line into ten line segments and so on. MIDAS sends the prepared geometry with the requested properties to OOFEM and waits for the results.

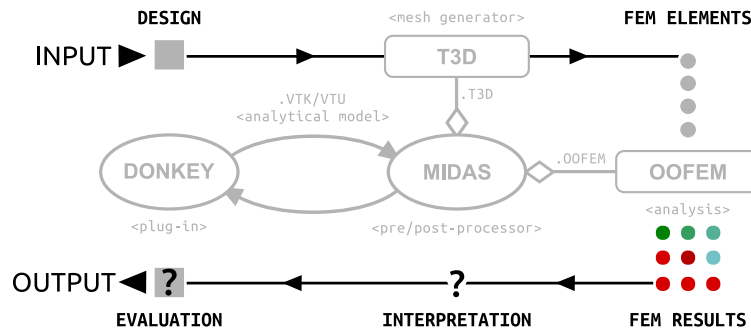


FIGURE 5.7: The profess work-flow;(a) from design to FEM elements  
(b) how to simplify FEM results to support their correct interpretation?

The results of FE analysis are loaded back to MIDAS, where they can be post-processed. MIDAS then creates resulting VTK file and sends the information about analysis success to DONKEY. DONKEY then reads resulting file and visualizes data in the Rhino3D/Grasshopper interface.

The benefit of FE analysis is its universality to use, but a key problem is that FE tools are usually too complex and require expert knowledge to be used correctly. Setting up the boundary conditions correctly and interpreting the results correctly is not what architects are usually trained for, so the identification of possible structural problems is not a straightforward task. And then, in particular, correctly concluding from the analysis how to improve the design is a hard task, even for an expert FE analyst.

The results of FE analysis are too complex to be correctly interpreted by a designer with a lack of structural engineering knowledge and experience. Therefore, the simplification of the FE results would be beneficial in early stages of the design process. A simplified result interpretation should help designers to identify structural problems and guide them towards structurally improved designs.

<sup>8</sup>For more details about content and structure of file format see Appendix A.

## Chapter 6

# FEM results interpretation support

*Knowing more, does not necessarily translate into being able to make better decisions; as there is an inductive synthesis and interpretation process also known as understanding, which is required before one can begin making decisions using data.<sup>1</sup>*

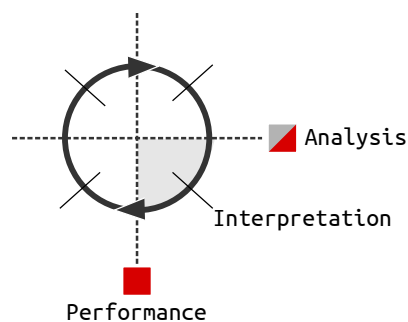


FIGURE 6.1: From analysis to performance.

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<sup>1</sup>Sam Conrad Joyce. "Web Based Data Visualisation Applied to Creative Decision Making in Parametric Structural Design". In: August. 2015.

## 6.1 Levelling system

This chapter focuses on simplifying the results of the FE analysis in order to help architects interpret them in the conceptual design stage. After analyzing the comprehensibility of the FE analysis results, the resulting structural properties were divided into four levels, based on the difficulty level of the results interpretation, as well as their usability in particular project phases (lower part of Figure 6.2).

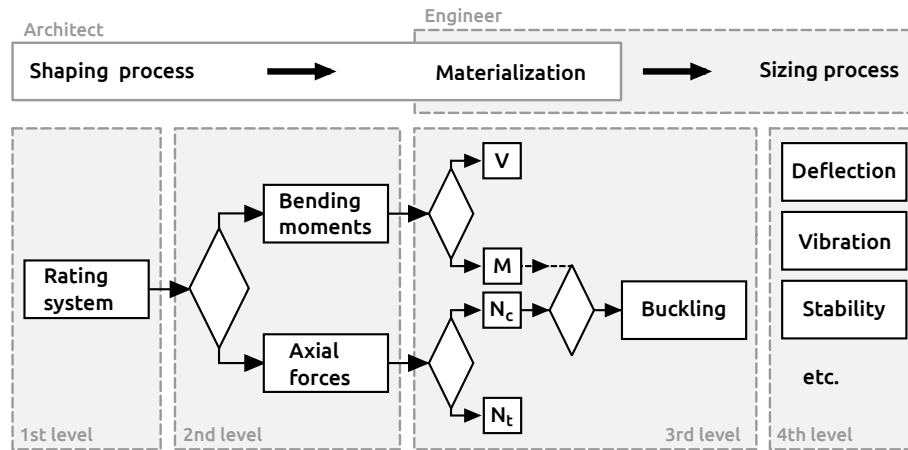


FIGURE 6.2: Levels of FE analysis results simplification based on design stage.

### WORKFLOW AND COOPERATION

This methodology, dividing the structural design process into four levels, responds to a specific design approach when the form finding, the geometry and the structural principles precede the actual materialization and sizing. The methodology also considers an architect as the lead form-maker while the structural engineer takes responsibility for the bearing capacities and safety of the structure. Such role division is often used in common practice. The overlap of both roles happens in the materialization phase (see upper part of Figure 6.2).

### 1st level

The proposed first level of simplification is represented by the Rating system. This system was inspired by the fitness value which, similar to video game rating systems, evaluates resulting design by one scalar value. Consequently the user can compare various designs and select the most successful one.

### STRUCTURAL PROBLEMS

The overall rating value itself, however, is generally not sufficient to ensure better structural performance. It is no less crucial to comprehend and realize the design's potential weaknesses (structural problems). Realization of such negative aspects opens a wider range of solutions that might be structurally more efficient. The proposed Rating system therefore consists of two resulting values. The first one assesses the structural effectivity of the design and the second one informs about the degree of potential structural problems.

## 2nd level

To support better understanding of potential structural problems the Second simplifying level of the FE analysis is used (see Figure 6.2 - 2nd level). The proposed Rating system is based on von Mises criterion that summarizes stresses in every direction and is represented by one scalar value. In the Second level this scalar value is decomposed to bending moments and axial forces. This enables visualization and better identification of the prevailing forces within the structure. The user is then informed in greater detail about problematic areas in the structure.

## 3rd-4th levels

The other two levels represent the latest project stage when the design is materialized and its dimensions are defined in cooperation with the structural engineer. Safety and utility measures are the main constraints in this phase.

## Implementation

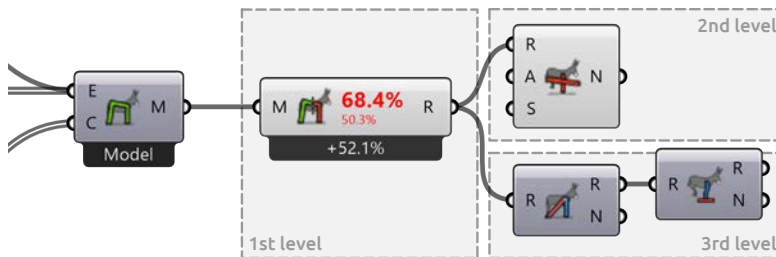


FIGURE 6.3: Levels of FE analysis results implemented in developed plugin.

The implementation of the FE analysis results simplification and its levels is based on a principle of Grasshopper components. The visualization of the First level of simplification is achieved by a single basic component displaying the Rating values. This component can be additionally extended by the components of the upper proposed levels. For example, the Second level component might be directly connected to extend the Rating system by the visualization of the moment curvature diagram. This way it is possible to connect other upper level components (Figure 6.3). As a result users are able to visualize the data of their interest and gain knowledge. Less experienced users are always led straight towards the basic First level of simplification.

## 6.2 Rating system

### Von Mises Criterion

The proposed rating system summarizes the resulting stress tensor into one scalar value using von Mises Stress (mainly used in ESO as a fitness value).

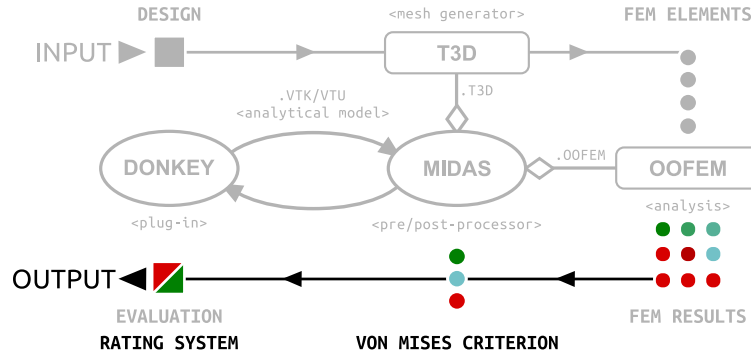


FIGURE 6.4: Proposed data work-flow of analysis feedback (output data).

The resulting rating value  $\eta$  is calculated as a von Mises Stress divided by the maximal allowed stress  $f_y$  of the material property:

$$\eta = \frac{\sigma_R}{f_y} \quad (6.1)$$

The interval of the rating value  $\eta$  is from zero to infinity, and is divided into two sub-intervals to allow the user to identify structural problems. The first sub-interval, from 0 to 1, represents the bounds of elasticity and the results in this interval can be interpreted as the "structural efficiency" of material and profile usage. The value 1 represents the Yield point (see Figure 6.5), therefore, the second sub-interval, from 1 to infinity, represents the plastic region, which is characterized as a permanent deformation or even material failure. The results in this sub-interval can be interpreted as a "structural overloading," which represents structural problems.

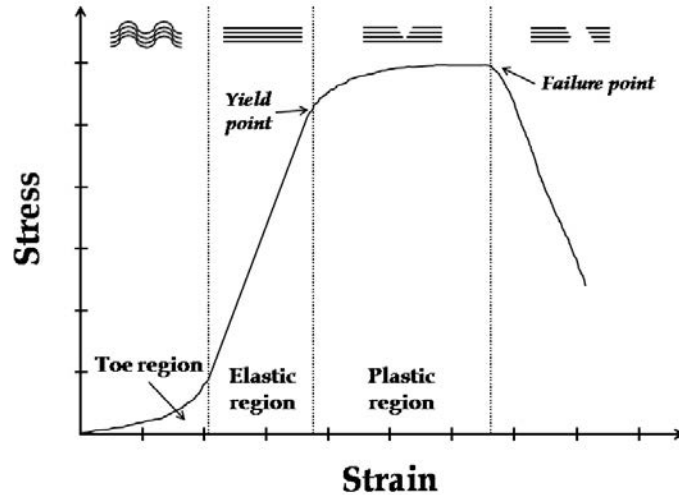


FIGURE 6.5: Typical stress-strain curve for destructive tensile testing of skeletal soft tissues. Collagen fibril straightening and failure, related to different regions of the stress-strain curve, are also schematically shown. (Korhonen and Saarakkala, 2011)

By summarizing the resulting stress tensor into one scalar rating value  $\eta$ , it is possible to take into the consideration dominant stresses in any directions. In addition to axial stresses, which are typically dominant for form- and

vector-active structures, the use of a stress tensor also allows exploring bending stresses, which are dominant for section-active structures (Engel, 2013). This gives the user design freedom to explore more structural systems and easily identify possible structural problems, which is essential in the conceptual design phase.

### Evaluating the whole design

A design typically consists of many structural elements with different stress values. Furthermore, the stress in a structural element is usually not distributed uniformly, this is why the structural element is divided into segments with each segment having its own rating value (Figure 6.6).

For rating a structural element and then consequently the whole structure, a summarization of rating values is required. To inform one about problems and clearly classify feasibility of a solution, SEA uses two summarized values. The first "overloading" rating value  $\eta_o$  comes from the failure design principle, which is usually used by structural engineers. In this case, a structure is rated by the highest, i.e. worst, resulting value (Figure 6.7 (b)). This is a good method to describe the amount of problems, but, the information about the rest of resulting values is lost. The second "efficiency" rating value  $\eta_e$  takes into consideration all the rating values. It is calculated as the average of the distances of all rating values from 1 (fully stressed design),

$$\eta_e = \sum_{i=1}^m \frac{1 - \mu_i}{m} \quad (6.2)$$

in which the distance from fully stressed design is calculated as

$$\mu_i = |\eta_i - 1|, \text{ where } \eta_i \leq 2. \quad (6.3)$$

The proposed rating system allows to clearly visualize differences between feasible and infeasible solutions using the overloading  $\eta_o$  value. The second efficiency value  $\eta_e$  assesses structural performance (informs i.e. how close to fully stressed design a solution is). This way architects can compare different design alternatives, which can be stored during design process.

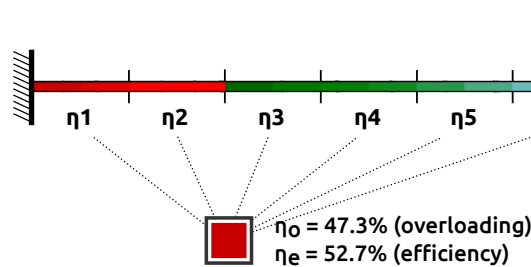


FIGURE 6.6: Evaluation of cantilevered structure use proposed rating system.

