ADVANCES IN AUTOMATIC OPTIMIZATION OF CIVIL STRUCTURES

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ABSTRACT

Increasingly, owners are demanding structures that are more cost-effective, that can be designed in less time, and have less impact on our environment. These requirements can be more easily addressed thanks to emerging computational technologies that allow engineers to easily define problems, and efficiently run and compare hundreds, or even thousands of calculations to derive an optimal design that best meets the exact user criteria.

This paper introduces the concept of automatic optimization of civil structures, and the pros and cons of various optimization methods. It describes how computers are being used to blend these various methods and help engineers leverage the power of the computer to derive optimal solutions to practical and complex design problems. Real-world applications of these optimization methods are provided, and the benefits documented.

Keywords: Computer Technology, Parametric Optimization, Structural Design

INTRODUCTION

Up to now, the term “structural optimization” is mostly understood to be an automatic search for the most economical beam profile or plate thickness. However, structural design is much more. The criteria defined by modern standards and codes are very complex, they are much more than just fulfilling the bearing capacity of beams and slabs. There are many inputs and constraints to consider in combination with engineering analysis/design. Such considerations include dimensions with respect to the serviceability of the structure and its safety, as well as practical limitations coming from manufacturing and construction.

On-going developments in computing technology now allows engineers to leverage the computational power of the computer to analyse, in a reasonable time, huge numbers of structure variants. These technologies allow engineers to setup design problems and have the computer automatically search for an optimal structure variant (or, variants), which can be proposed to the designer.

These problems can be setup to consider all relevant aspects of the design including engineering, manufacturing, construction and costs.

Mathematically explained, optimization methods search for local extremes of a prescribed objective function, which describes a certain characteristic of the optimized structure. Quite often it is possible to find more than one local extreme. These extremes are, “interesting” variants that the engineer can use to help guide a solution. In the final step, it is up to the designer of the structure to evaluate the variants and choose a design solution. Alternatively, if the found variants do not meet the designers' expectations, they can modify the input data for the optimization and re-run the search.

WHY IS A SIMPLE CODE-COMPLIANT STRUCTURE DESIGN NOT ENOUGH?

In recent years the industry has seen an increased demand for cost reduction, material savings, compressed design/construction schedules, and environmental protection. The result is increased competitiveness, and companies being asked to do more with the same, or sometimes fewer resources. Investing in new technology is one way firms are addressing these issues.

A good example of how firms are leveraging technology to increase productivity, offer new services, and stand out from the competition, is the four year research project done in collaboration between Nemetschek Scia and the 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 on-going for many years. The research project was supported by a grant of the Czech Ministry of Industry. The outcome of this research is the Engineering Optimization Tool (EOT), whose principals are explained in this paper,

THE TWO TECHNOLOGIES NEEDED FOR OPTIMIZATION

The Engineering Optimization Tool (EOT) is not a software program, but a solver. As such it requires a front end structural design program for modelling, analysis and code checking. The front end structural design program used in this research is Scia Engineer, a commercial analysis and design software developed by Nemetsek AG, but a number of software programs could be used.

1. **Commercial Structural Analysis and Design Software**
   Commercial Structural Analysis and Design software is required for modelling, analysis, and checks of the structural model. The Structural Design Software is required to:

   - Build and parameterize the model

   - To automatically search for an optimal design for a particular structural entity, e.g. the optimal size of a steel cross-section, or an optimal reinforcement scheme in a concrete cross-section. These are based on the calculated internal forces,

   - Provide support for multi-material design and multiple international building codes.

   - Provide an XML interface for communication with EOT.

2. **Engineering Optimization Tool (EOT)**
   The EOT is a solver. It takes the inputs from the Structural Design and Analysis software. Here the engineer defines the objective function for the optimization, determines relations between the parameters, and selects the suitable optimization method. The EOT solver finds the optimal solution according to the engineer's input, trying to finish the task within the minimum number of steps.

THE OPTIMIZATION WORKFLOW

The optimization process can be clearly seen in Fig.1. Once the required input data is entered by the user, the optimization search runs automatically--no interaction from the user is required. In many problems several optimal solutions may be found. In such situations, it is up to the user to make the final decision as to which solutions best meets the design problem.

