

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

Decision-making support for conceptual structural design

by

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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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# Chapter 1

## 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>

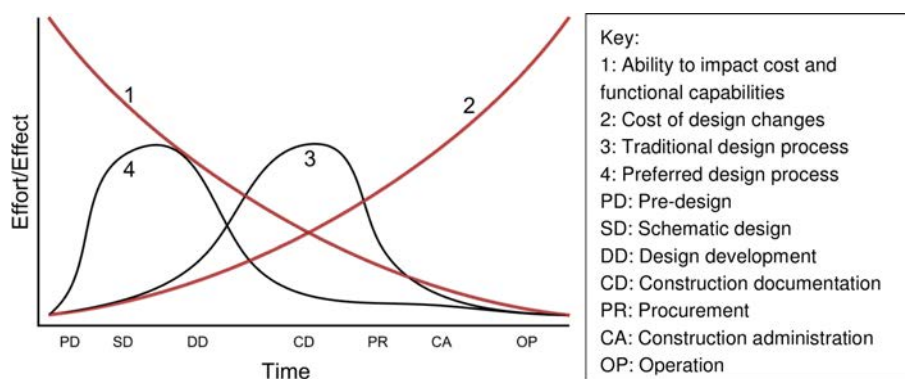


FIGURE 1.1: The MacLeamy Curve. (Ramsden et al., 2015)

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

## 1.1 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.

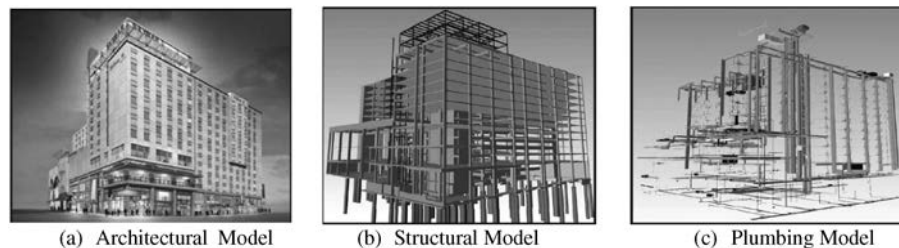


FIGURE 1.2: Building information models of the Aquarium Hilton Garden Inn Project (Courtesy of Holder Construction Company, Atlanta, GA). (Azhar, 2011)

#### 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.

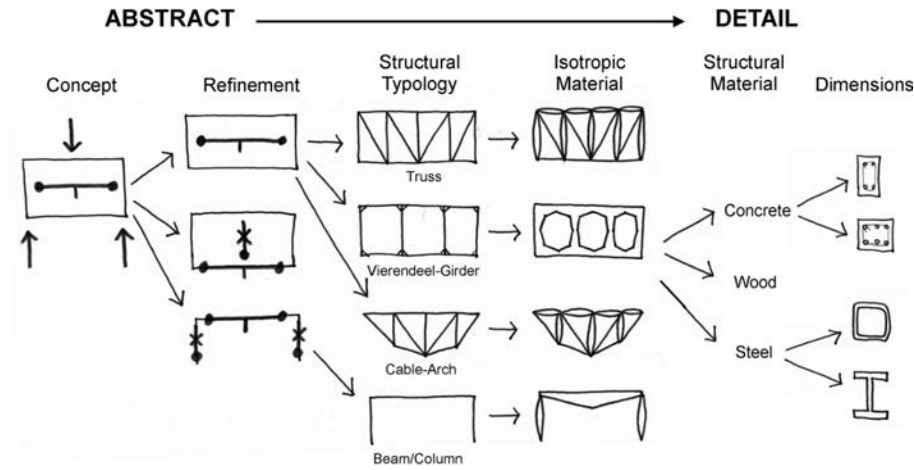


FIGURE 1.3: Application of developed language for concept creation and refinement. (Luyten, 2015)

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

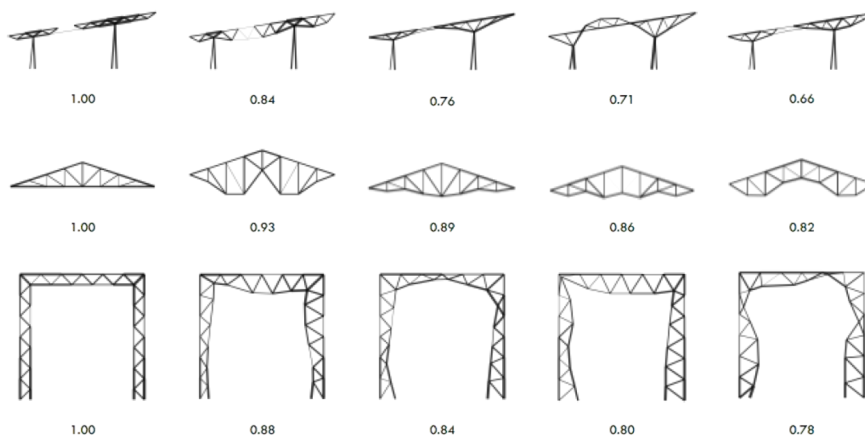


FIGURE 1.4: Example of optimization used by genetic algorithms. (Mueller, 2014b)

<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).

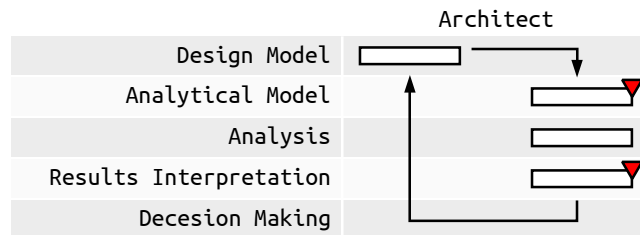


FIGURE 1.5: Problems of direct use of structural analysis by the architect.

## 1.2 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.

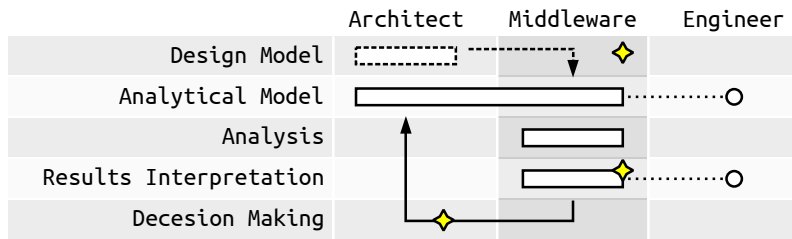


FIGURE 1.6: Proposed solution based on middleware development; yellow stars represents goals of this research, white circles represents engineer’s support by consultation.

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

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.

### 1.3 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 ??). 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 ??. 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 ??.

**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 ??) of Part IV shows a practical application of the middleware at school and in practice.

## Chapter 2

# 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>

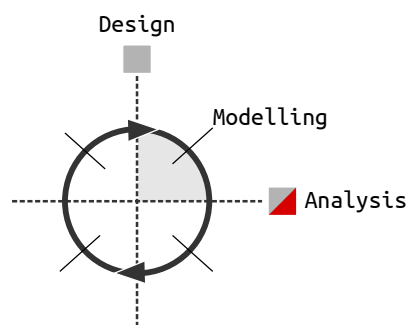


FIGURE 2.1: From design to analysis.

<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.