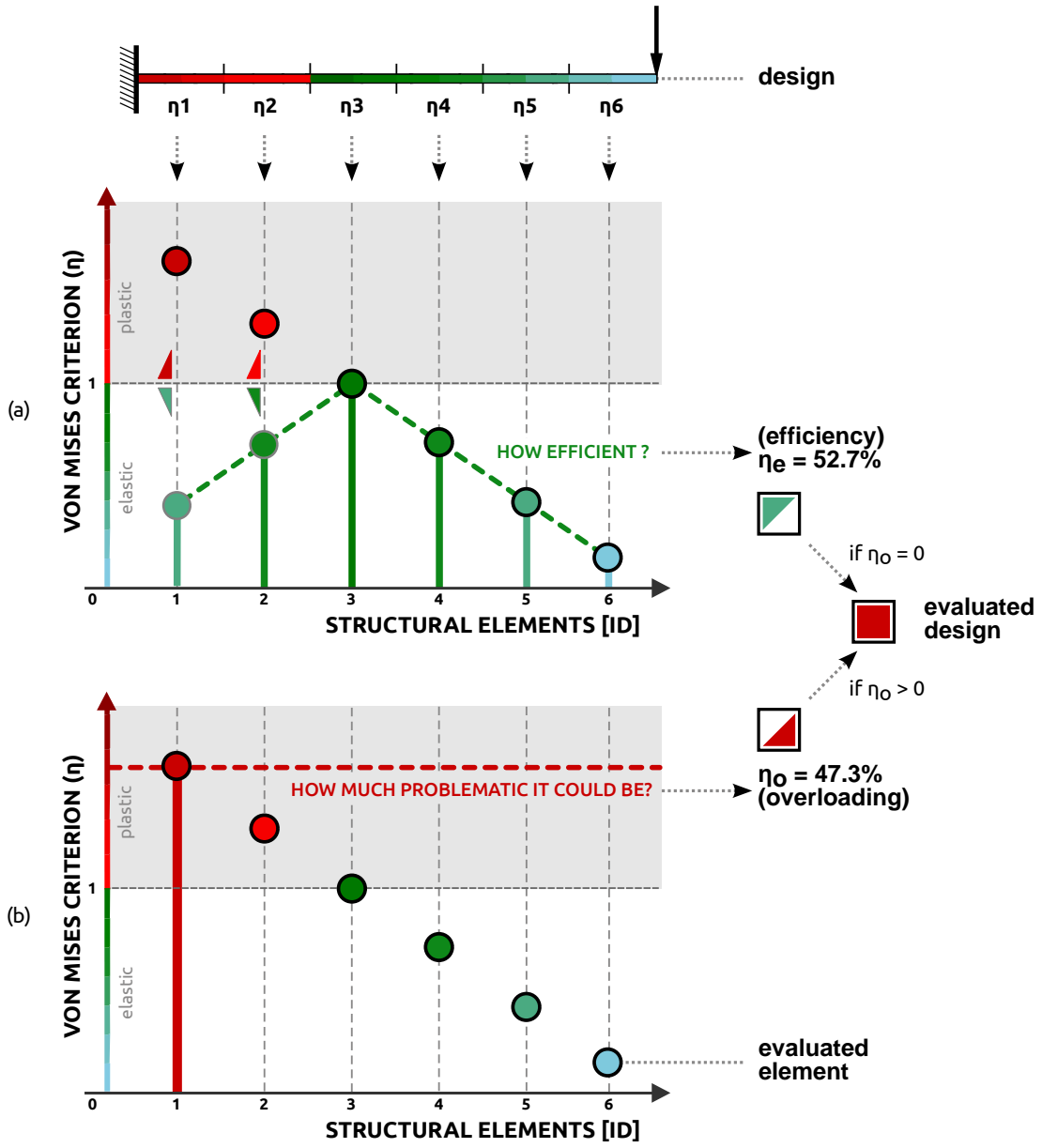


FIGURE 6.7: Rating system methodology: (a) efficiency, (b) overloading value.



## Chapter 7

# Evaluate and decision making support

*"The final phase of the design is evaluation. This includes checking individual alternatives to ensure that they are save and feasible, and the comparison of feasible alternatives in order to choose the 'best' one."<sup>1</sup>*

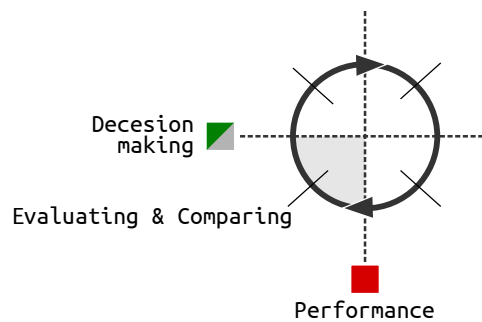


FIGURE 7.1: From performance to decision-making.

<sup>1</sup>A. Holgate. *The art in structural design: an introduction and sourcebook*. Clarendon Press, 1986. ISBN: 9780198561675, p. 223.

## 7.1 Design tracker

### Storing and visualizing different designs

Two values of the Rating system were presented in the previous chapter: the efficiency  $\eta_e$  and the overloading  $\eta_o$  value. When design solutions are stored in the Design tracker, each design is visualized based on the above mentioned two values. The first efficiency value is visualized in the diagram on a horizontal – X axis, which represents a domain from 0% to 100% efficiency (see Figure 7.2 (a)).

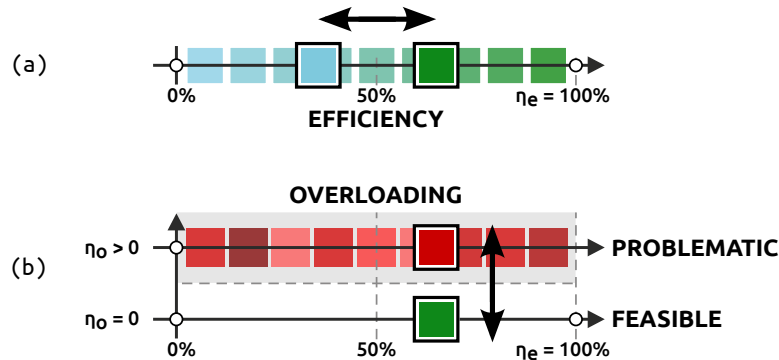


FIGURE 7.2: Design tracker visualization approach; (a) feasible – efficiency row, (b) problematic – overloading row.

To clearly distinguish between feasible and infeasible – problematic solutions, another axis is added above the efficiency axis (see Figure 7.2 (b)). When a solution is scored with the overloading value  $\eta_o$  higher than 0, it means that some structural problems are identified in it, and the solution is automatically stored in the upper – problematic row. The position in the row represents the solution efficiency while the colour of the square represents the degree of problems.

### Design comparisons and goals

The developed visualization approach (Figure 7.2) allows to guide users towards two structural goals: a fully stressed design by maximizing structural efficiency or minimizing stress to find a better form of the structure.

#### SIZING PROCESS

The first goal – maximizing structural efficiency can guide users during the sizing process of section-active structures. The cantilevered structure shown in Figure 7.3 represents this process. Four design alternatives are generated by changing the cross section diameter. In the first two of them, some problematic parts were identified. Such alternatives are classified as infeasible solutions and they are stored in the upper problematic row of the Design Tracker (Figure 7.3 on the top). The other two alternatives do not have any overloaded parts, so they are classified as feasible solutions and stored in the Feasible bottom row.

To identify the best solution from the explored ones, one has to understand where the design goal is situated in the Design tracker. In this case, the goal

is situated in 100% of structural efficiency in the Feasible row (see green circle in Figure 7.3), so the best solution is the third one with 120 mm diameter (see the solution outlined in black in Figure 7.3).

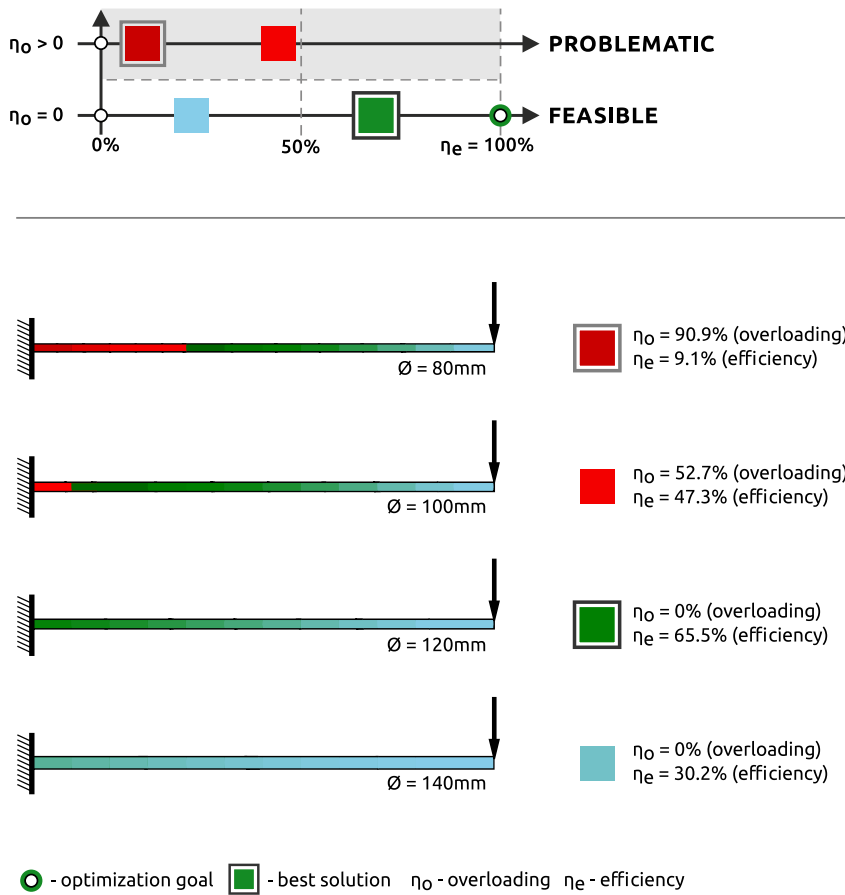
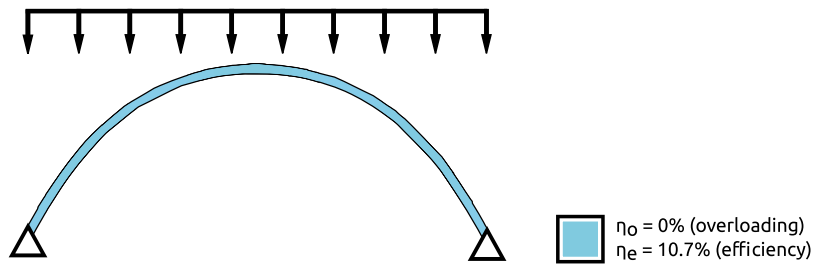
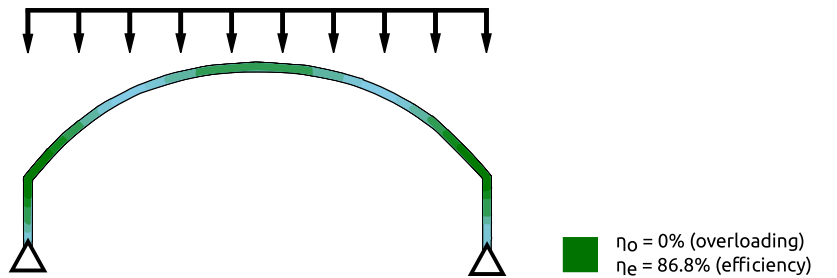
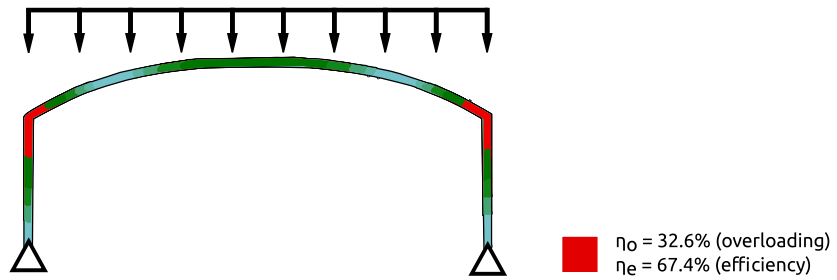
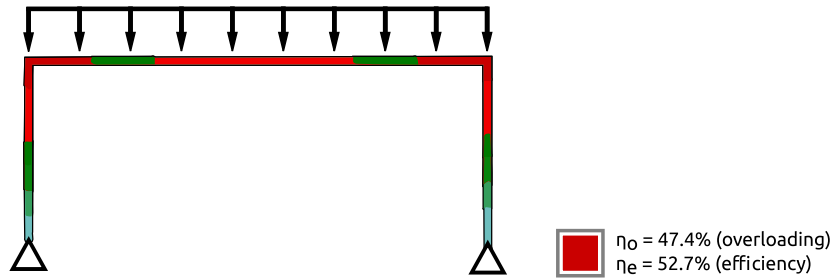
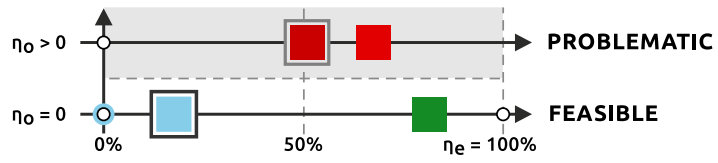


FIGURE 7.3: An example of results visualization for sizing process.

The second and the main approach of this research is to use the Design tracker to guide users during the shaping process. The goal of the shaping process is to minimize stress in the structure. Less stress in the structure means that the shape of the structure follows the forces more (see form-finding approach in Section 4.2). Figure 7.4 shows an example of transforming a frame structure into an arch in four steps. The best found solution is the arch (4th solution outlined in black in Figure 7.4).

SHAPING PROCESS

The goal of the shaping process in the Design tracker is situated on the left end of the feasible row (see blue circle in Figure 7.4). This can be confusing for users, because the goal of the shaping process can be also interpreted as the aim to achieve the 0% efficiency, which is not right. In this case, the lower efficiency means that the profile is over-dimensioned according to the stress in the structure (if there are no problematic parts identified in the structure). By reducing the profile size (similar to Figure 7.3), users can increase sensitivity of the Rating system to identify problematic parts which do not follow forces. This can help them to adjust the Rating system for a more detailed shaping process.



○ - optimization goal   □ - best solution    $\eta_0$  - overloading    $\eta_e$  - efficiency

FIGURE 7.4: An example of results visualization for shaping process.

