White Paper

Scia Engineer MOOT: Automatic Optimization of Civil Engineering Structures

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Scia Engineer MOOT:
Automatic Optimization of Civil Engineering Structures

Scia Engineer MOOT (Multi Objective Optimization Tool) is an example of a new generation of software for the design of civil engineering structures. It is software which calculates internal forces, checks the compliance to the code, and on top of that, this software is able to "find" the final optimal structural design.

Up to now, the term "structural optimization" is understood mostly as an automatic search for the most economical beam profiles or plate thicknesses. However, the structural design is much more. The criteria defined by modern standards and codes are very complex, they are much more than just fulfilling of bearing capacity of beams or slabs. There are many constraints for dimensions with respect to the serviceability of the structure and its safety and there exist also limitations and constraints coming from the construction process.

To reach really optimal structural design, it is necessary to consider all relevant aspects and demands. These are rather general and complex and, therefore, the software tool supposed to cope with them must be also very general and flexible.

The ongoing development in computing technologies enables that computers can analyse in a reasonable time a huge number of variants and thus search for optimal structure variant or variants and propose them to the designer. Mathematically explained, optimization methods search for local extremes of a prescribed objective function, which describes a certain characteristic of the optimized structure, and quite often it is possible to find more than one local extreme. Those local extremes are always kind of "interesting" variants. In the final step, it is up to the designer of the structure to evaluate them and choose one. Alternatively, if the found solutions do not meet the designers' expectations, they can modify the input data for the optimization and run search for other variants.

Why is a simple code-compliant structure design not enough?
Why to go for an optimized solution?

In recent years we are witnesses of an increased demand for cost reduction, material savings, fast realization and environmental protection, which result in increased competitiveness of companies. All these requirements can now be more easily addressed thanks to the power of current computational technologies.

A good example of the progress in this field is the four year research project done in collaboration between Nemetschek Scia and Faculty of Civil Engineering CTU Prague, Czech Republic. This project is based on the theoretical knowledge of optimization methods at the university, where this research work has been ongoing for many years, and on the practical experience with the Scia Engineer software together with a good knowledge of practical demands of civil engineers. The research project was supported by a grant of the Czech Ministry of Industry.

The outcome of this research is the Scia Engineer MOOT optimization tool whose principles will be explained in this paper.

Scia Engineer MOOT

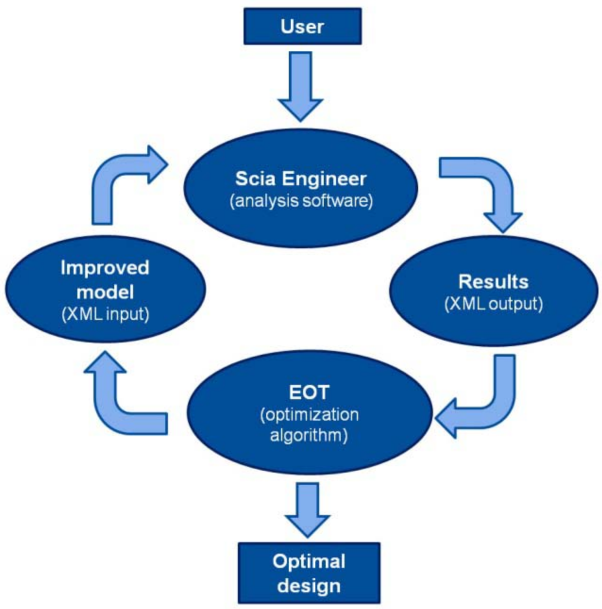
Scia Engineer MOOT is a cutting edge software tool for the overall optimization of civil engineering structures. It represents a combination of a widespread structural analysis software (Scia Engineer) and a separate optimization engine (EOT – Engineering Optimization Tool). The two programs have been integrated together and offer a versatile and complete optimization solution for all types of civil engineering structures.