## 2.1 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).

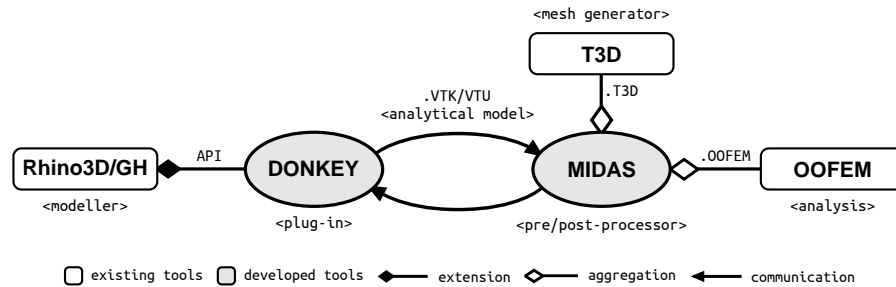


FIGURE 2.2: Middleware, the software architecture graph.

### 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 2.3: 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.

## 2.2 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).

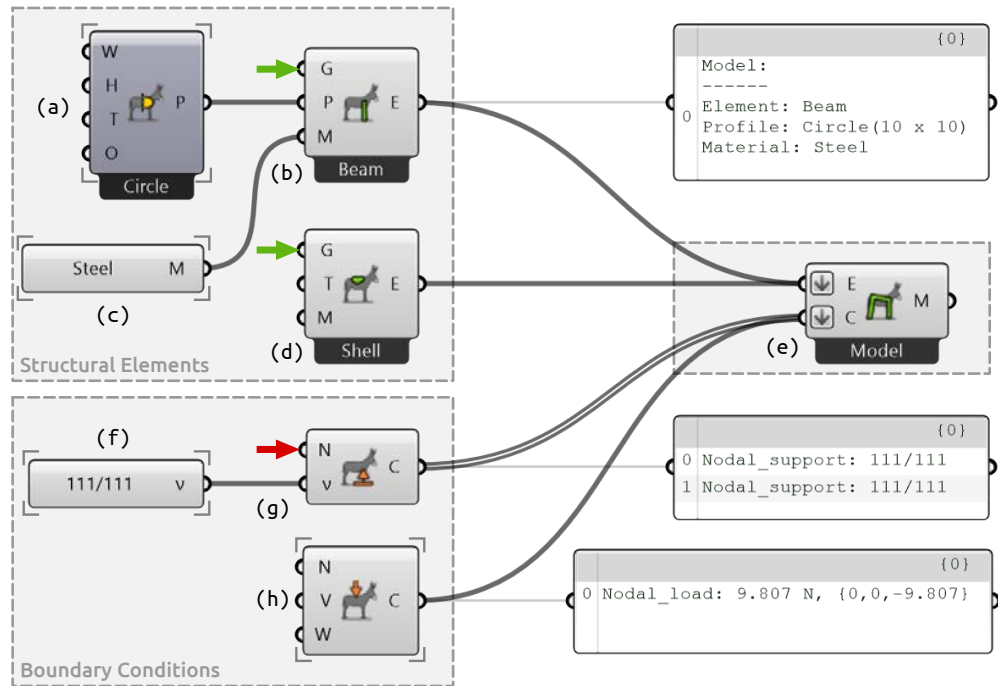


FIGURE 2.4: Analytical model definition using the developed DONKEY components.

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.

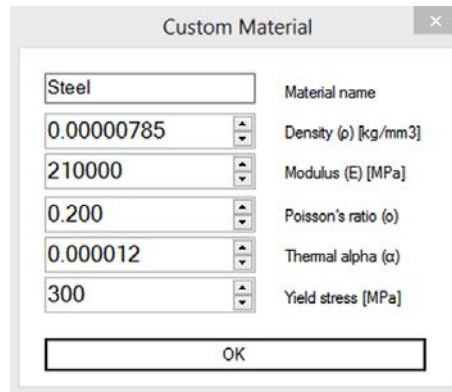


FIGURE 2.5: Custom material implemented in pop-up window.

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).

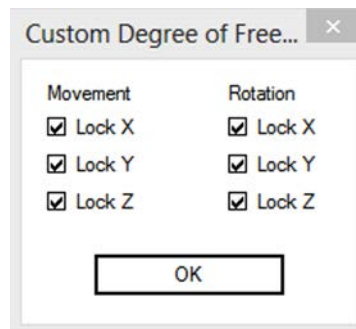


FIGURE 2.6: Custom degree of freedom implemented in pop-up window.

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.

## 2.3 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.

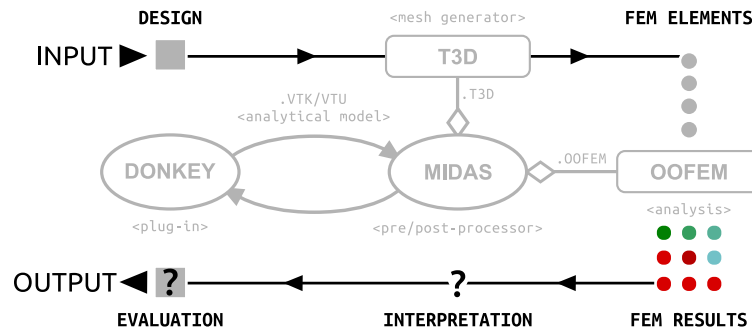


FIGURE 2.7: The profess work-flow;(a) from design to FEM elements  
(b) how to simplify FEM results to support their correct interpretation?

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 3

# 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>*

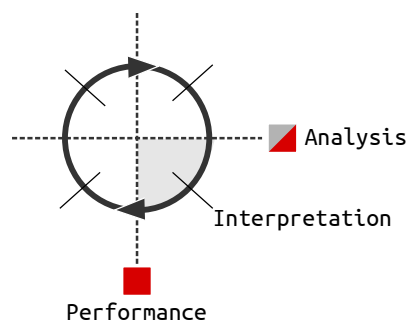


FIGURE 3.1: From analysis to performance.

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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.

### 3.1 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).

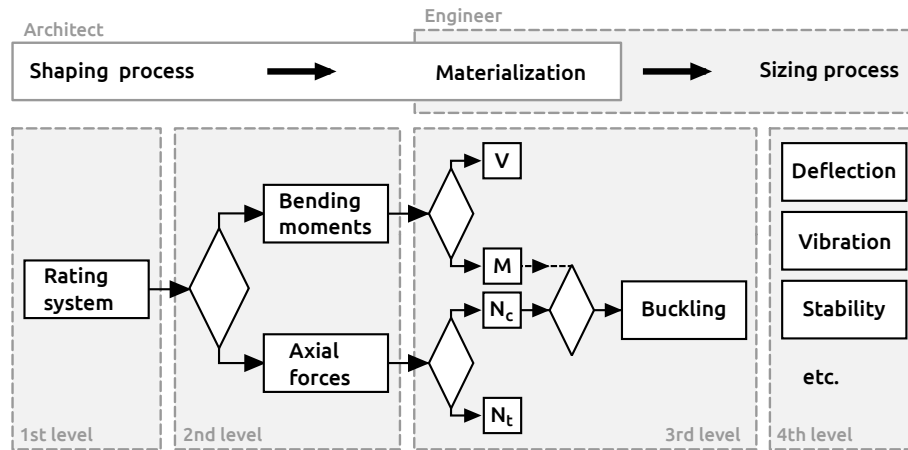


FIGURE 3.2: Levels of FE analysis results simplification based on design stage.