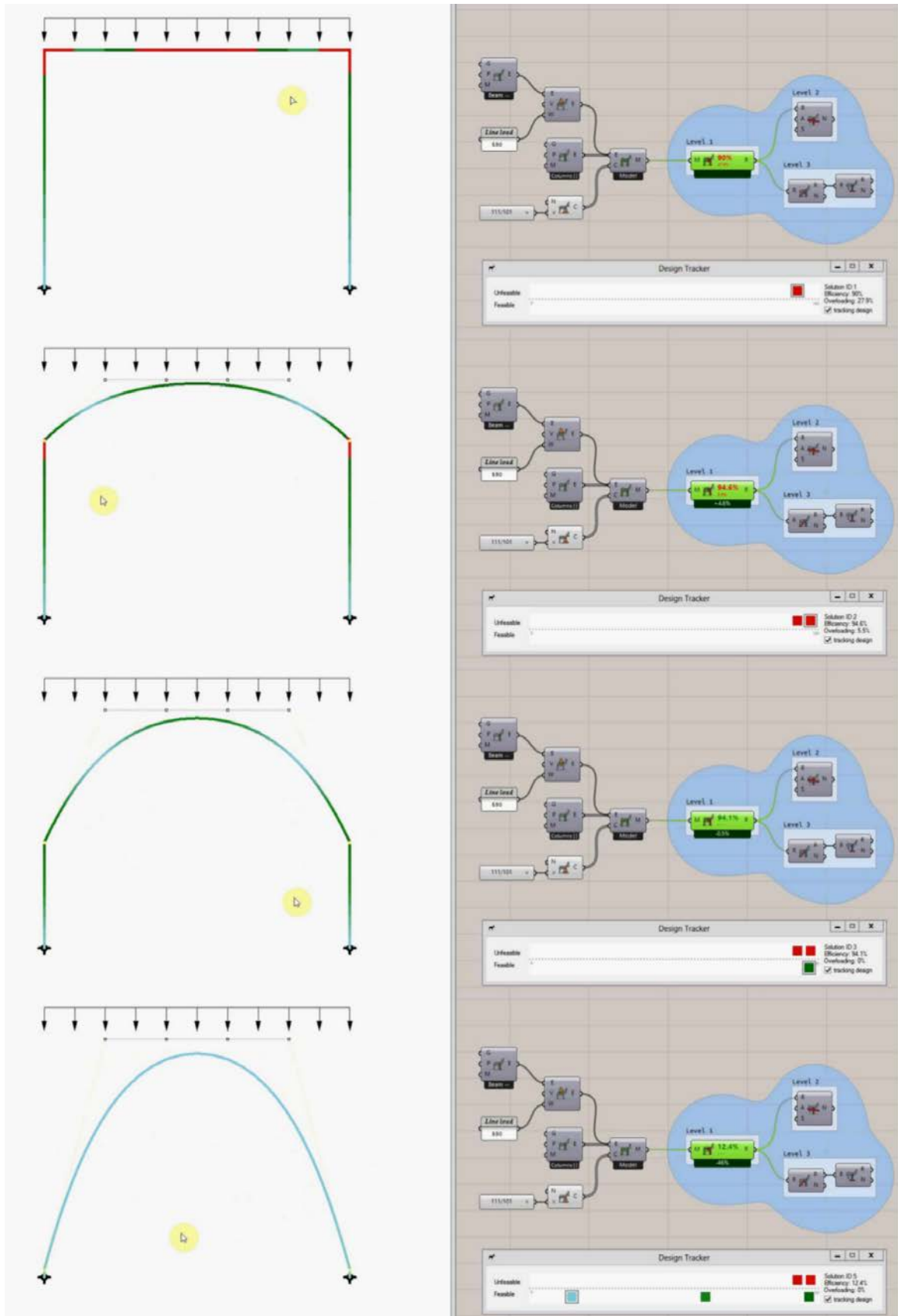


FIGURE 7.5: Real implementation of the shaping process example.  
 (<https://youtu.be/sQNvZ7GSFIQ>)

## Implementation

Changing the profile size to adjust the threshold of problems visualization is the one, but not the best option which users have in the Design tracker. The second option is to use a threshold setting which was added during the implementation of the Design tracker into Grasshopper's components (see Figure 7.6).

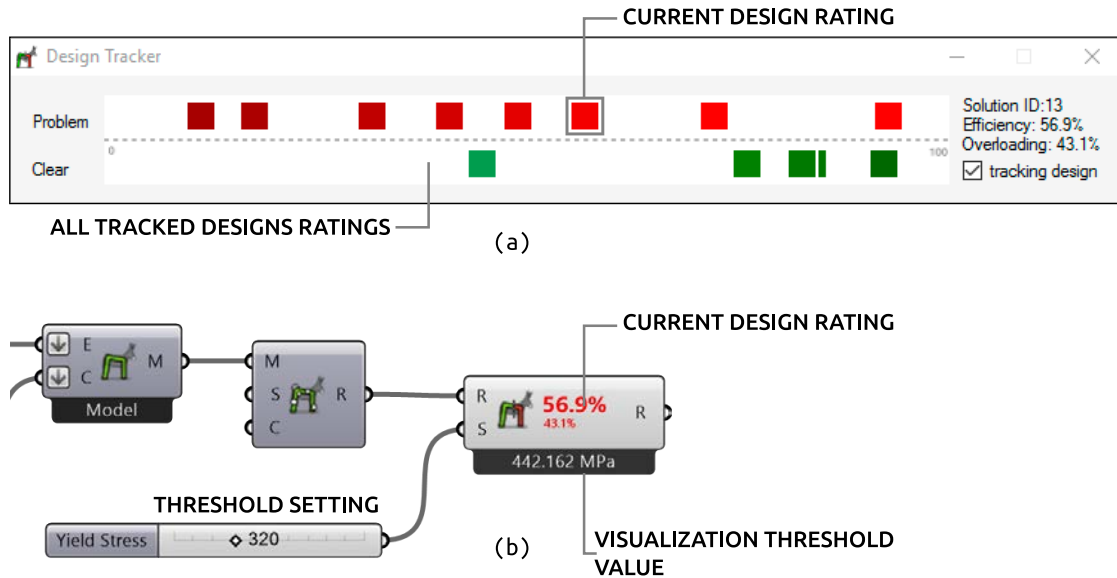


FIGURE 7.6: Design tracker implementation: (a) pop-up window with explored design space, (b) developed Grasshopper components with Rating system visualization.

### POP-UP WINDOW

The implementation of the Design tracker method is designed in a pop-up window (Figure 7.6 (a)), which is always visible and accessible while Grasshopper canvas is minimized. The pop-up window can be opened by double clicking on the SEA component. The window consists of a design space panel represented by two rows described above (see Figure 7.2) and an information panel on the right side of the window. The coloured squares are specific buttons which represent explored design alternatives. By clicking on the button, the related design alternative is visualized in Rhino's viewport and its Rating values are visualized in the information panel as well as in the SEA component. Tracking (storing) of newly created alternatives can be controlled by the checking button at the bottom of the information panel.

### ADJUSTING VISUALIZATION THRESHOLD

By changing the threshold value, the whole design space is dynamically rearranged (see Figure 7.7). A value in the threshold represents the Yield point, the upper boundary of elastic region (see Section 6.2), in other words, the maximal allowed yield stress in the structure. Changing the threshold value, is similar to a change in material properties (see material properties in Section 5.2) but it happens in the post-analysis process. In this way, users can dynamically adjust the sensitivity of the Design tracker visualization without a change in the analytical model, and thus avoid time-consuming calculation of FE analysis. By using this threshold setting, users can train their sense of material properties. To help users adjust the correct threshold value the maximal stress in the design is visualized below the SEA component.

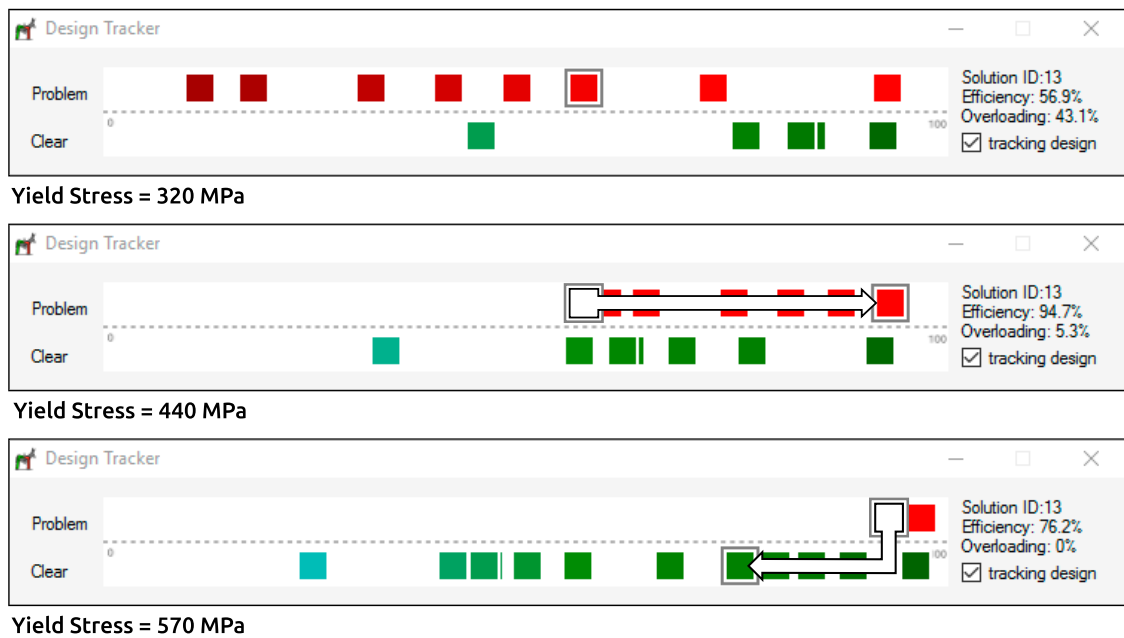


FIGURE 7.7: Organization of design space by changing Yield Stress value.





**Part IV**

**Applications**



## Chapter 8

# Guidance of design process

*"All of us, unfortunately, have the weakness of making exasperating mistakes, and the best that can be done is to keep them to the absolute minimum. The best structural designer is not necessarily the one who makes the fewest mistakes initially, but probably is the one who discovers the largest percentage of his or her mistakes and corrects them."*<sup>1</sup>

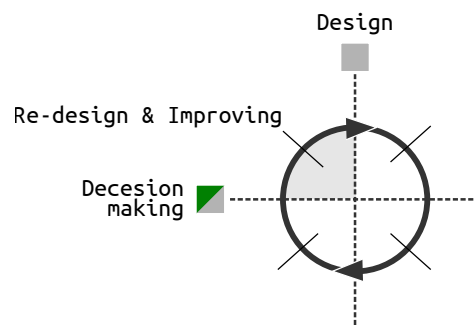


FIGURE 8.1: From decision-making to a change in the design.

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<sup>1</sup>J. C. McCormac. *Engineer's Standpoint: History of Structural Analysis*. 2010. URL: <http://www.engineerstandpoint.blogspot.cz/2010/09/history-of-structural-analysis.html> (visited on 01/11/2016).

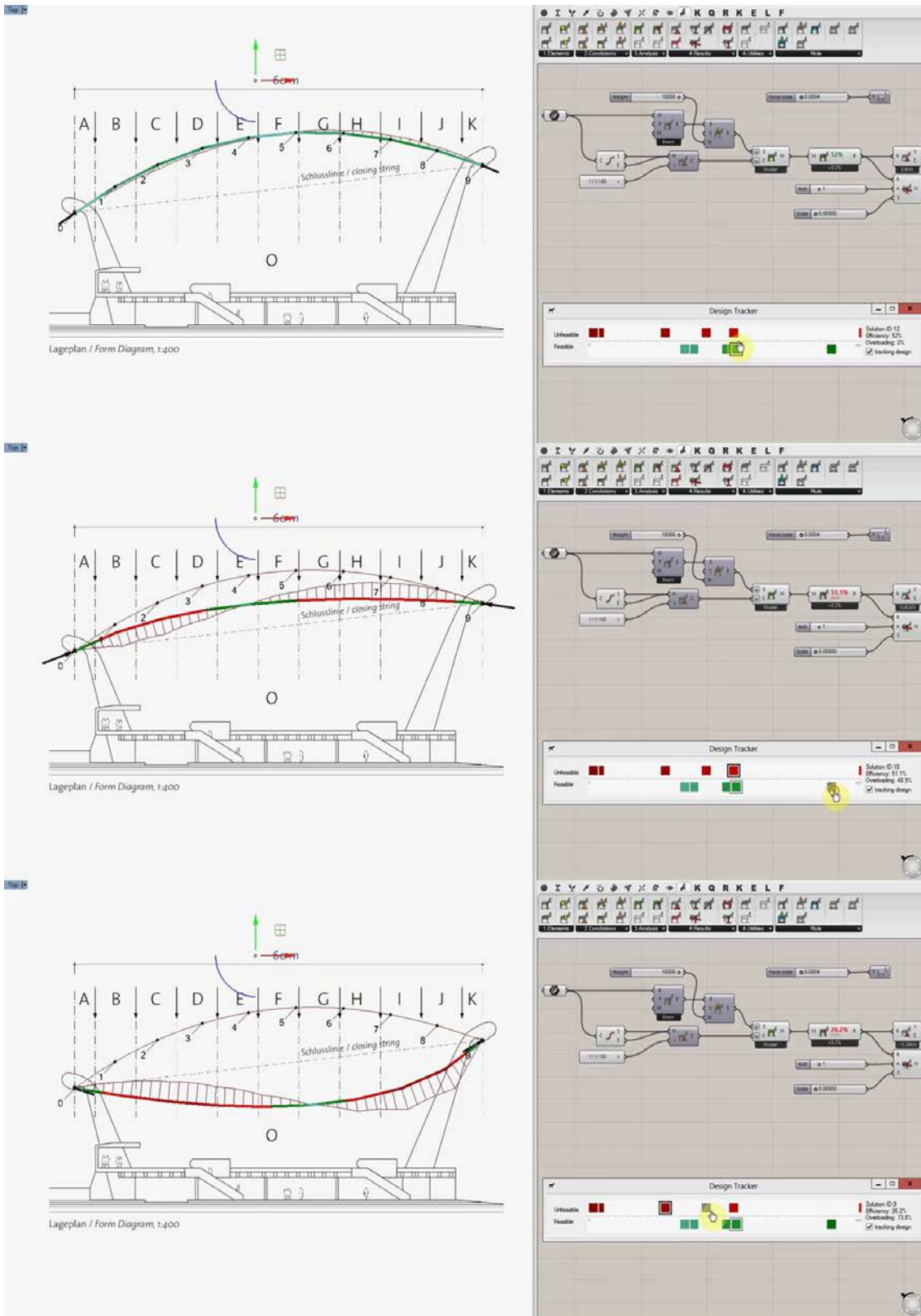


FIGURE 8.2: Post-analytical design space exploration with secondary extended results visualization. (<https://youtu.be/wVk80VyHCOU>)

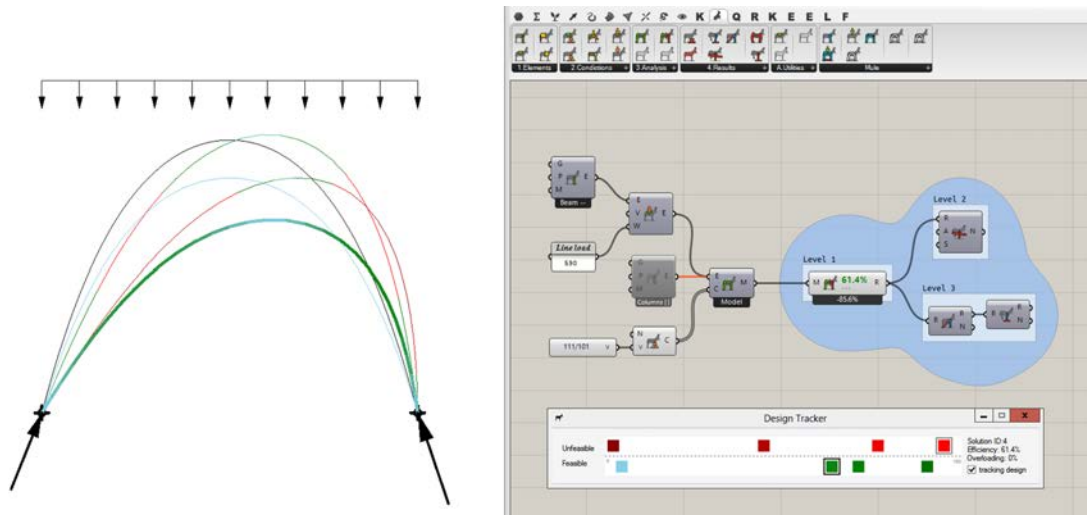


FIGURE 8.3: Visualizing all explored alternatives can guide the user during shaping process. (<https://youtu.be/Vu28QTjP9Sc>)

## 8.1 Design exploration process

### Interactive

The possibility of storing previous design alternatives opens other possibilities that can support deduction and decision-making during design process. One is the possibility to visualize previously created solutions to learn from them. For this reason, the bake-all function was added into the Design tracker. It creates geometry of all explored alternatives from the Design tracker in the Rhino viewport and colours them based on the Rating system rules. This is how the limits of feasible solutions can be visualized, and thus, guide the user to find a better solution inside these limits (see Figure 8.3).