- **Scia Engineer** is a comprehensive software package for analysis, design and checks of civil engineering structures. The integration of Scia Engineer into the process of the overall optimization is enabled by its above-standard features:
  - **Parameterization of the model**: direct (numerical) values of individual properties of entities in Scia Engineer can be replaced by parameters. The parameters can be viewed and edited directly in Scia Engineer or via an open communication interface.
  - **AutoDesign**: automatic search for an optimal design for a particular structural entity – e.g. an optimal size of a steel cross-section or an optimal reinforcement in a concrete cross-section determined on the base of calculated internal forces.
  - **XML interface** for communication with other applications.
- **EOT** is an optimization solver in which the user defines the objective function for the optimization, determines relations between the parameters and selects the suitable optimization method. The solver finds the optimal solution according to the user's input, trying to finish the task within the minimum possible number of steps.

Optimization workflow

The optimization process can be clearly seen in the picture. Once all the required input data are entered, i.e. the model of the analysed structure is defined, the search for the optimal solution runs fully automatically and no interaction from the user is required. For real-life problems several optimal solutions can be found. In such situations, it is up to the user to make the final decision.

1. **Creation of the model and its parameterization**
   The model of the analysed structure is created using standard Scia Engineer tools and functions. The geometry, boundary conditions, loads, etc. are defined.
   Parameters are assigned to the properties that can vary during the optimization. The parameter indicate that a particular property becomes variable and that the user defines its initial value and, if required, also the limits.
   If suitable or needed, it is possible to specify also relations between individual parameters (e.g. the relation between the width and height of a cross-section).



2. **Definition of the objective function and selection of the optimization method**
   The objective function defines what is to be optimized. It can be a price, weight, dimensions, position of a support, location of a load.
   Furthermore, it is necessary to select one of the available optimization methods. The selection of the method may affect the time needed for the solution of the sought-after result.

3. **Optimization cycle**
   a) The optimization solver (EOT) generates the sets of parameters used for the creation of particular variants of the model.
   b) Scia Engineer receives these parameters, runs the prescribed calculations, code-check and, if required, also AutoDesign.
   c) In the next step, EOT gets back the results and evaluates them to modify the parameters in order to get closer to the desired optimal solution.
   d) And this process is repeated until the optimum is found.

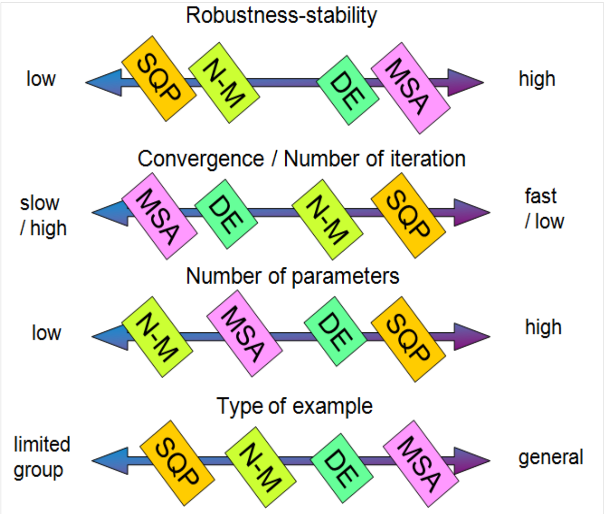
4. **Evaluation of the optimal solution**
   As already stated, the optimization finds one or more optima. It is the user who compares them and takes the final decisions.

EOT Optimization methods

Several different methods have been implemented in the EOT optimization solver:

- **Gradient method: Sequential quadratic programming (SQP)**
  Gradient methods are known as very efficient methods for continuous optimization problems. They are suitable for example when searching for the optimal positions of nodes, supports, or optimal geometry of cross-sections etc. They cannot be used for optimization tasks working with discrete values, such as a selection of rolled profile or for the determination of the number of reinforcement bars etc. Gradient methods can be very fast, but on the other hand convergence problems may occur in projects with a large number of parameters and in tasks with a complicated shape of gradients.

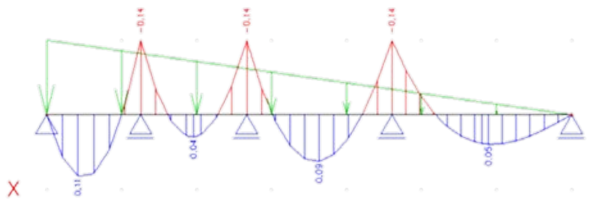
- **Stochastic methods: Modified simulated annealing (MSA), Differential evolution (DE)**
  Simply said, stochastic methods search for the result by means of "trial-and-error" and evaluation of these "trials". This group contains methods that are also called genetic algorithms. Stochastic methods are the most stable, but on the other hand, the required calculation time is much higher compared to the gradient method.