#### 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

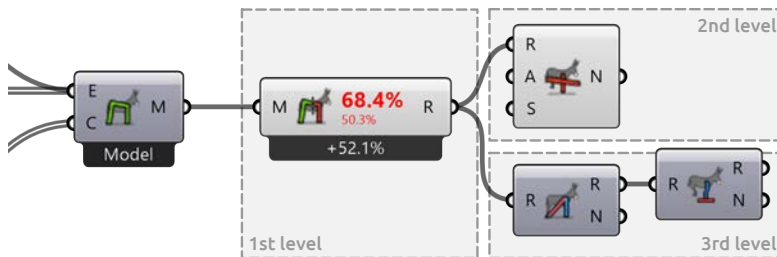


FIGURE 3.3: Levels of FE analysis results implemented in developed plugin.

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.

## 3.2 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).

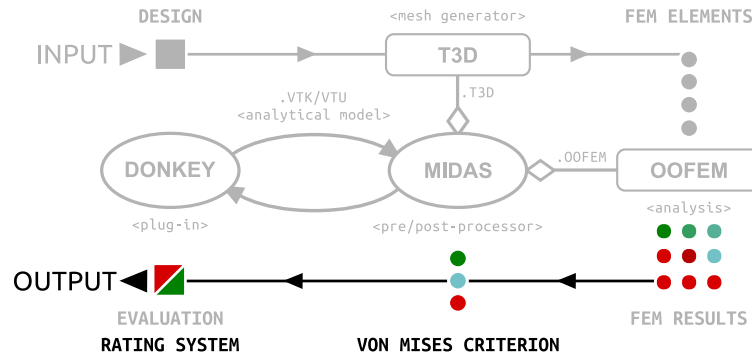


FIGURE 3.4: Proposed data work-flow of analysis feedback (output data).

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

$$\eta = \frac{\sigma_R}{f_y} \quad (3.1)$$

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.

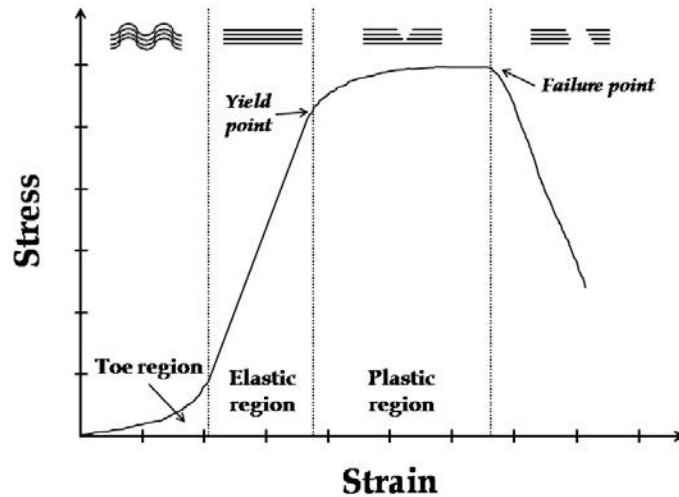


FIGURE 3.5: Typical stress-strain curve for destructive tensile testing of skeletal soft tissues. Collagen fibril straightening and failure, related to different regions of the stress-strain curve, are also schematically shown. (Korhonen and Saarakkala, 2011)

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),

$$\eta_e = \sum_{i=1}^m \frac{1 - \mu_i}{m} \quad (3.2)$$

in which the distance from fully stressed design is calculated as

$$\mu_i = |\eta_i - 1|, \text{ where } \eta_i \leq 2. \quad (3.3)$$

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.

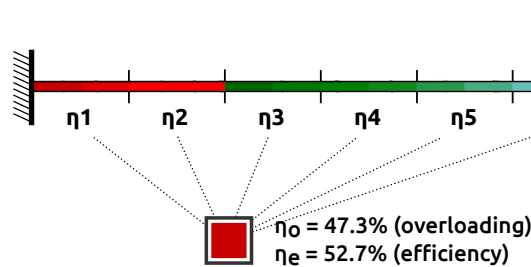


FIGURE 3.6: Evaluation of cantilevered structure use proposed rating system.

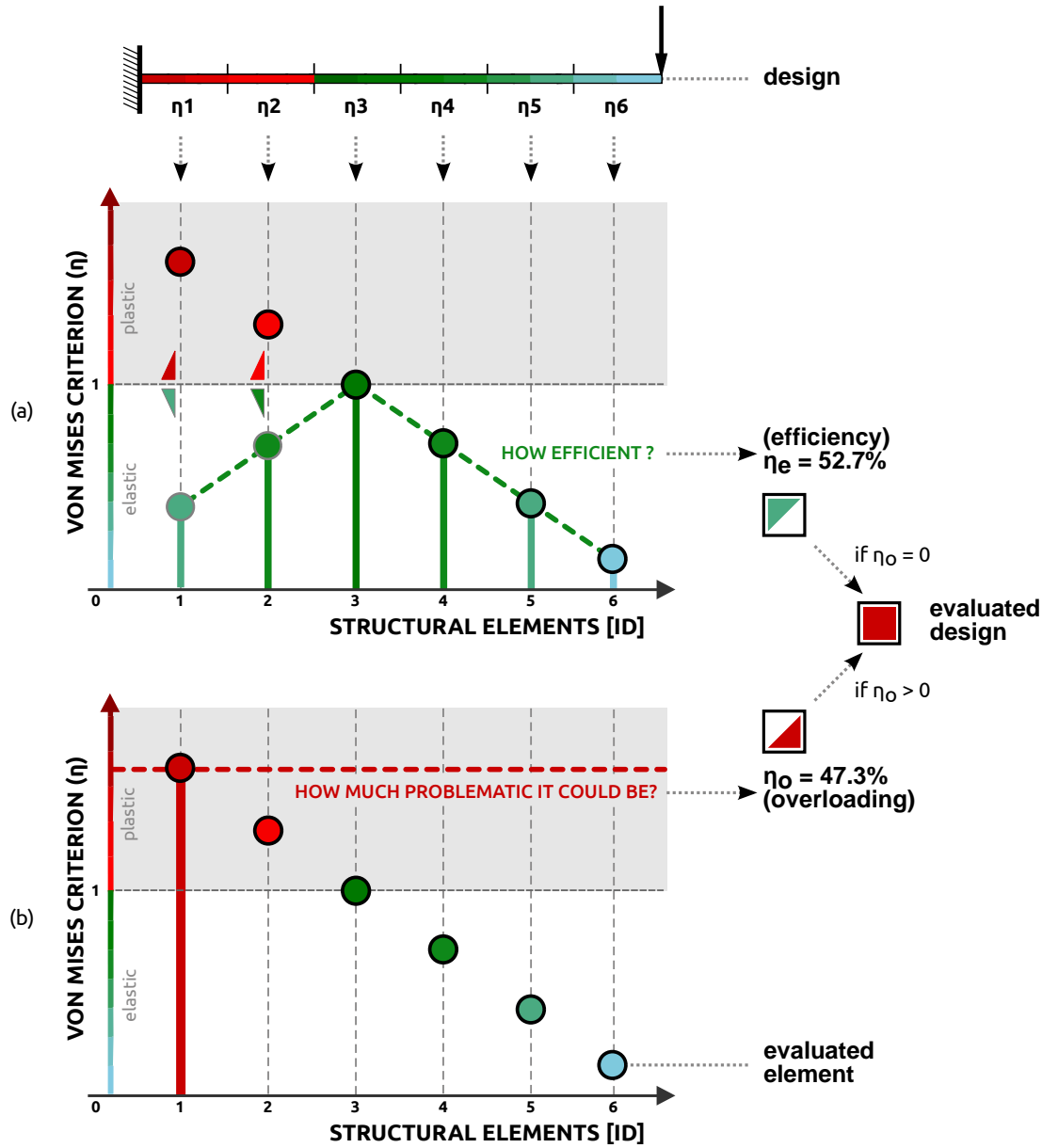


FIGURE 3.7: Rating system methodology: (a) efficiency, (b) overloading value.