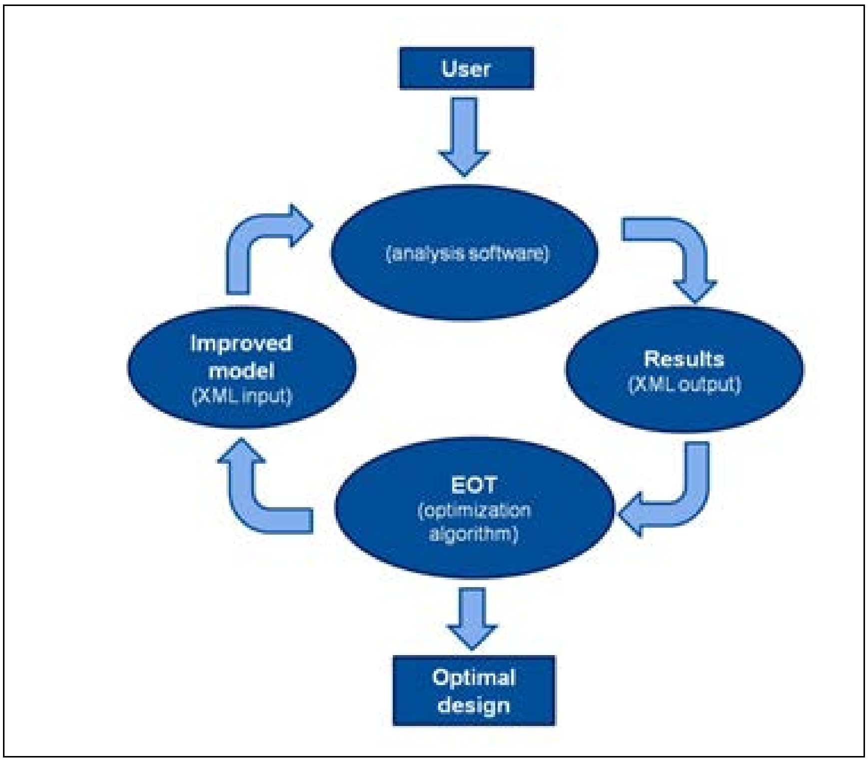

Fig. 1 Optimization Workflow

The following steps describe the process:

1. **Creation And Parameterization Of The Model**
   A model of the structure is created. The geometry, boundary conditions, loads, etc. are defined. Parameters are assigned to the properties that can vary during the optimization. Parameters indicate that a particular property becomes variable. Users can define its initial value and, if required, its limits. If needed, it is possible to specify 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. Examples of objective functions include things like 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 will affect the time needed to derive a solution.

3. **Optimization Cycle**
   a) The EOT generates sets of parameters used for the creation of particular variants of the model.
   b) The analysis software receives these parameters, runs the prescribed calculations and code-checks, and in some cases returns an ideal member size.
   c) In the next step the EOT gets back the results and evaluates them to modify the parameters in order to get closer to the desired optimal solution.
   d) This process is repeated until the optimum is found.

4. Evaluation Of The Optimal Solution

As already stated, if the optimization finds more than one optima. It is the user who compares them, and makes the final decision.

EOT OPTIMIZATION METHODS

Several different methods have been implemented in the EOT solver:

Gradient Methods: Sequential Quadratic Programming (SQP)

Gradient optimization methods are known to be very efficient methods for continuous optimization problems. They are suitable for solving problems like searching for the optimal positions of nodes, supports, or the optimal geometry of cross-sections. They cannot be used for optimization tasks working with discrete values, such as a selection of rolled profiles, or for the determination of the number of reinforcement bars. 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 complicated shapes.

Stochastic Methods: Modified Simulated Annealing (MSA) and Differential Evolution (DE)

Simply said, Stochastic methods search for the result by means of, "trial-and-error". This group contains methods that are also called genetic algorithms. Stochastic methods are the most stable, but on the other hand, the required calculation times can be much higher compared to the Gradient methods.

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.

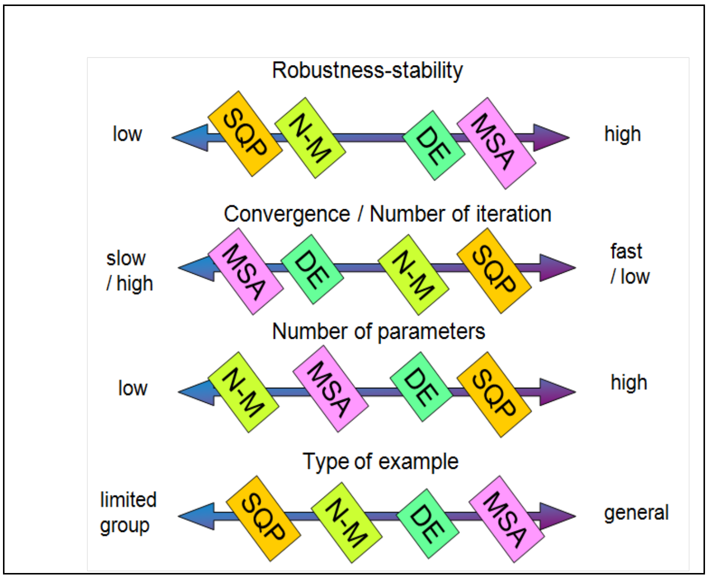

Fig. 2 Summaries of the Individual Methods

The differences between individual methods are illustrated in Fig 2.

PRACTICAL EXAMPLES

The optimization methods implemented in this paper have been successfully used for several types of projects.

Optimal Position Of Supports For A Continuous Beam

The optimization task in this example was to find the ideal positions of three intermediate supports for a continuous beam that produces minimum bending moments (both hogging and sagging). The fastest results were achieved by using the Sequential Quadratic Programming (SQP) method.