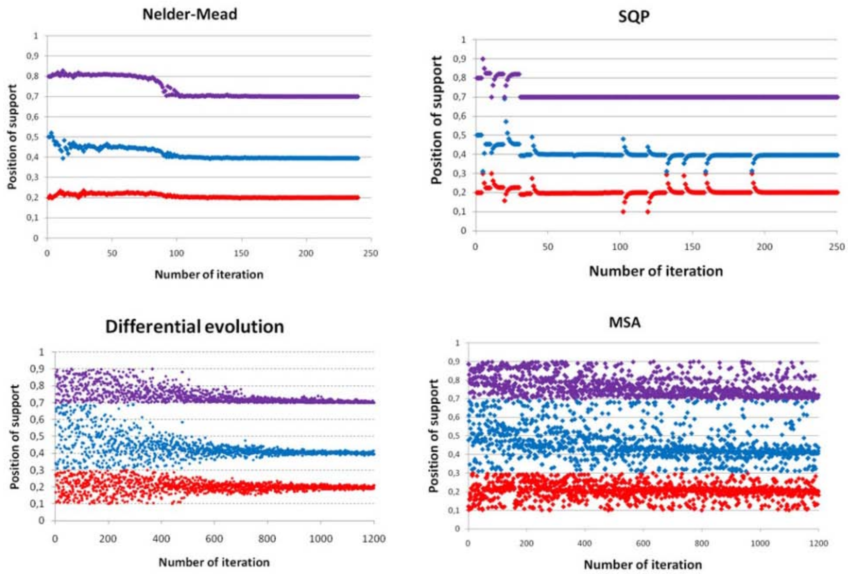
- **Heuristic methods: Nelder-Mead (N-M)**
  Heuristic methods share the properties of both gradient and stochastic methods. Their speed, as well as the stability, is somewhere in between stochastic and gradient methods as well as the stability.

The difference between individual methods is illustrated on the following example. The optimization task is to find such positions of three intermediate supports of the continuous beam that produces minimum bending moments (both hogging and sagging). The pictures show the "progress" of individual methods from the starting (user-defined) state to the final computed state. Each colour in the diagrams corresponds to one of the intermediate supports. It is clearly seen that each method has its "own way" how to find the solution. In this particular example the SQP method proved to be the fastest one, nevertheless, there is no general rule that would always say in advance which method is the best for which type of optimisation task.

Initial positions of the supports



Optimized positions of the supports



Progress of individual methods
(horizontal axis=number of optimization steps, vertical axis=relative position of the supports

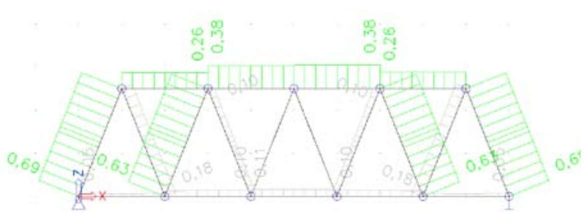
Practical examples

The optimization methods implemented in Scia Engineer MOOT have been successfully used for several types of projects.

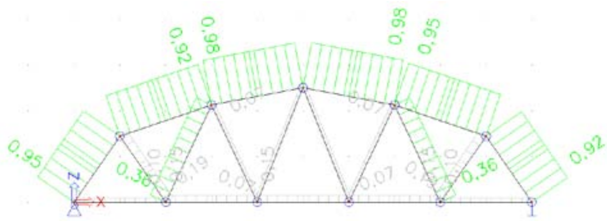
Shape optimization of steel truss girder

The objective of this example was to find the optimal geometrical shape of the girder itself and of individual profiles in order to reach the minimum total mass of the whole structure.

The structure is a symmetrical simply supported truss girder made of RHS profiles subjected to point loads acting in the nodes of the bottom chord. Independent variables were the positions of the nodes and cross-sections of the members.