## Chapter 4

# 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>*

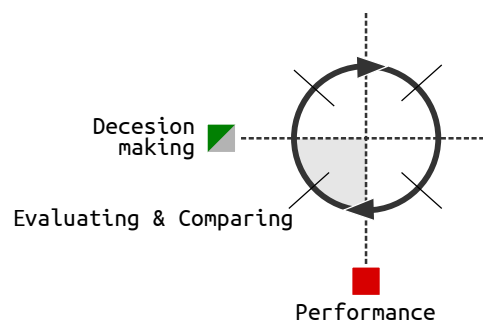


FIGURE 4.1: From performance to decision-making.

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

## 4.1 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)).

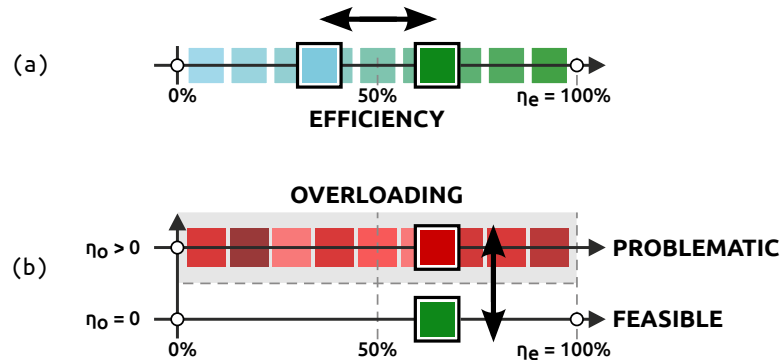


FIGURE 4.2: Design tracker visualization approach; (a) feasible – efficiency row, (b) problematic – overloading row.

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).

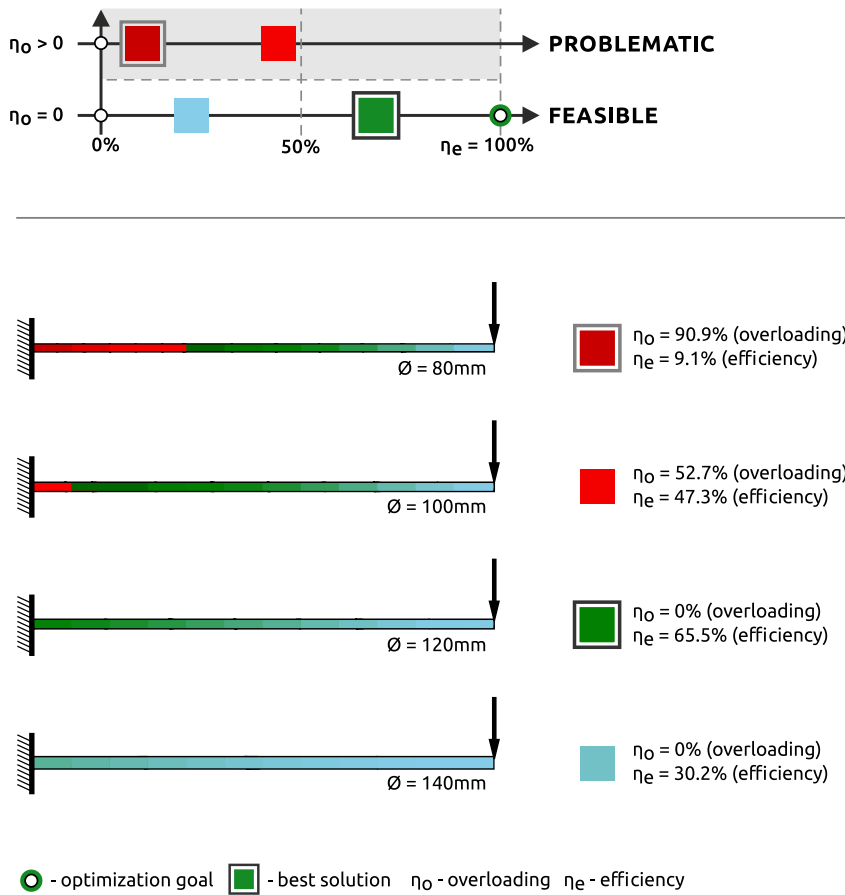
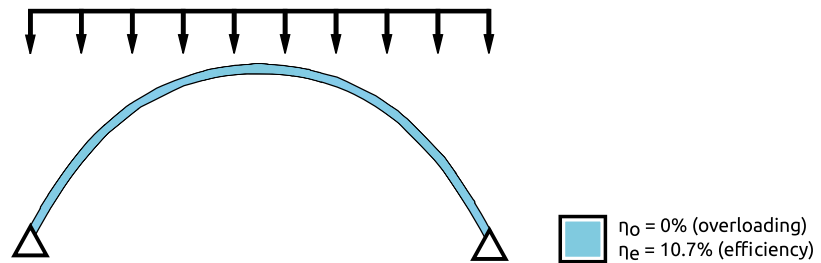
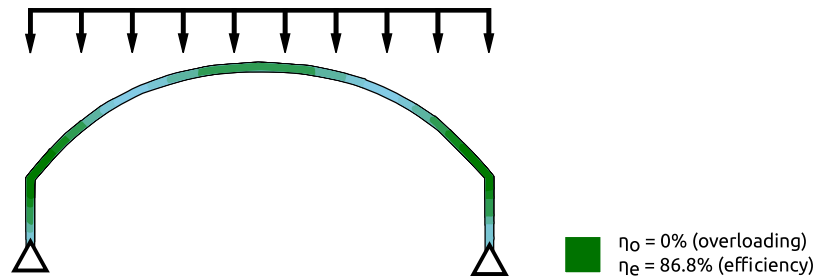
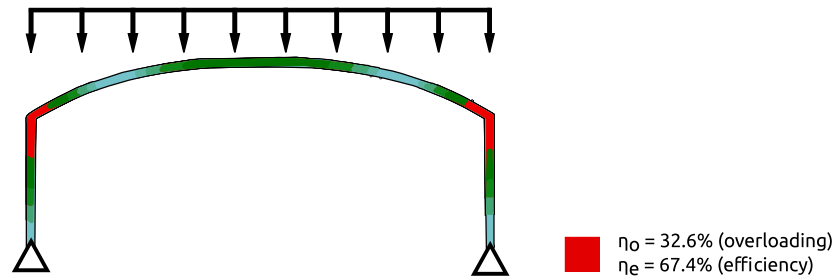
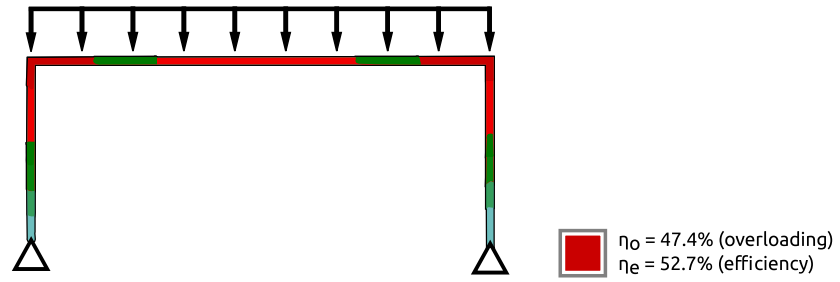
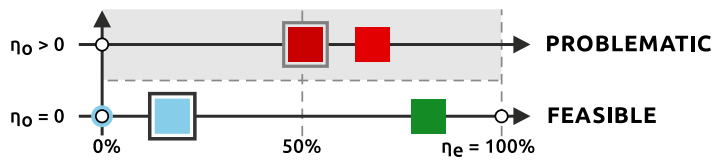


FIGURE 4.3: An example of results visualization for sizing process.