BAKE-ALL

By adjusting the shape of curves users can design, for example, the profile of a long span roof (see Figure 8.2) with required height and still have the control over stresses in the structure. In the same way, through shaping curves, users can adjust the form of a shell structure. Figure 8.4 shows the design process of a student designing a shell on her preferences (a). Supported by SEA and the Rating system, the student was able to find a more funicular shape by manual modelling. This way, the student found out that the elliptical shape first proposed is less efficient than the found parabolic shape.

EXAMPLES OF APPLICATION

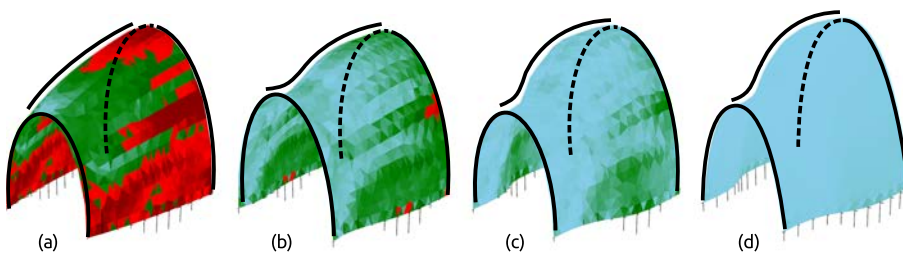


FIGURE 8.4: Finding a better form of shell structure based on shaping controlled curves.

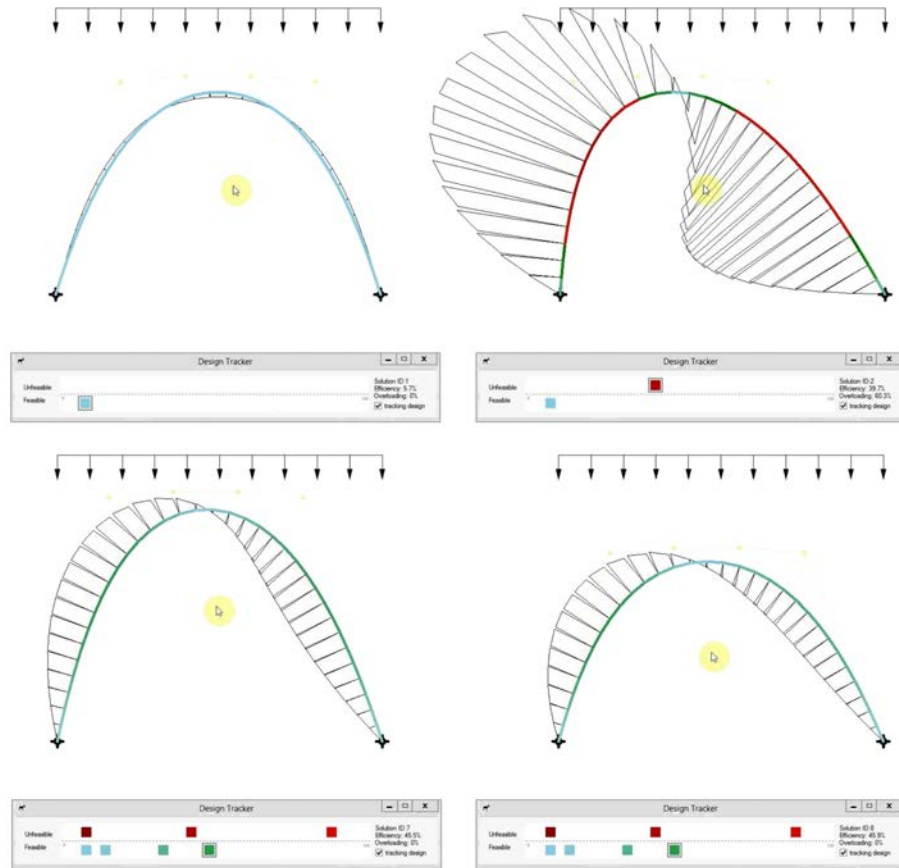


FIGURE 8.5: The second level of result interpretation – moments.

#### SECOND LEVEL

To extend understanding of structural behaviour and help users to find less stressed design forms, the second level of results visualization can be used (see Levelling system Section 6.1). Thus, the visualization of moment lines is added in the viewport. Following the rule of minimizing moments in the structure, mentioned in Form-finding Section 4.2, the moment line can guide the user towards less stressed solutions (see Figure 8.5).

### Post-analytical

The extension of the first level of results visualization by the second one can be done also in the post-analysis process, when the user is exploring previously stored design alternatives by clicking on a specific button in the Design tracker (see Figure 8.2). This can be useful for example, after consultations with a structural engineer. An engineer can point out important structural properties, which the user overlooked due to lack of knowledge. The user can easily extend results visualization and start to focus on newly highlighted structural properties. This can also teach the user to better understand the structural behaviour of the designed structure and extend his/her structural knowledge.

#### BENEFITS OF RESULTS EXTENSION

The additional results visualization also helps the user to discover structural properties hidden behind the identified overloading problems coloured in red. Usually the problem is caused by perpendicular forces – the moments,

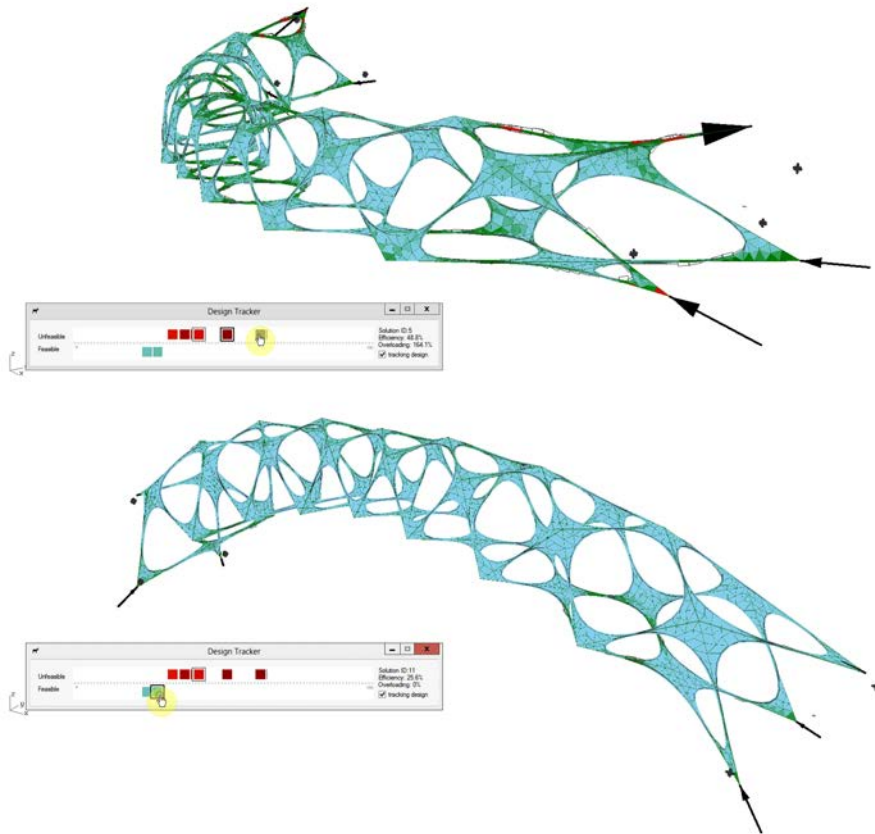


FIGURE 8.6: Rapid post-analytical exploration of design with more complex geometry.

which are more dominant than axial forces. As shown in Figure 8.3 or 8.5, the red coloured parts of the structure have also the biggest offset of the moment line.

Exploring previously stored solutions is beneficial not only to the additional extension of results visualization level but it can be also useful when analysis interactivity is broken by longer calculation time. This usually happens in designs with more complex geometry. Figure 8.6 shows an example of a more complex structure consisting of both the shell and beam elements, where the analysis takes around 3 seconds. In this case, the fast post-analytical exploration is very useful.

BROKEN INTERACTIVITY

## 8.2 Sensitivity to change

The Design tracker can be also used to visualize the sensitivity to change. A parametric model of my diploma project – Annelida, was created along an longitudinal axial curve which controls its main curvature. The first example (Figure 8.7) shows that the boundary conditions of the structure are defined by a hinged support on the left and a movable support on the right side, that allows a movement in the longitudinal direction. The whole structure behaves as a simple beam, therefore, the particular shape change does not have a significant effect on the structure efficiency (only a subtle change of the rating

UNDERSTANDING OF COMPLEX  
BASED ON SIMPLE SCHEME

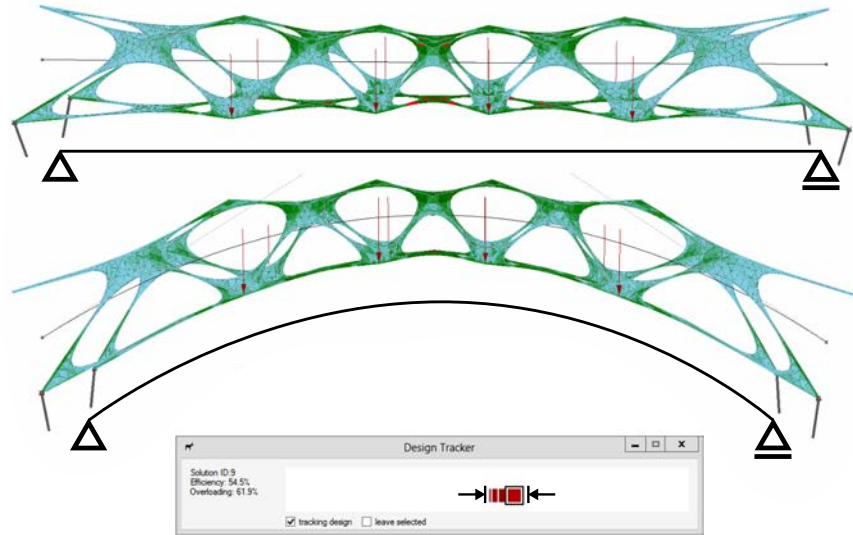


FIGURE 8.7: The effect of shaping: simply supported beam structure.

in the Design tracker can be seen). The structure reacts as the active-section system (see Engel classification Figure 3.2), where the key parameters are the profile dimensions (in this case it would be mainly the profile height).

#### FORM-ACTIVE STRUCTURE

The second Figure 8.8 shows that both supports have been changed to the fixed ones. Subsequently, the Design tracker gets immediately into the blue area meaning that the stress in the structure was minimized. The change of the boundary conditions – and therefore the structural system – causes completely different behaviour. A simple beam has been transformed to an arch system that is not relying so much on the profile dimensions but rather the structural form (form-active structure). Therefore, the shape change in this case has a more significant effect than in the previous example. The distance between the design alternatives represented by the green square buttons is twice as large as the distance between red squares in the previous example.

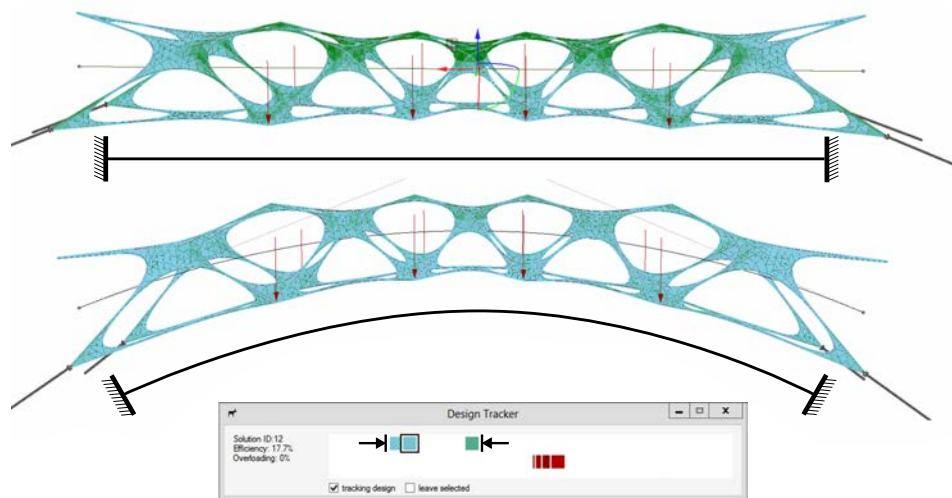


FIGURE 8.8: The effect of shaping: an arch structure.