Unity check for the original shape

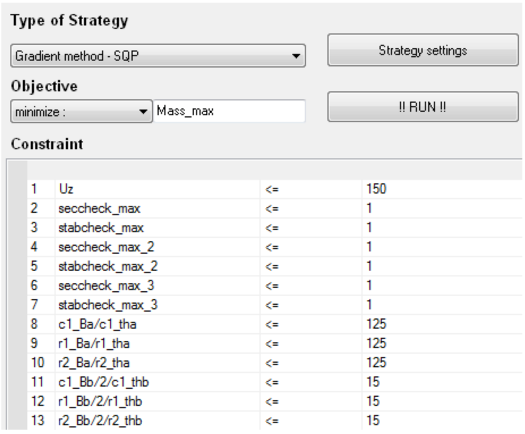


Unity check for the optimized shape

The original weight of the structure was 524kg and optimized was only 335kg. It means savings of the material of about 36%.

The best optimization method for this case seemed to be the Nelder-Mead method which reached the solution after 230 iterations.

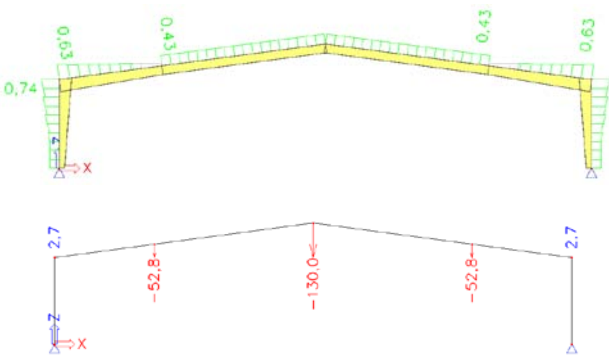
Minimum weight of steel frame hall



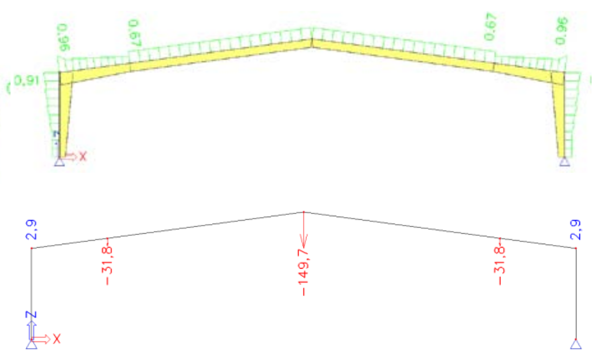
Optimization criteria

A typical steel hall frame of 30m span consists of two columns and two rafters. I-shaped cross sections are welded, made of steel S355. Its depth is variable along the elevation of the columns and rafters are with haunches. The objective was to reach the minimal mass of the structure through the optimization of the column variable cross-sections and haunches on rafters.

The Sequential quadratic programming method reached the optimum after 360 iterations. Mass of the original structure was 2115kg, the optimized one was about 1713kg.



Global check and deformation for original shape



Values for optimized shape

Price optimization of continuous reinforced concrete beam

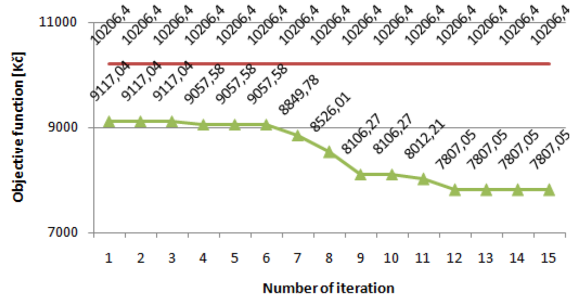
The objective of this optimisation project was to get the minimum total price of a two-span reinforced concrete beam. The beam is subjected to permanent and variable line loads. The rectangular cross-section (C25/30) is reinforced by longitudinal bars and stirrups. Independent parameters were the dimensions of the cross-section, number and diameters of longitudinal reinforcement bars and the diameter and the distance of stirrups.

The total time of the whole optimization procedure was about 4 hours 30 minutes and 1150 iterations were run. The final reinforcement pattern is shown in the following table.