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 ??). 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    η<sub>0</sub> - overloading    η<sub>e</sub> - efficiency

FIGURE 4.4: An example of results visualization for shaping process.

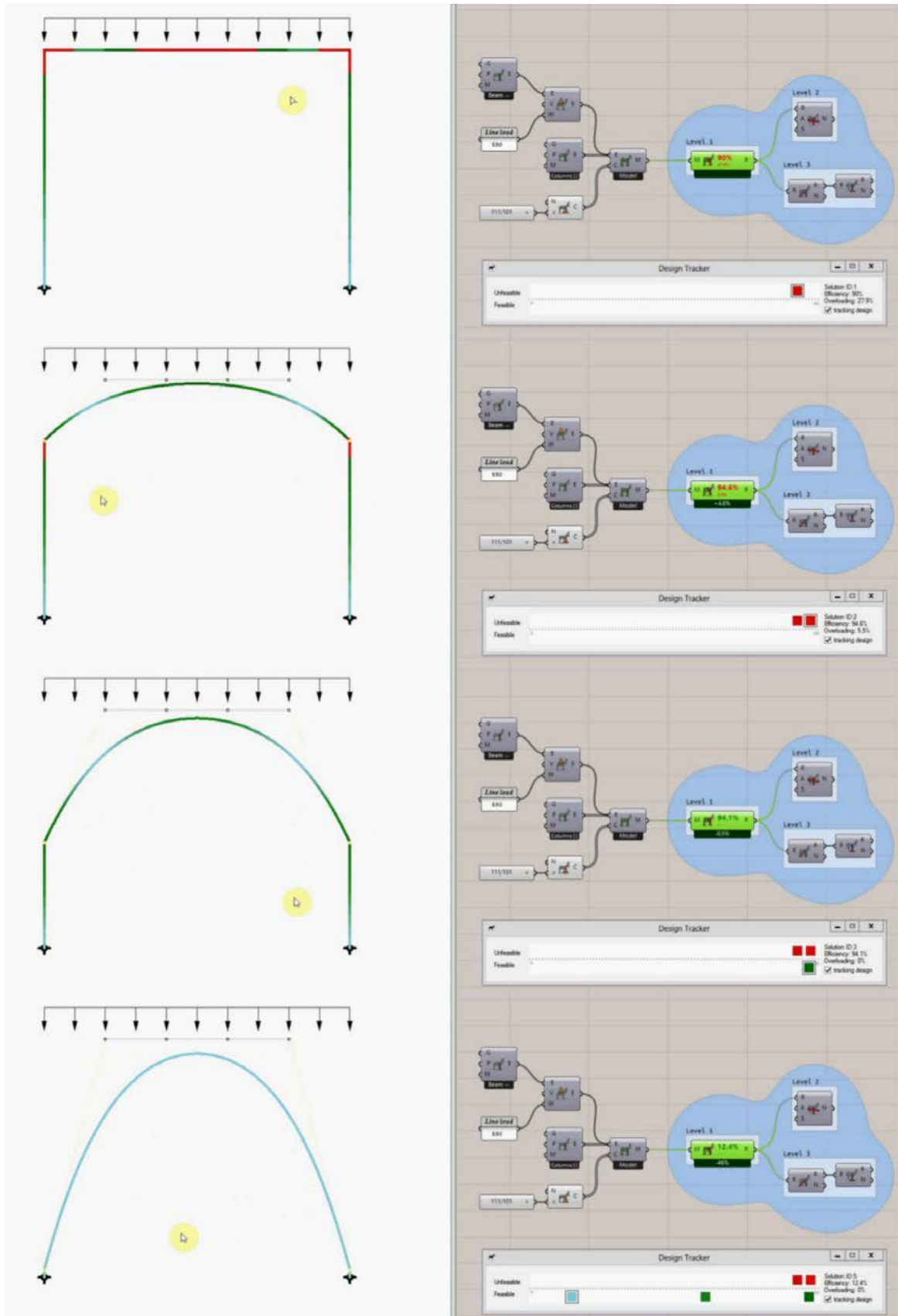


FIGURE 4.5: Real implementation of the shaping process example.  
 (<https://youtu.be/sQNvZ7GSFIQ>)

## 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).

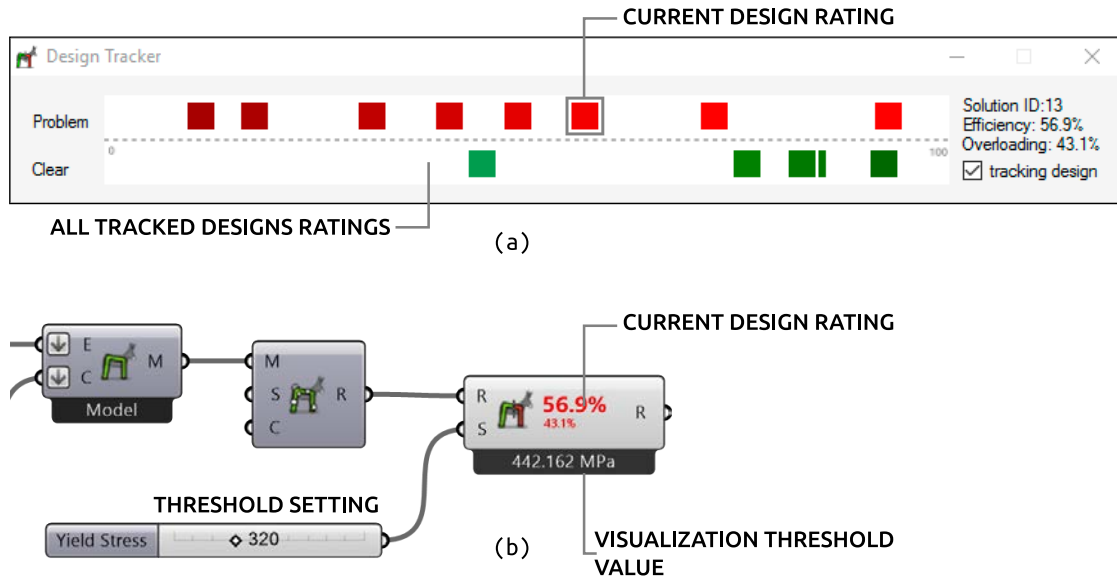


FIGURE 4.6: Design tracker implementation: (a) pop-up window with explored design space, (b) developed Grasshopper components with Rating system visualization.

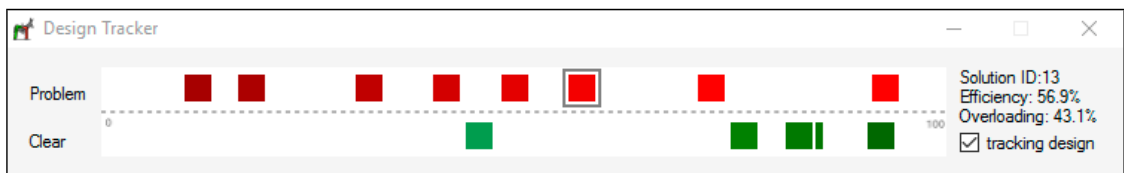
### POP-UP WINDOW

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.