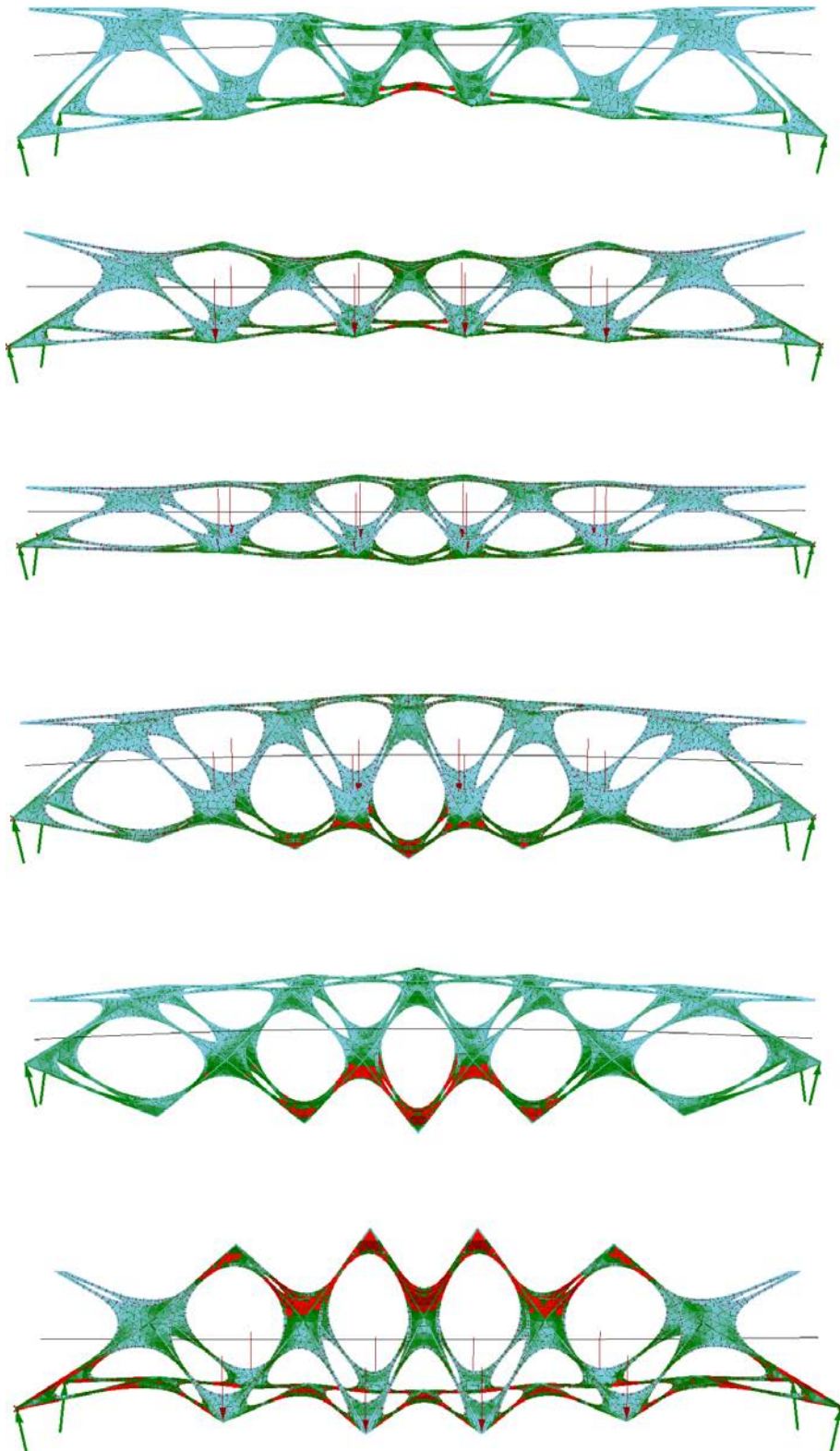


FIGURE 8.9: Examples of different profile distribution generated by exploring design parameters.



## Chapter 9

# Case studies

*"Imagination and creativity: In order to criticize a proposed solution the designer must envisage how it will perform in future service. He must imagine what could go wrong... the designer requires a degree of imagination which must be closely related to creativity. The more innovative the design, the more creativity will be required in its criticism."<sup>1</sup>*



FIGURE 9.1: Many projects in this chapter are students' work from Studio FLO|W at Faculty of Architecture, Czech Technical University in Prague.  
(<http://www.studioflorian.com/>)

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<sup>1</sup>A. Holgate. *The art in structural design: an introduction and sourcebook*. Clarendon Press, 1986. ISBN: 9780198561675, p. 224.

## 9.1 Geometry Death Frequency–141

One of the first project where SEA was used was Geometry Death Frequency–141 project designed by Federico Diaz, as a 2-year exhibition project for the MASS MoCA museum in Massachusetts.

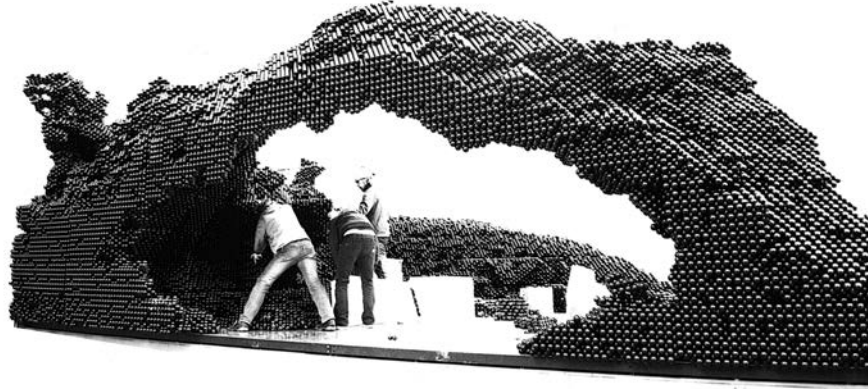


FIGURE 9.2: Resulting shape of supported fluid-form structure consisting of 250 000 spherical elements.

### PROBLEM STATEMENT

The whole sculpture consists of approximately 420 thousand spherical elements made from ABS plastic material, each being 4,7cm in diameter and weighing 9g. The entire structure is 10 meters long, 5,4 meters wide and 4 meters high. The resulting wave structure was designed for outdoor conditions, where it has to resist a large amount of snow. We were afraid about load-capacity of some parts of the object, so we decided to conduct a structural analysis. In the analytical model, all the spheres were transformed into a beam finite element mesh with nodes placed in their centres. The bearing capacity of the beams, normal and bending stiffness were obtained experimentally by the load test of several cantilever girders consisting of ten axially aligned spheres. The measured quantities were verified by SEA.

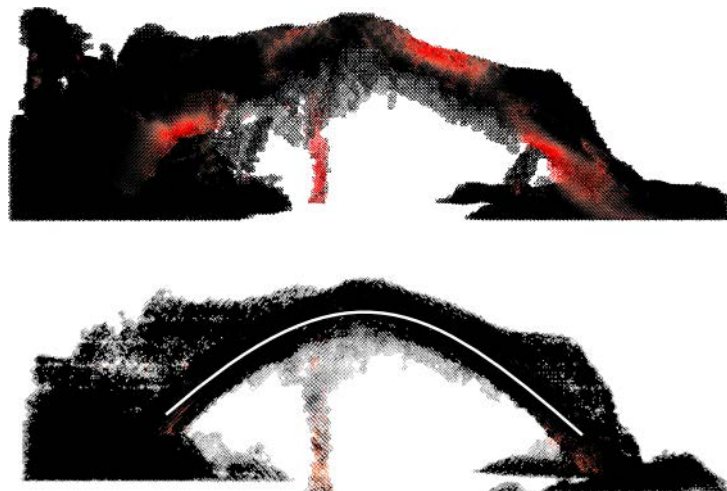


FIGURE 9.3: Analysis of generated structure (top) and its improvement based on the identified possible problems (bottom).

Loading conditions of the analysis were dead-loads plus additional snow loads. The analysis showed that about 10% of spheres from 250 000 spheres of the fluid-form structure were considered as critical (see Figure 9.3 (top)). Therefore, the reinforcement of the structure was needed. We considered steel rod supports, but we were discouraged by complications concerning calculations and the poor synergy of combining these materials.

ANALYSIS

Therefore, we created the reinforcement for the structure from the same material – spheres. Based on the identified problems of the Rating system, more reinforcement solutions were designed and evaluated. The final design of a parabolic shape reinforcement was merged with the fluid-form structure. This ensured a sufficient load bearing capacity for the most exposed part of the structure (see Figure 9.3 (bottom)).

REINFORCEMENT



FIGURE 9.4: The realized structure and the final loading test by the nature.

## 9.2 Origami folding structure

The aim of this project was to explore possible origami structures, which can be later used as an adaptive, foldable roofing or façade. During semester Filip Lishak, a student, researched different types of origami grids. He analysed their flexibility and forms as a product of self-organized shaping process. Possible forms of different origami grids were explored based on physical models and computer simulations. For computer simulation Kangaroo software tool was used (see Figure 9.5).

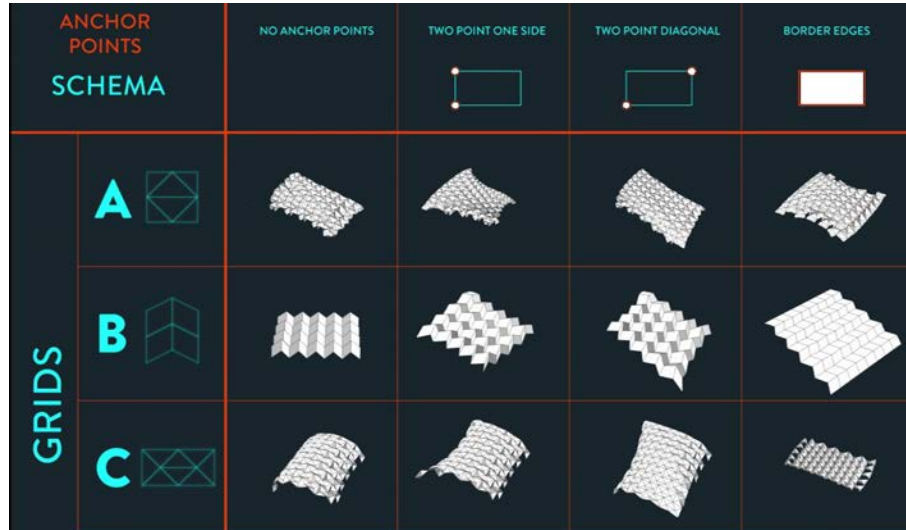


FIGURE 9.5: Research of different origami grids. ([https://youtu.be/1\\_eJdel2Fck](https://youtu.be/1_eJdel2Fck))

### SEA APPLICATION

In this project, SEA was used to analyse folding phases of each generated grid shape (see Figure 9.6). Thanks to this analysis, it was possible to understand the forces distribution inside the structure during its movement. Based on this analysis, the grids were scored and compared. This project represents an overview of possible folding structural systems and their structural requirements. It can be useful for designing adaptive structures which can react to different climate conditions or space requirements.

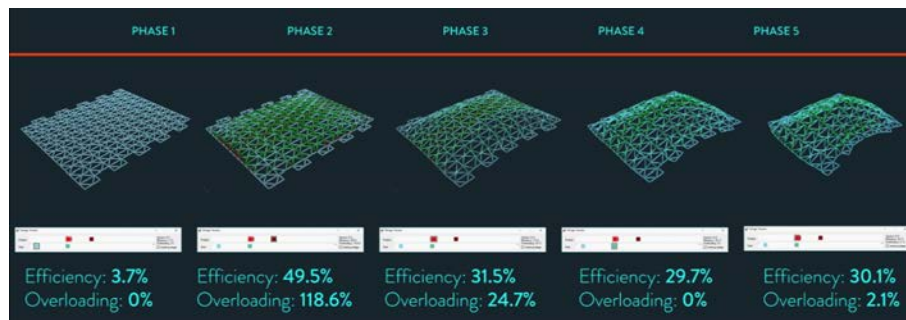


FIGURE 9.6: Generated design space.

### 9.3 Swarming CARBONfibre bridge

SEA was also used in the CARBONfibre bridge project by Jakub Fišera<sup>2</sup>. Jakub used an agent based simulation where the geometry was generated based on wandering swarming agents, which moved between the banks of the Thames river. This process allowed to generate numbers of design alternatives (see Figure 9.7)<sup>3</sup>.

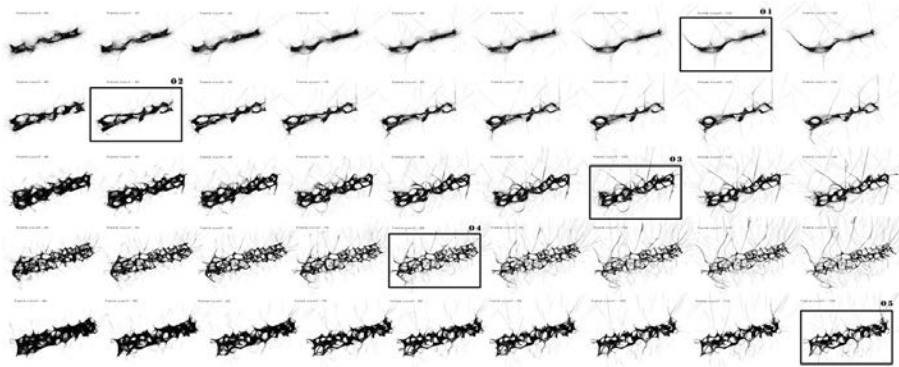


FIGURE 9.7: Generated design space.

The generated geometry was too complex and inconsistent for FE analysis (see Figure 9.8). Therefore, based on consultations with a structural engineer, the student transferred the geometry to structural schemes that were analysed by SEA (see spatial analysis on the top of Figure 9.9). That way, the student trained his sense to identify a load bearing structure inside complex geometry, and developed his understanding of the structural behaviour. Jakub used the Rating system to identify the best solutions and he explored how to improve the rating, that would eliminate the overloading values and increase the structure efficiency (see Figure 9.9).