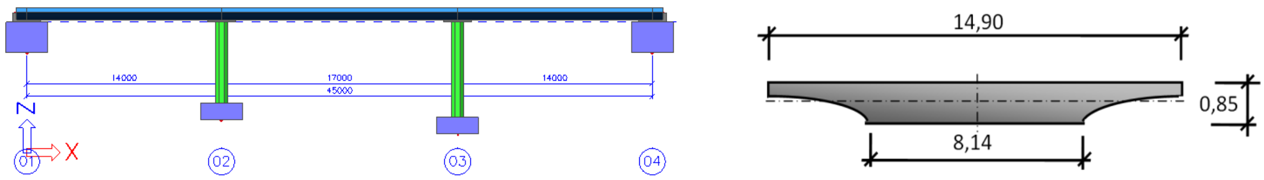
The optimization found the dimensions and reinforcement of the beam. In the picture the gradual decrease of the objective function can be followed. The reduction of the total price reached was about 11%.

	Original	Optimized 1	Optimized 2
Span	2ØR20, 2ØR20, H=0,5m, B=0,3m	2ØR16, 2ØR12, H=0,52m, B=0,25	2ØR14, 2ØR16, H=0,38m, B=0,35
Middle support	2ØR20, 2ØR20, H=0,5m, B=0,3m	3ØR16, 2ØR12, H=0,52m, B=0,25	4ØR14, 2ØR16, H=0,38m, B=0,35

Table 1. Comparison of reinforcement patterns

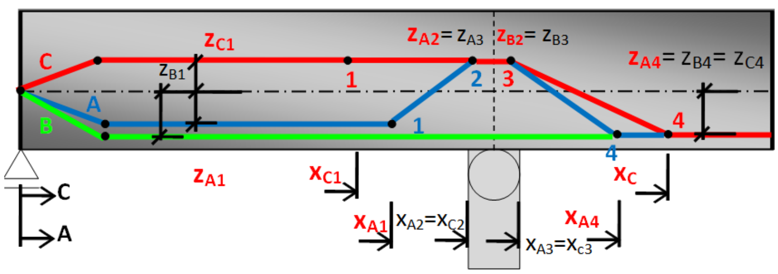


Optimization of tendons geometry of post-tensioned concrete bridge



Bridge spans and cross-section

Concrete bridge is 46.54m long, has three spans (14.0+17.0+14.0) and two edge crossbeams. Construction stages are taken into account with time effects (creep and shrinkage of concrete). Pre-stressing is introduced by means of 10 tendons of Ls15.5-1860 material. Three different tendon shapes are used (see the picture). The objective is to optimize the shape of the tendons with the aim to minimize the total area of cross-sections of tendons.



Geometry of tendons (symmetrical half of bridge)

Concrete bridges have to satisfy many kinds of design checks (ULS, SLS, details etc.). But not all of them must be necessarily included in the optimization in order to prevent too time-consuming calculations. Therefore, only the check of allowable concrete stresses has been introduced as a constraint in the optimization. The method of modified simulated annealing has been used. This algorithm found several optima. These optima were manually analyzed and only some of them satisfied all of the checks required by the code (i.e. the checks that were not included in the optimization).

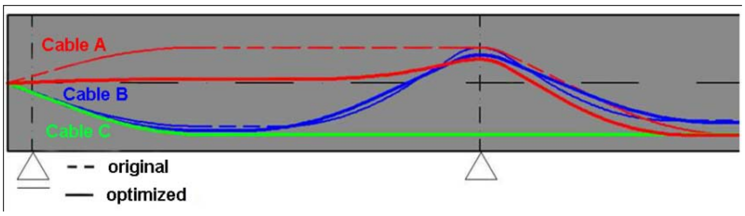
	Initial state	Sol.2	Sol. 6	Sol. 7
$A_{p,req}[mm^2]$	27300	23100	25200	27100
Save [%]	-	15.4	7.7	4.4
Number of iterations [-]	770			
Total time of optimization	11h 56min 40s (55.8s per iteration)			

Table 2: Comparison of accepted solutions

The comparison of the accepted optima is illustrated in table 2. Savings in pre-stressing steel are about 15% in the solution number 2.

The optimized layout of tendons is the following:

- 6 pcs of 17-strand tendon with geometry A
- 2 pcs of 9-strand tendon with geometry B
- 2 pcs of 17-strand tendon with geometry C



Comparison of tendon geometry (solution 2)