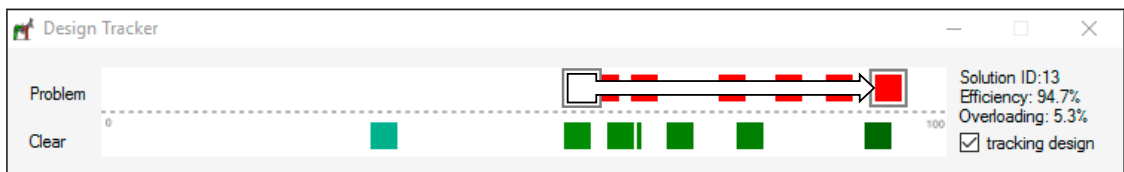
### ADJUSTING VISUALIZATION THRESHOLD

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.

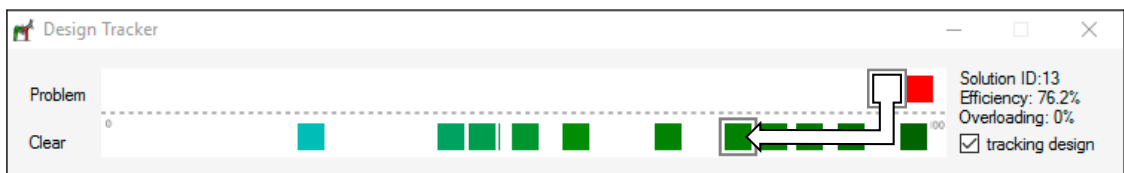




**Yield Stress = 320 MPa**



**Yield Stress = 440 MPa**



**Yield Stress = 570 MPa**

FIGURE 4.7: Organization of design space by changing Yield Stress value.



## Chapter 5

# 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>

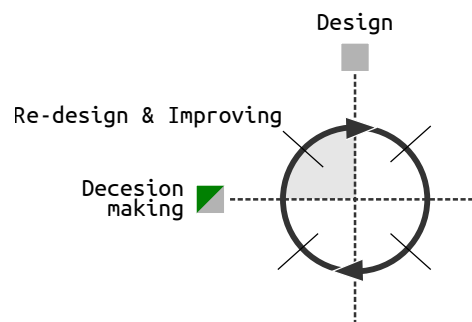


FIGURE 5.1: From decision-making to a change in the design.

<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).

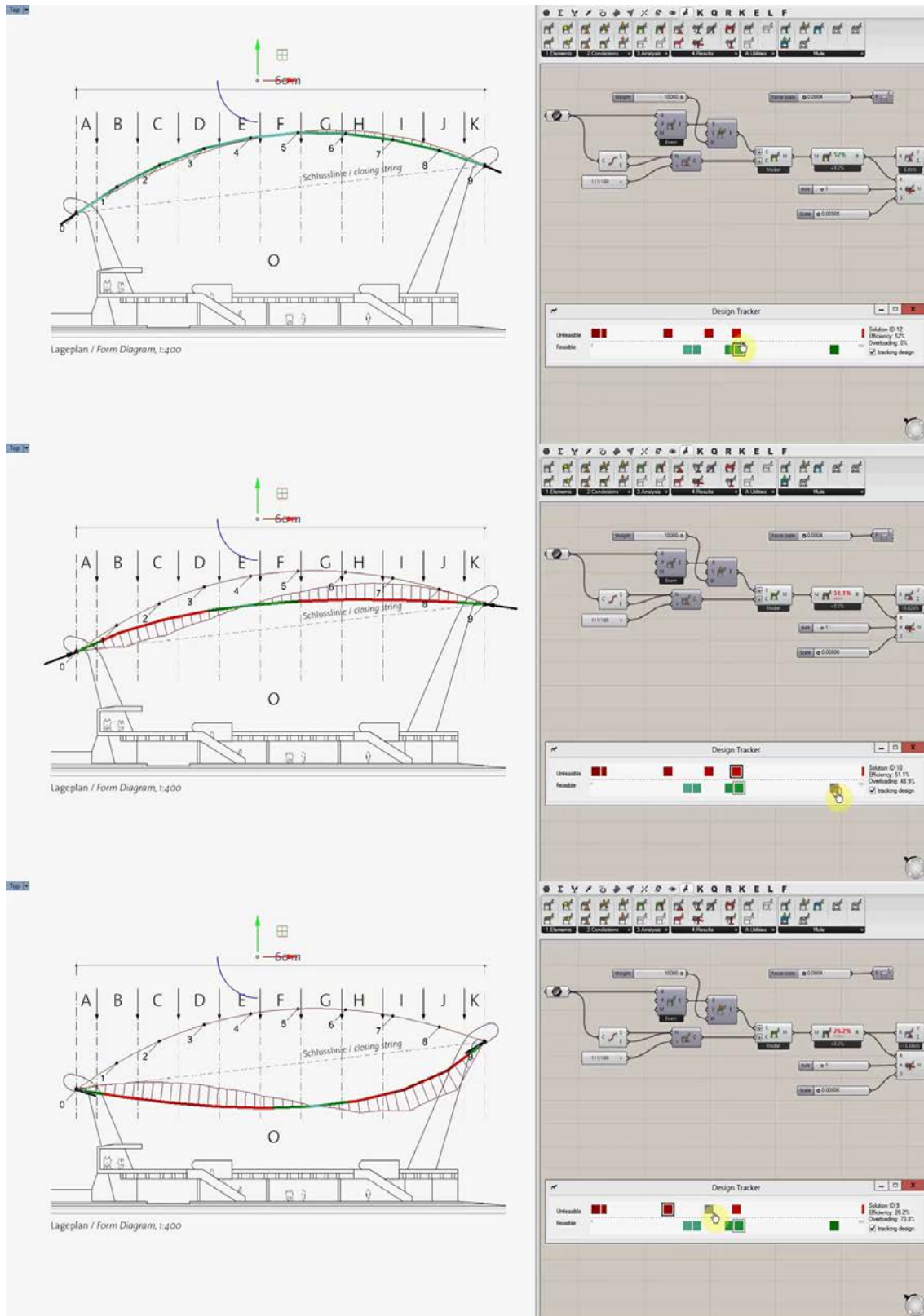


FIGURE 5.2: Post-analytical design space exploration with secondary extended results visualization. (<https://youtu.be/wVk80VyHCOU>)

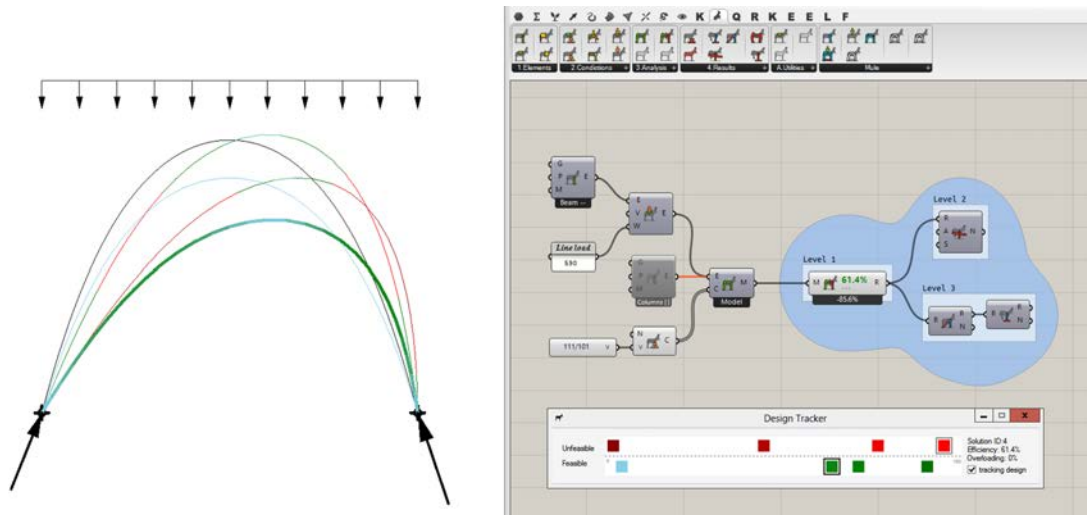


FIGURE 5.3: Visualizing all explored alternatives can guide the user during shaping process. (<https://youtu.be/Vu28QTjP9Sc>)