DESIGN METHODOLOGY

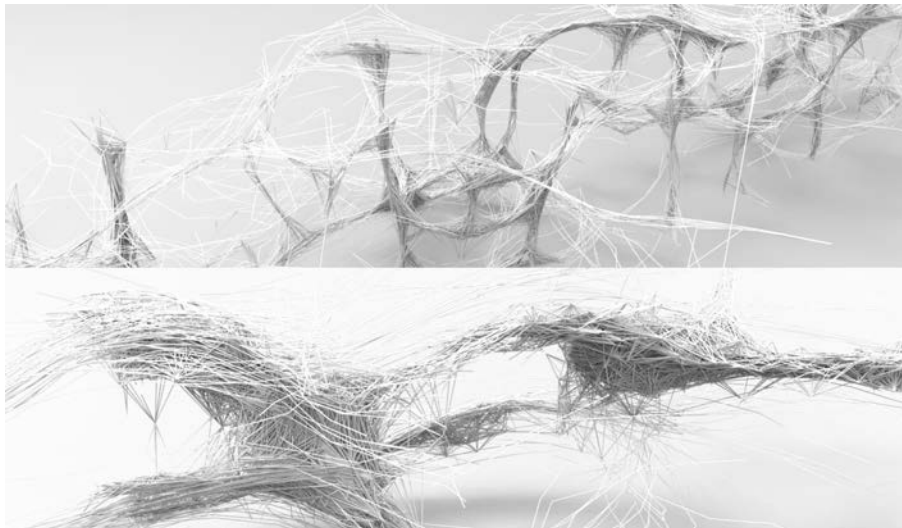


FIGURE 9.8: CARBONfibre bridge, detail of the generated geometry representation.

<sup>2</sup><http://www.studioflorian.com/projekty/307-jakub-fisera-carbonfibre-bridge>

<sup>3</sup><https://youtu.be/yX5bamaz7eQ>

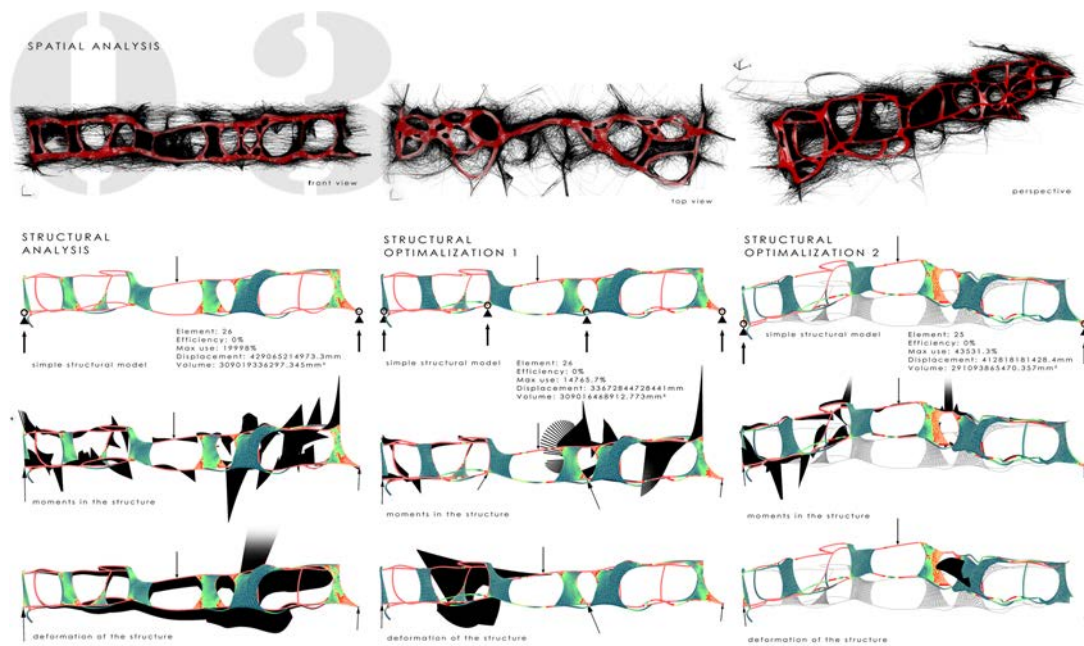


FIGURE 9.9: Structural analysis of selected designs.



## 9.4 Adaptive Danjiang Bridge

The Danjiang Bridge was designed by Miroslav Hlava<sup>4</sup>. For its adaptation to current load conditions the bridge is using 468 linear actuators located within the diagonals of the main arch shaped girders (336 elements) and also within the vertical supports at both ends of the bridge (132 elements), see red layer in Figure 9.10. These active elements are expected to create counter forces to the loads affecting the structure and thus reduce the stresses caused by traffic or wind, to distribute loads within the structure, reduce deformations and vibrations, prevent aeroelastic flutter, etc.

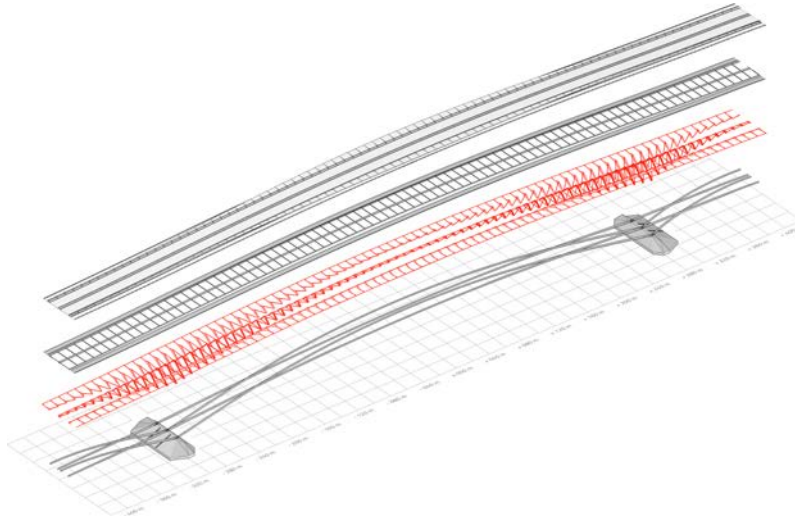


FIGURE 9.10: Layers of adaptive bridge design.

Danjiang Bridge is designed as a combination of 4 main arch shaped girders from high performance steel HPS 100W (yield strength 780 MPa), which are significantly low (30 m) compared to the length of the main span 580 m. This ration length / height (about 1:20) allows the main bridge deck to be located directly on top of the girders while having a longitudinal slope less than 6%. The main road located on the bridge consists of two lanes on both sides and has a proposed speed of 80 km/h. There are also pedestrian and cycling lanes located on both sides of the bridge. As a result of these requirements the bridge is 55 m wide at the widest point.

SEA's interactive analysis enabled Miroslav to test and understand different structural behaviour of various bridge concepts on architect's side, which was crucial for this project. This project is also a good example of a structurally more skilled student, who clearly knows what he wants to achieve. Therefore, for the exploration process instead of the Design tracker an evolutionary algorithm was used. However, the Rating system from SEA was used as the fitness value for structural optimization. This project also shows the flexibility of the developed SEA, as its visualization and application can be customized for specific design needs.

DESIGN PROPERTIES

CONCLUSIONS

<sup>4</sup><http://www.studioflorian.com/projekty/364-miroslav-hlava-danjiang-bridge>

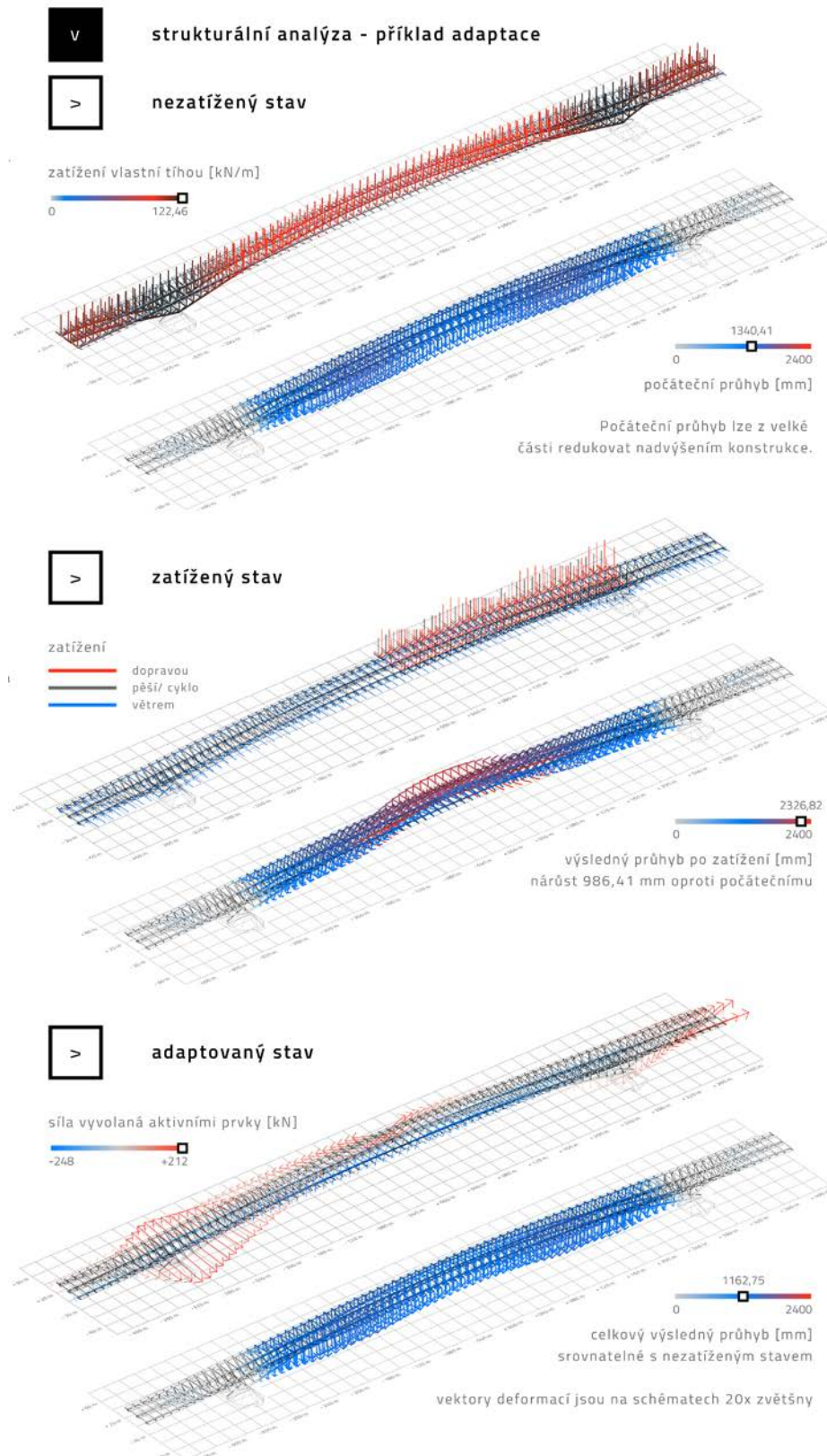


FIGURE 9.11: Comparison of unloaded (top), loaded (middle) and adapted structure (bottom).

## 9.5 Workshop: Chimney – Watchtower

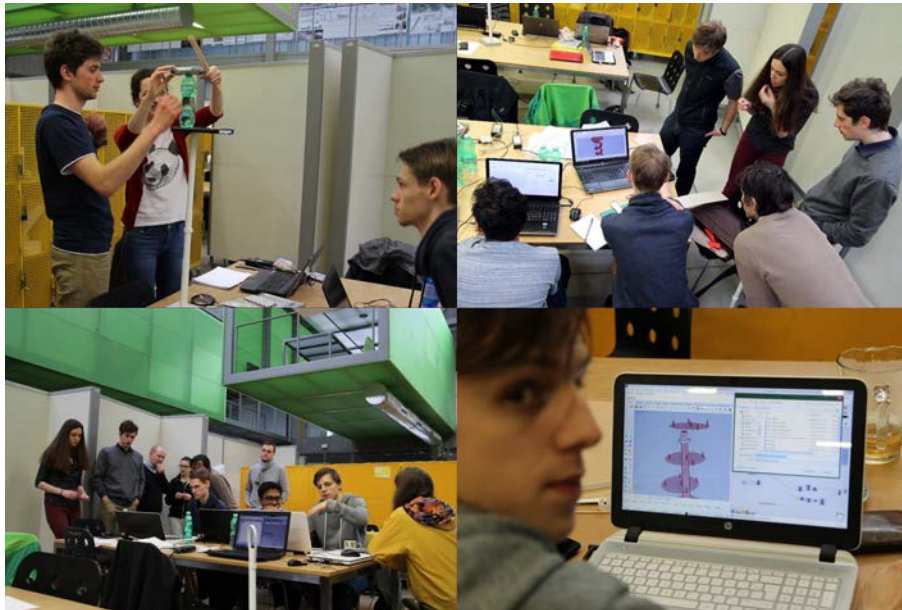


FIGURE 9.12: Documentation photos of the Chimney – Watchtower workshop.

The workshop was organized with a design task to extend an existing chimney in Ždár na Sázavou by an observation tower. The main goal was to test SEA with different types of users, which should prove the usability of the tool. Analytical results interpretation was supported by physical models and consultation with a structural engineer.

WORKSHOP OBJECTIVES



FIGURE 9.13: Consultation of structural behaviour using physical models.

The workshop was opened with a brief presentation of possible structural systems. Then the SEA tool was introduced using an example of transforming a frame structure to an arch. Afterwards, the participants worked in pairs on both the virtual and the physical models. In most cases an interesting interaction emerged since the task was the same but the tools were differed.

WORK SESSIONS

The initial premise that consultation with a structural engineer is crucial for the development of an analytical model was confirmed. Some students struggled with completing the analytical model and some misinterpreted its functionality.

MODELLING ISSUE

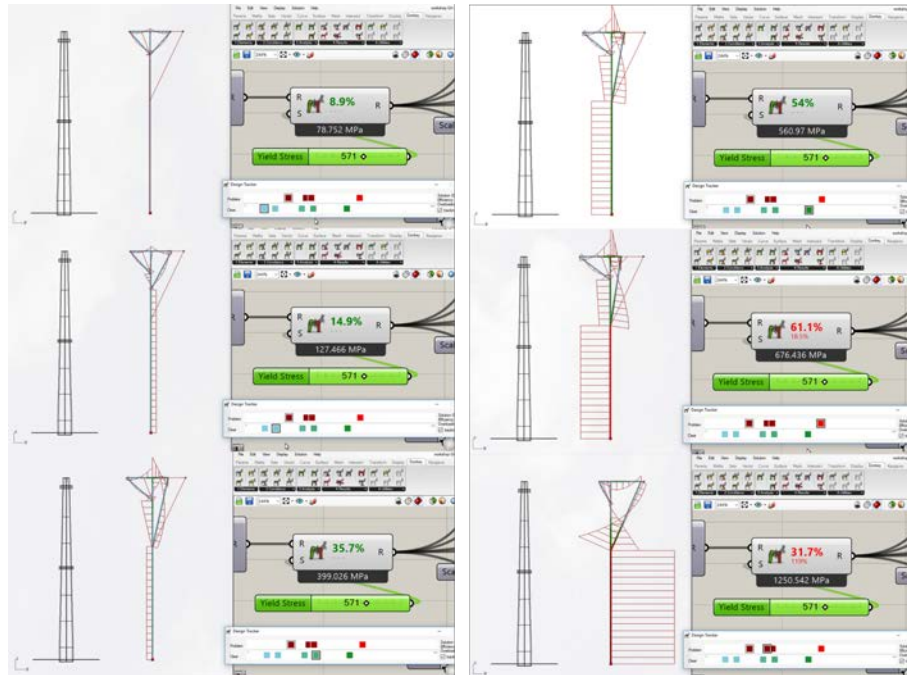


FIGURE 9.14: Evaluation of different design alternatives using SEA.

#### DESIGN TRACKER

Once the models were consistent, various design alternatives were created and evaluated. For improvement of design structural performance, participants used the Design tracker. They explored various strategies, such as the overall shape change, alteration of material and cross-section properties (sizing) or testing different boundary conditions. The use of Design Tracker has proved to be efficient and comprehensible. The participants always found the way how to improve their designs and understood why their designs had improved.



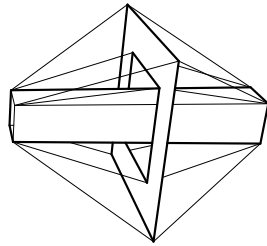
FIGURE 9.15: Resulting physical models.



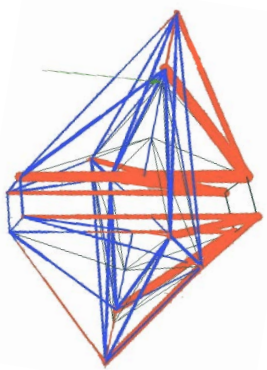
FIGURE 9.16: Renders of chosen designs.

Watchtower above the old chimney

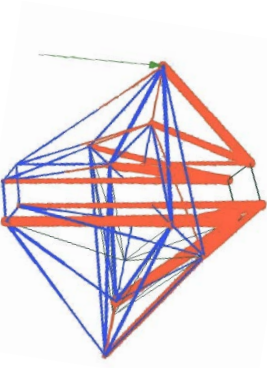
Žďár nad Sázavou | FA ČVUT | Balán Jan | Chavan Tejas



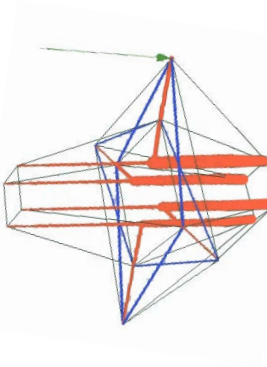
This is our first design. We decided to create a simple square-shaped platform which will be held by cables connected to the extension of top of the chimney. The structure wasn't stable against wind and rotation.



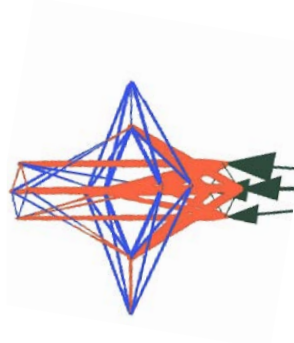
We decided to play with our design and see the impacts of those changes. We pulled symmetrically two corners. The more we pulled the worse the results were. It didn't solve our problems with rotation either.



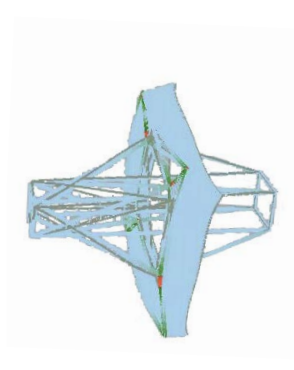
Then we pulled just one corner which results in better structural behaviors even if it wasn't symmetrical. It was clear that the more the platform will be to center, the more stable it will be.



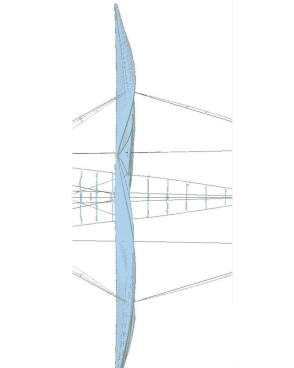
We took out the cables and put just four supporting beams at the bottom. It solve problems with rotation, but general the results was worse because of big pressure. Also it changed our idea of platform in sky held just by subtle cables.



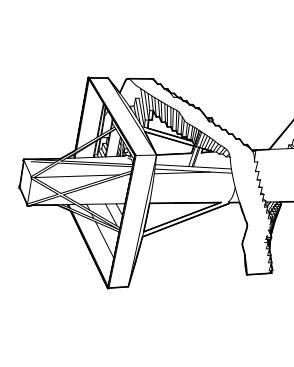
Back with idea with cables, we take out all cables in outer ring. Also the cables aren't just vertical, we cross them to solve the rotation. It results in the most stable design, which is resistant even against rotation and the pull-up from wind.



Platform is held only on one side the platform, hence, thanks to its own weight, it is deformed on the outer edges.



We pulled up outer edges of platform a little to pre-stress it for the gravity. The deformation effects then lowered drastically.



Final design is completed by staircase. Design is inspired by the gradation between square platform on top and circle base on the bottom.

FIGURE 9.17: Documented exploration process and design improvement.

**Part V**

**Conclusions**





## Chapter 10

# Findings and future work

"One of the most common mistakes of students in design is to become so mesmerized by the detailed stress calculations that they forget about fundamental criteria, such as overall stability."<sup>1</sup>

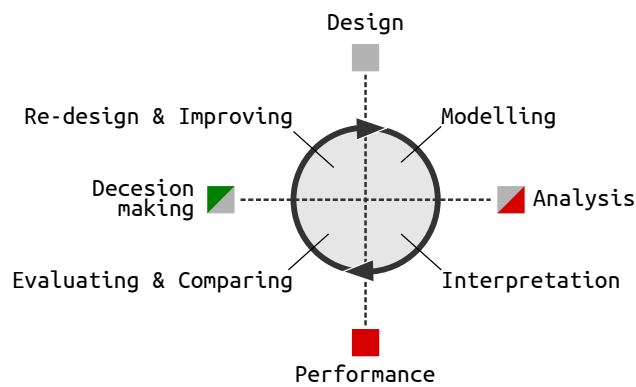


FIGURE 10.1: Stages of proposed design process supported by SEA.

<sup>1</sup>A. Holgate. *The art in structural design: an introduction and sourcebook*. Clarendon Press, 1986. ISBN: 9780198561675, p. 225.

## 10.1 Research results

### DIGITAL TOOLS

The result of this research is the Structurally Evaluation Assistant (SEA) implemented into the digital tool Donkey<sup>2</sup>. The development of this tool was divided into two steps. In the first step, an interactive structural analysis was developed in the architectural model environment (see Section 5.1). In the second step, the research focused on supporting decision-making during the design process. Three methods were developed to support architect's decision-making in the conceptual structural design.

### METHODS

The first method – *Levelling system* (see Section 6.1) defines three levels of structural analysis results simplification (FE). The first level offers less experienced users the analysis results in the form of a simplified scoring of individual design alternatives. The next two levels serve to understand the cause of the identified static problems in more detail. This enables the user to gradually deepen his/her structural knowledge.

The next method – *Rating system* (see Section 6.2) represents the first level of simplification. Through a pair of scalar values it informs an architect about the effectiveness and potential structural problems in a design.

The last of the developed methods is *Design tracker* (see Section 7.1), which records and compares solutions created during the design process. Mutual comparison of alternatives supports the user's decisions and awareness of the impact of changes on structural performance.

## 10.2 Comparison

### Existing tools

The developed SEA tool compared with other tools for structural design is innovative as it connects the user-based modelling with decision-making support.

### KARAMBA

Tools enabling direct modelling (eg. Karamba), are only analytic tools that do not provide decision-making support during the design process. These tools are designed for professional users. The complexity of their environment is too complicated for an average user.

### USER BASED MODELLING

The second group of tools examined (Galapagos, Structure FIT, etc.), because of fully automated searching for the optimal solution do not allow direct user-based modelling. User-based modelling is important for training users' structural intuition. Individually made changes – actions and subsequent responses – reactions support the ability to learn and better understand simulated physical laws.

<sup>2</sup>Lukas Kurilla. *DONKEY*. version 0.84. [software]. 2017. URL: <http://donkey.kurilluk.net/> (visited on 09/15/2017).

## Existing methods

The inspiration to simplify the structural result used in the Rating system method comes from the fitness value. The fitness value supports users' decisions in selecting parents in the interactive evolution algorithm method. The advantage of the Rating system compared to the fitness value (used e.g. in Figure 4.13) is in the visualization of potential structural problems intended to support the user. The fitness value is primarily designed for the optimization algorithm to function. When evaluating using a fitness value, problematic solutions are hidden under the same evaluation value as feasible solutions. Problematic solutions are only penalized and thus they can achieve similar ratings as oversizing designs. But a clear distinction between a feasible and a problematic solution is very important for the users' decision-making.

FE RESULTS SIMPLIFICATION

## 10.3 Application

As exemplified in the case studies section, the SEA tool has been applied to studio teaching at the Faculty of Architecture CTU Prague. In particular geometrically bold concepts where statics played an important role were assessed. Thanks to the SEA tool students already in the conceptual phase were able to understand the relationship between the proposed form and structural performance. A similar application of the tool would be possible in structural design classes (not only at faculties of architecture but also at faculties of civil engineering), where students, after understanding the theory, could use the SEA tool to verify various creative modifications of the model assignment. This should help students more thoroughly understand the previously learned material and further develop their creativity, which is important in the structural design.

ACADEMIC

Using the SEA tool during consultations with a structural engineer confirmed the purpose of the tool, which is not to replace the role of a structural engineer, but to allow the architect and structural engineer communicate better in the conceptual design process. Structural analysis on the architect's side raises architect's interest in the structural properties of his/her design, while at the same time relieves the structural engineer from the routine activity of evaluating alternative solutions, through which the architect decides and becomes familiar with the structural behaviour of his/her design. Thus, a structural engineer plays an important role as a consultant who helps an architect to create an analytical model, checks the accuracy of interpretation of the structural analysis results, and leads the architect to achieve a better result.

INTERDISCIPLINARY  
COOPERATION

## 10.4 Discussion

The proposed Rating system is based on von Mises yield criterion where the element's stress components are integrated into one equivalent stress and divided by the yield stress of a defined material. With this calculation method, the results are very precise for steel materials, but they are less precise for

PRECISION

anisotropic materials. However, the aim of the Rating system is not to get a final – most accurate assessment, but only to guide architects in their decision-making process. In this respect, the analysis provides users with instant and sufficient information about the overall stress distribution in the entire model, which helps architects realise problematic parts of their design.

#### BUCKLING AND STABILITY

Other important values that can increase the Rating system's precision especially for structures with compressed elements, is buckling and overall stability (see Holgate citation in this chapter page). The buckling coefficient can be calculated based on Swiss code [SIA 263]. The Rating system value can be reduced based on the calculated buckling coefficient, thus reducing the allowable stress for compressed structural elements.

#### AVOIDING BLACK-BOX SOLUTION

But the question is, if too sophisticated Rating system will not be confusing for less experienced users. In order to keep it from becoming a black-box solution, the other important structural properties, which are relevant to structural problems, are designed as an additional extension of the Rating system (see Levelling system Section 6.1). The Rating system informs user only about forces distribution. The same is the case with overall stability. It is also implemented in SEA but it is not the part of the Rating system.

## 10.5 Future work

#### SIMPLIFICATION METHOD

There are two fields of possible future work related to this research. The first one can be a further development of FE analysis simplification method which can be tested on more diverse types of structure. For example the von Mises criterion can be replaced by maximal allowed crack size in shell structures to achieve a better, more precise interpretation of feasible and problematic solutions.

#### GUIDING METHOD

The second option for future work is related to the guiding method. The Design tracker does not include a direct method of leading a user to a better result. The user decides how to make a change based on his/her own deduction from the previous attempts. In future research, it would be possible to deal with a method that would lead the user to a better result based on the visualization of the proposed structural shifts. Research could deal with the interaction between a designer and an artificial intelligence algorithm, in order to encourage user's creativity and enable him/her to learn during the design process.

**Part VI**

**Appendix**



## Appendix A

# Analytical model

### A.1 Structure

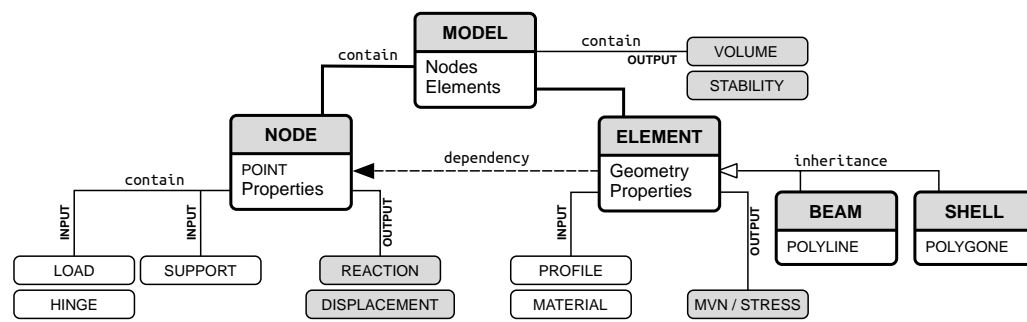


FIGURE A.1: Structure of an analytical model.

For the analytical model, an object oriented approach was chosen. A MODEL is the root object of the data structure. It contains a list of two basic objects: NODES and ELEMENTS of the structure. Each of these objects has its own specific properties and geometric representation. Geometric representation of the nodes is a point. The geometry of elements depends on the points, which ensures a clear definition of connections between elements (see below in the model definition, component model) and allows direct response of an element's shape to the change in the nodes position. Geometric representation of elements varies according to the type of element (beam, shell). From the real shape of an element the smallest (proportionally negligible) dimension is excluded and in the form of PROFILE is stored in the element properties. A beam is thus represented as a line (1D element) and a shell as a surface, polygon (2D element). Geometric simplification has the advantage especially in reducing time-consuming calculations, and it also allows rapid changes in the size of an element.