## 5.1 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

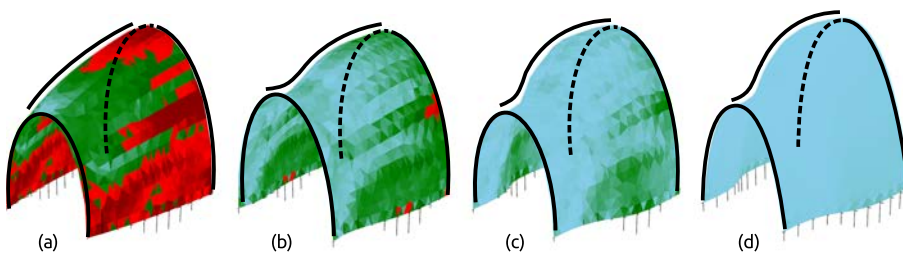


FIGURE 5.4: Finding a better form of shell structure based on shaping controlled curves.

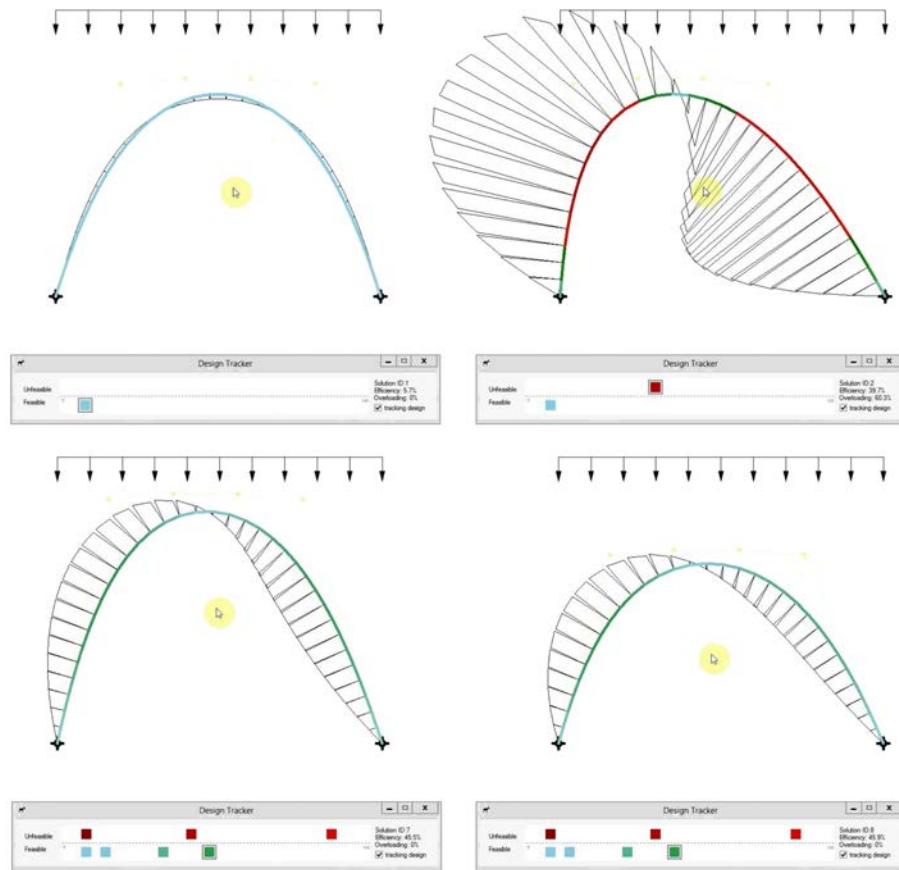


FIGURE 5.5: The second level of result interpretation – moments.

## 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 ??, 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,

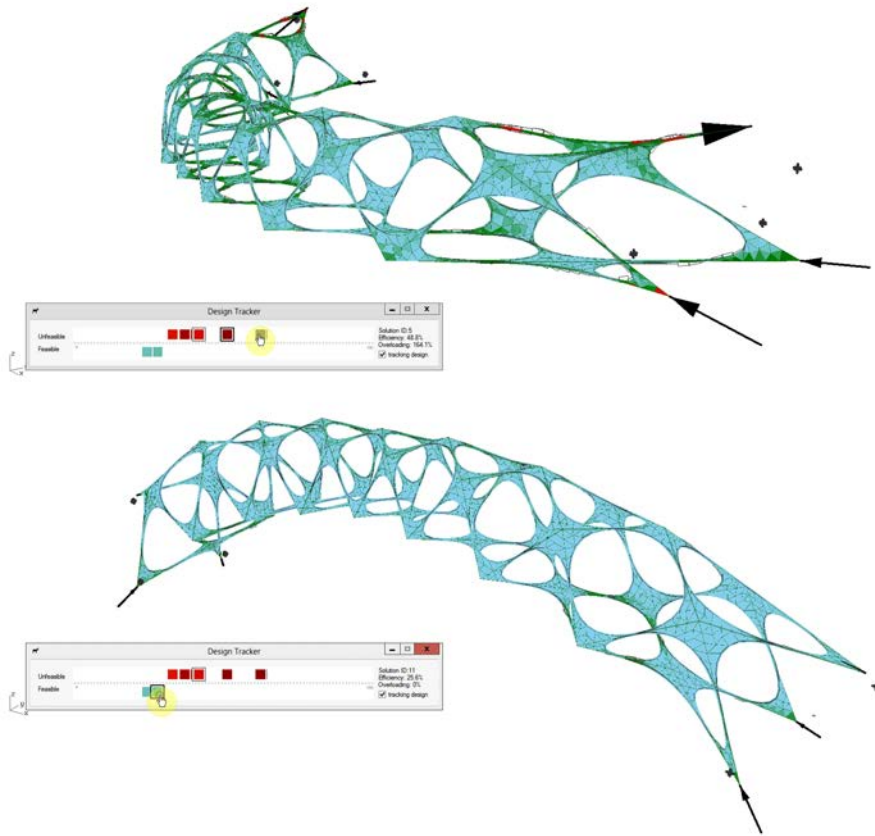


FIGURE 5.6: Rapid post-analytical exploration of design with more complex geometry.