## A.2 File format

The ASCII VTK (Visualization Tool Kit, see Figure A.2) has been chosen as a primary format. It has a human readable syntax and can be visualized directly in the modeller or using either of free visualization tool-kits as Paraview or MayaVi2. Thanks to this, the data interchange can be simply controlled especially during the software development and debugging. Note that the ASCII can be replaced with the binary format in order to speed up the data flow.

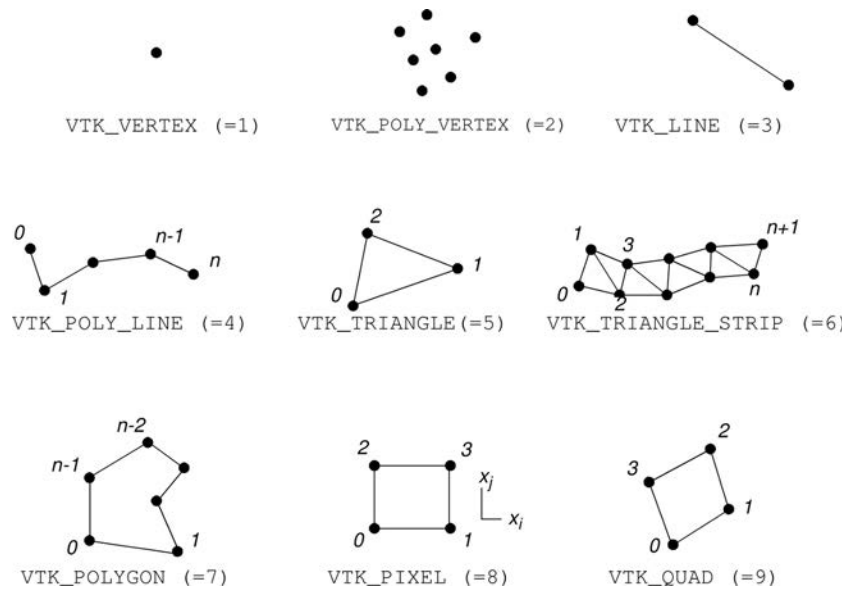


FIGURE A.2: Cell types in VTK file format version 4.2.  
 (www.vtk.org/VTK/img/file-formats.pdf)

## Input data

```

1 <?xml version="1.0" encoding="utf-8"?>
2 <VTKFile type="UnstructuredGrid" version="0.1" byte_order="LittleEndian">
3 <UnstructuredGrid>
4 <Piece NumberOfPoints="3" NumberOfCells="2">
5
6 <Points>
7 <DataArray type="Float32" NumberOfComponents="3" format="ascii">
8 0 0 0
9 1000 0 0
10 301.729708549064 715.834198733914 0
11 </DataArray>
12 </Points>
13
14 <Cells>
15 <DataArray type="Int32" Name="connectivity" format="ascii">
16 0 1
17 0 1 2
18 </DataArray>
  
```



```
19
20 <DataArray type="Int32" Name="offsets" format="ascii">
21   2
22   5
23 </DataArray>
24
25 <DataArray type="UInt8" Name="types" format="ascii">
26   3
27   7
28 </DataArray>
29 </Cells>
30
31 <PointData >
32   <DataArray type="Int32" Name="ID_Boundary_Condition" format="ascii">
33     2
34     0
35     0
36   </DataArray>
37
38   <DataArray type="Int32" Name="ID_SET_IDS_Prescribed_Values" format="ascii"
39     >
40     0
41     1
42     1
43   </DataArray>
44
45   <DataArray type="Int32" Name="Full_Hinge" format="ascii">
46     0
47     0
48     0
49   </DataArray>
50 </PointData >
51 <CellData >
52   <DataArray type="Int32" Name="Virtual" format="ascii">
53     0
54     0
55   </DataArray>
56
57   <DataArray type="Int32" Name="ID_Material" format="ascii">
58     1
59     1
60   </DataArray>
61
62   <DataArray type="Int32" Name="ID_Cross-Section" format="ascii">
63     1
64     2
65   </DataArray>
66
67   <DataArray type="Int32" Name="ID_Boundary_Condition" format="ascii">
```

```

68     1
69     1
70 </DataArray>
71
72 <DataArray type="Int32" Name="ID_Boundary_Condition" format="ascii">
73     0
74     0
75 </DataArray>
76
77 <DataArray type="Int32" Name="ID_SET_IDS_Prescribed_Values" format="ascii"
78     >
79     0
80     0
81 </DataArray>
82
83 <DataArray type="Int32" Name="Property" format="ascii">
84     0
85     1
86 </DataArray>
87
88 <DataArray type="Float32" Name="LCS_xz_vector" format="ascii"
89     NumberOfComponents="3">
90     0 0 1
91     0 0 1
92 </DataArray>
93 </CellData>
94 </Piece>
95 </UnstructuredGrid>
96 <AppendedData>
97   _<Characteristics>
98   <PROBLEM_TYPE_DOF Number="1">
99     <item>3dRot</item>
100 </PROBLEM_TYPE_DOF>
101
102 <LIST_PRESCRIBED_VALUES Number="1">
103   <item>1 NodePV 6 1 1 1 1 1 1 </item>
104 </LIST_PRESCRIBED_VALUES>
105
106 <LIST_CROSS-SECTIONS Number="2">
107   <item>1 Circle width 100 height 100 </item>
108   <item>2 2Dcs thickness 0.1 </item>
109 </LIST_CROSS-SECTIONS>
110
111 <LIST_MATERIALS Number="1">
112   <item>1 IsoLinEl E 210000 nu 0.2 tAlpha 1.2E-05 density 7.85E-06 Ry 300</
113     item>
114 </LIST_MATERIALS>

```

```

115 <LIST_BOUNDARY_CONDITIONS Number="2">
116   <item>1 DeadWeight components 3 0 0 -1</item>
117   <item>2 NodalLoad components 6 0 0 -49032.75 0 0 0</item>
118 </LIST_BOUNDARY_CONDITIONS>
119
120 </Characteristics>
121 </AppendedData>
122 </VTKFile>

```

## Output data

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <VTKFile type="UnstructuredGrid" version="0.1" byte_order="LittleEndian">
3 <UnstructuredGrid>
4   <Piece NumberOfPoints="55" NumberOfCells="90">
5
6     <Points>
7       <DataArray type="Float32" NumberOfComponents="3" format="ascii">
8         9.301778e+002 7.157851e+001 0.000000e+000
9         8.603495e+002 1.431632e+002 0.000000e+000
10        7.905273e+002 2.147417e+002 0.000000e+000
11        7.206975e+002 2.863279e+002 0.000000e+000
12      </DataArray>
13    </Points>
14
15    <Cells>
16      <DataArray format="ascii" type="Int32" Name="connectivity">
17        0 3
18        3 4
19        0 3 27
20        3 4 28
21      </DataArray>
22
23      <DataArray format="ascii" type="Int32" Name="offsets">
24        2
25        4
26        6
27        8
28      </DataArray>
29
30      <DataArray format="ascii" type="UInt8" Name="types">
31        3
32        3
33        5
34        5
35      </DataArray>
36    </Cells>
37

```

```

38 <PointData>
39 <DataArray format="ascii" type="Float32" Name="uknw_displacement"
    NumberOfComponents="3">
40 0.000000e+000 0.000000e+000 -1.127875e+001
41 0.000000e+000 0.000000e+000 -9.033630e+000
42 0.000000e+000 0.000000e+000 -6.931469e+000
43 0.000000e+000 0.000000e+000 -5.020038e+000
44 </DataArray>
45
46 <DataArray format="ascii" type="Float32" Name="uknw_rotation"
    NumberOfComponents="3">
47 -2.707839e-007 -2.388124e-002 0.000000e+000
48 -2.586069e-007 -2.364331e-002 0.000000e+000
49 -2.457980e-007 -2.292913e-002 0.000000e+000
50 </DataArray>
51
52 <DataArray format="ascii" type="Float32" Name="reactions_forces"
    NumberOfComponents="3">
53 0.000000e+000 0.000000e+000 4.964000e+004
54 0.000000e+000 0.000000e+000 5.275100e-001
55 </DataArray>
56
57 <DataArray format="ascii" type="Float32" Name="reactions_moments"
    NumberOfComponents="3">
58 3.057400e+002 4.933600e+007 0.000000e+000
59 -2.567600e+001 -1.117400e+002 0.000000e+000
60 </DataArray>
61 </PointData>
62
63 <CellData>
64 <DataArray format="ascii" type="Int32" Name="ID_model_parent"
    NumberOfComponents="1">
65 0
66 1
67 </DataArray>
68
69 <DataArray format="ascii" type="Int32" Name="Property" NumberOfComponents
    ="1">
70 0
71 1
72 </DataArray>
73
74 <DataArray format="ascii" type="Float32" Name="strain_beam3D_NVM"
    NumberOfComponents="3">
75 0.000000e+000 2.388000e+000 2.380000e-004
76 0.000000e+000 2.340000e+000 7.140000e-004
77 </DataArray>
78
79 <DataArray format="ascii" type="Float32" Name="strain_beam3D_NVyVz"
    NumberOfComponents="3">

```

```
80     0.000000e+000 0.000000e+000 -2.388000e+000
81     0.000000e+000 0.000000e+000 -2.340000e+000
82 </DataArray>
83
84 <DataArray format="ascii" type="Float32" Name="strain_beam3D_MxMyMz"
      NumberOfComponents="3">
85     1.217000e-008 -2.380000e-004 0.000000e+000
86     1.281000e-008 -7.140000e-004 0.000000e+000
87 </DataArray>
88
89 <DataArray format="ascii" type="Float32" Name="stress_beam3D_1_NVM"
      NumberOfComponents="3">
90     0.000000e+000 4.904800e+004 6.975600e+002
91     0.000000e+000 4.911500e+004 4.905300e+006
92 </DataArray>
93
94 <DataArray format="ascii" type="Float32" Name="stress_beam3D_1_NVyVz"
      NumberOfComponents="3">
95     0.000000e+000 0.000000e+000 -4.904800e+004
96     0.000000e+000 0.000000e+000 -4.911500e+004
97 </DataArray>
98
99 <DataArray format="ascii" type="Float32" Name="stress_beam3D_1_MxMyMz"
      NumberOfComponents="3">
100    1.046000e+002 6.975600e+002 0.000000e+000
101    1.100300e+002 -4.905300e+006 0.000000e+000
102 </DataArray>
103
104 <DataArray format="ascii" type="Float32" Name="stress_beam3D_2_NVM"
      NumberOfComponents="3">
105    0.000000e+000 4.910900e+004 4.907100e+006
106    0.000000e+000 4.917500e+004 9.819800e+006
107 </DataArray>
108
109 <DataArray format="ascii" type="Float32" Name="stress_beam3D_2_NVyVz"
      NumberOfComponents="3">
110    0.000000e+000 0.000000e+000 -4.910900e+004
111    0.000000e+000 0.000000e+000 -4.917500e+004
112 </DataArray>
113
114 <DataArray format="ascii" type="Float32" Name="stress_beam3D_2_MxMyMz"
      NumberOfComponents="3">
115    1.046000e+002 -4.907100e+006 0.000000e+000
116    1.100300e+002 -9.819800e+006 0.000000e+000
117 </DataArray>
118
119 <DataArray format="ascii" type="Float32" Name="strainD_shell_glob"
      NumberOfComponents="9">
120    0.000000e+000 0.000000e+000 -2.281651e-005
121    0.000000e+000 0.000000e+000 5.022161e-005
```

```

122     -2.281651e-005 5.022161e-005 0.000000e+000
123
124     0.000000e+000 0.000000e+000 -1.046652e-004
125     0.000000e+000 0.000000e+000 1.236314e-004
126     -1.046652e-004 1.236314e-004 0.000000e+000
127 </DataArray>
128
129 <DataArray format="ascii" type="Float32" Name="strainR_shell_glob"
      NumberOfComponents="9">
130     2.379346e-006 -6.059405e-006 0.000000e+000
131     -6.059405e-006 8.488327e-003 0.000000e+000
132     0.000000e+000 0.000000e+000 0.000000e+000
133
134     7.141820e-006 -6.748854e-006 0.000000e+000
135     -6.748854e-006 8.454437e-003 0.000000e+000
136     0.000000e+000 0.000000e+000 0.000000e+000
137 </DataArray>
138
139 <DataArray format="ascii" type="Float32" Name="stressD_shell_glob"
      NumberOfComponents="9">
140     0.000000e+000 0.000000e+000 -4.623438e-001
141     0.000000e+000 0.000000e+000 1.724216e-001
142     -4.623438e-001 1.724216e-001 0.000000e+000
143
144     0.000000e+000 0.000000e+000 -6.291504e-001
145     0.000000e+000 0.000000e+000 -8.802849e-002
146     -6.291504e-001 -8.802849e-002 0.000000e+000
147 </DataArray>
148
149 <DataArray format="ascii" type="Float32" Name="stressR_shell_glob"
      NumberOfComponents="9">
150     0.000000e+000 0.000000e+000 0.000000e+000
151     0.000000e+000 0.000000e+000 0.000000e+000
152     0.000000e+000 0.000000e+000 0.000000e+000
153
154     0.000000e+000 0.000000e+000 0.000000e+000
155     0.000000e+000 0.000000e+000 0.000000e+000
156     0.000000e+000 0.000000e+000 0.000000e+000
157 </DataArray>
158
159 <DataArray format="ascii" type="Float32" Name="CSusage_elast"
      NumberOfComponents="1">
160     4.998331e+001
161     1.000237e+002
162 </DataArray>
163
164 <DataArray format="ascii" type="Float32" Name="CSusage_elast_rel"
      NumberOfComponents="1">
165     1.666110e-001
166     3.334122e-001

```

```
167 </DataArray>
168
169 <DataArray format="ascii" type="Int32" Name="CSusage_elast_bool"
      NumberOfComponents="1">
170   0
171   0
172 </DataArray>
173 </CellData>
174
175 </Piece>
176 </UnstructuredGrid>
177 <AppendedData>_
178   <Volume> 7889773.343919 </Volume>
179 </AppendedData>
180
181 </VTKFile>
```





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