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

## 5.2 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

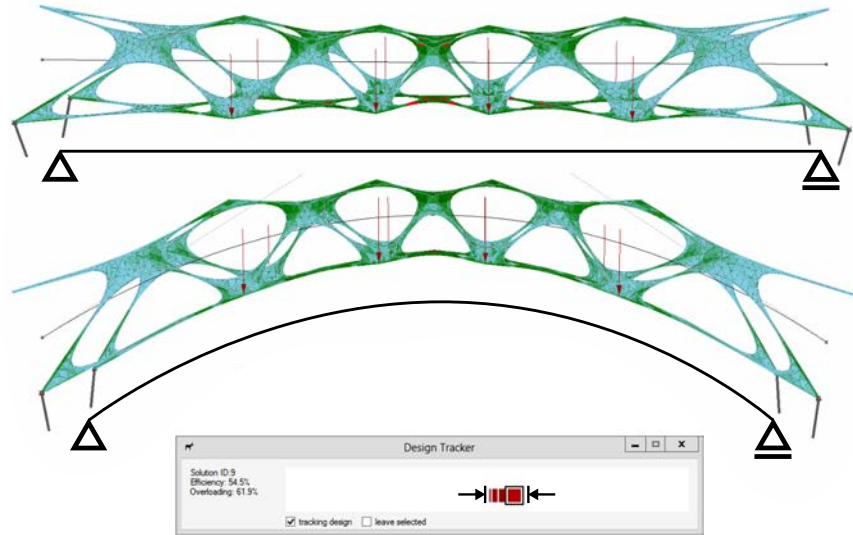


FIGURE 5.7: The effect of shaping: simply supported beam structure.

in the Design tracker can be seen). The structure reacts as the active-section system (see Engel classification Figure ??), 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.

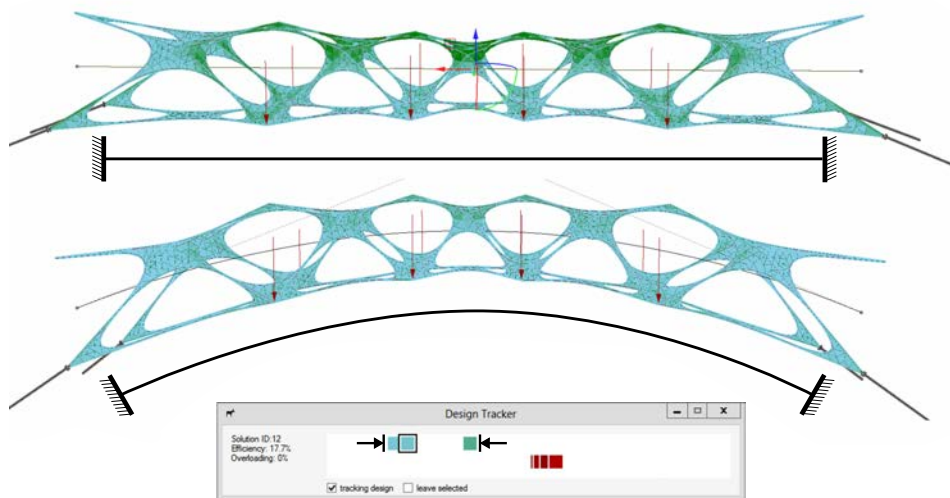


FIGURE 5.8: The effect of shaping: an arch structure.



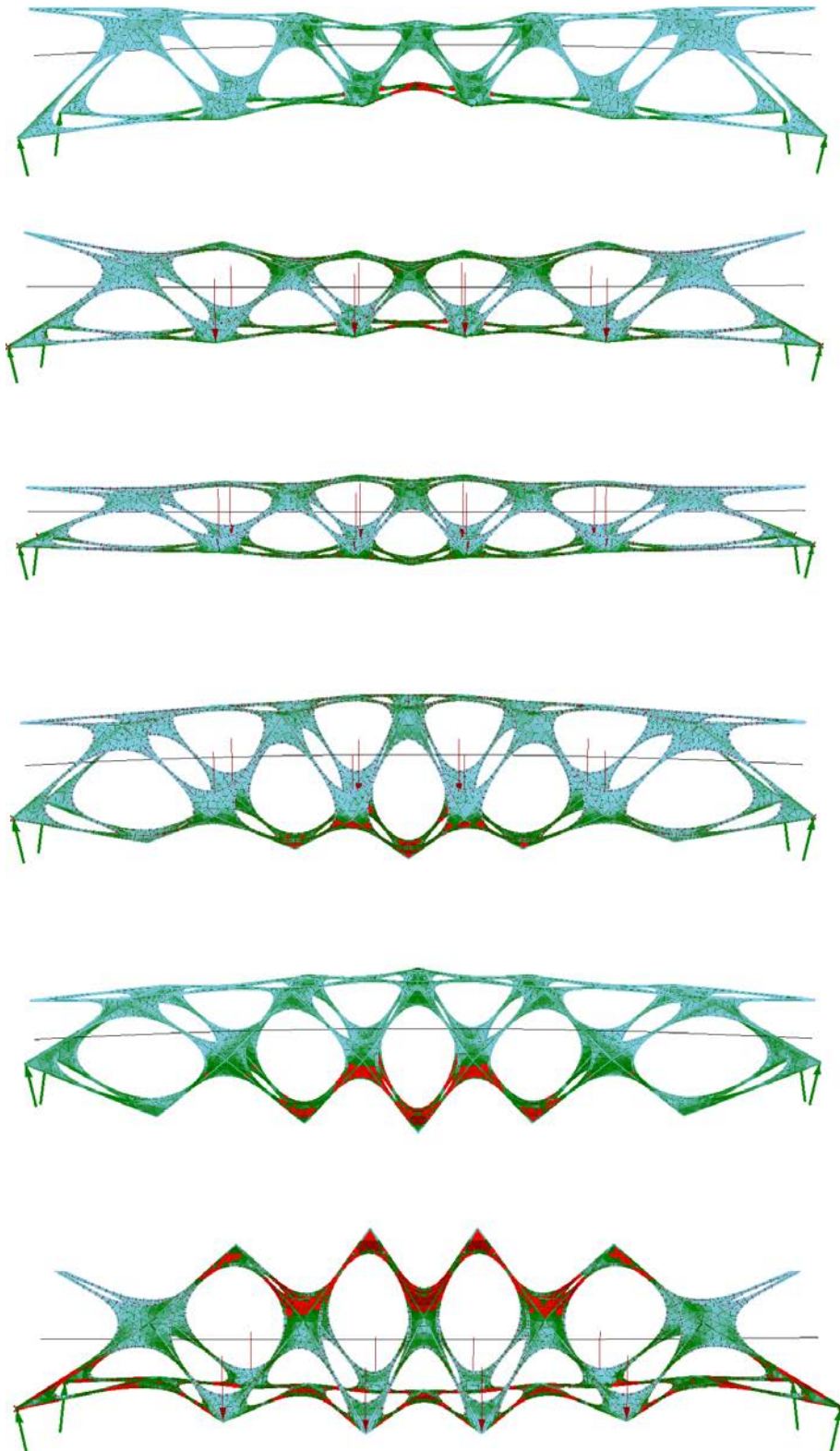


FIGURE 5.9: Examples of different profile distribution generated by exploring design parameters.



## Chapter 6

# 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>

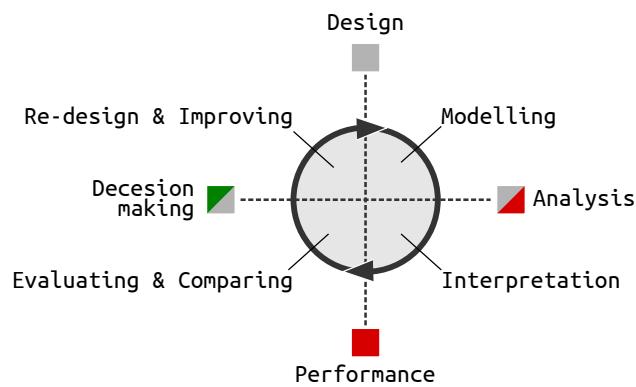


FIGURE 6.1: Stages of proposed design process supported by SEA.

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

## 6.1 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.

## 6.2 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.

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 ??) 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

## 6.3 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

## 6.4 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.

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.

## 6.5 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.