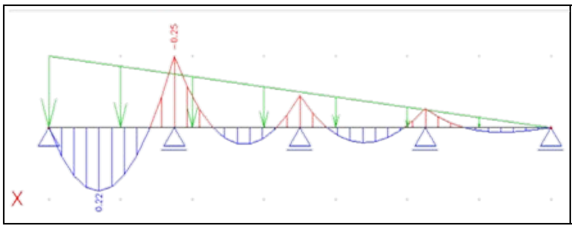

Fig 3a Initial Positions of the Supports

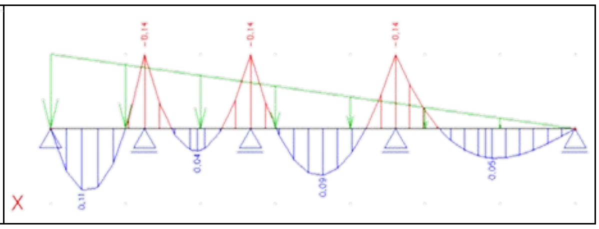

Fig 3b Optimized Positions of the Supports

Shape Optimization Of A Truss Girder

The objective of this example was to find the optimal geometrical shape of the girder as well as the shape of each individual profile, in order to minimize the total mass of the entire structure. The structure is a symmetrical simply supported truss girder made of steel Rectangular Hollow Section (RHS) profiles. The truss was subjected to point loads acting in the nodes of the bottom chord. Independent variables, in this project were the positions of the nodes and cross-sections of the members

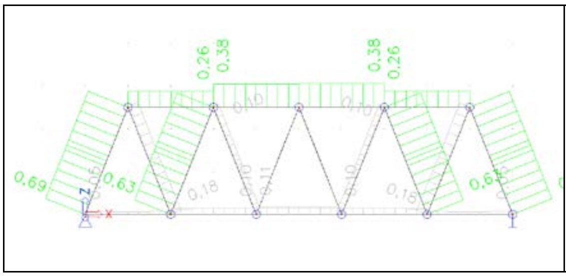

Fig.4a Unity Check for the Original Shape

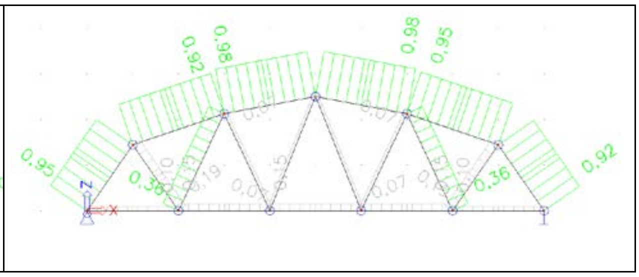

Fig. 4b Unity Check for the Optimized Shape

The original weight of the structure was 524kg. The optimized structure is 335kg. In the project the user achieved a 36% material savings.

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

Minimize The Weight Of A Steel Frame Hall

In this example the user was looking to optimize a typical steel hall frame. The Frame needed to span 30m. It consists of two columns and two rafters. I-shaped cross sections are welded, made of S355 steel (Standard Structural Steel Plate. 355 is the yield strength). The depth is variable along the elevation of the columns, and rafters are designed with haunches. The objective was to minimize the mass of the structure optimizing of the variable cross-sections of the columns and the rafter haunches.

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

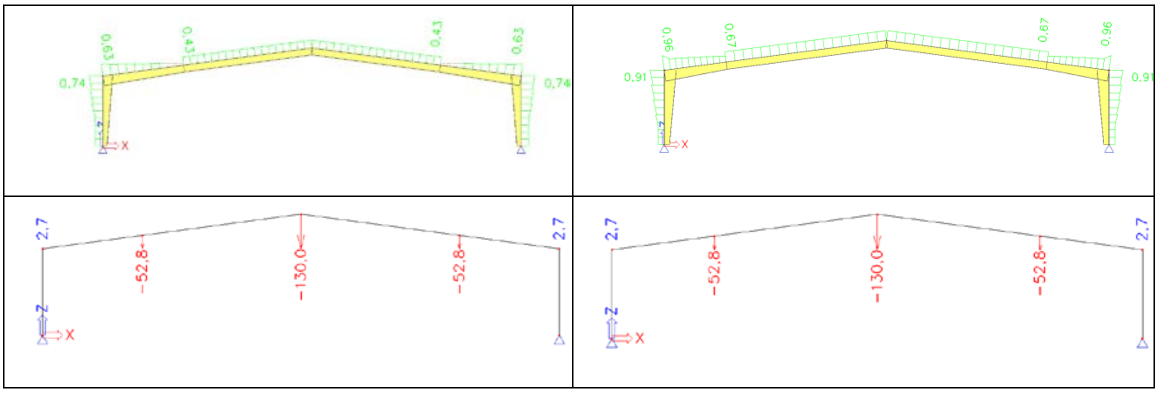

Fig.5 Global Check and Deformation for Original Shape

Price Optimization Of A Continuous Reinforced Concrete Beam

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

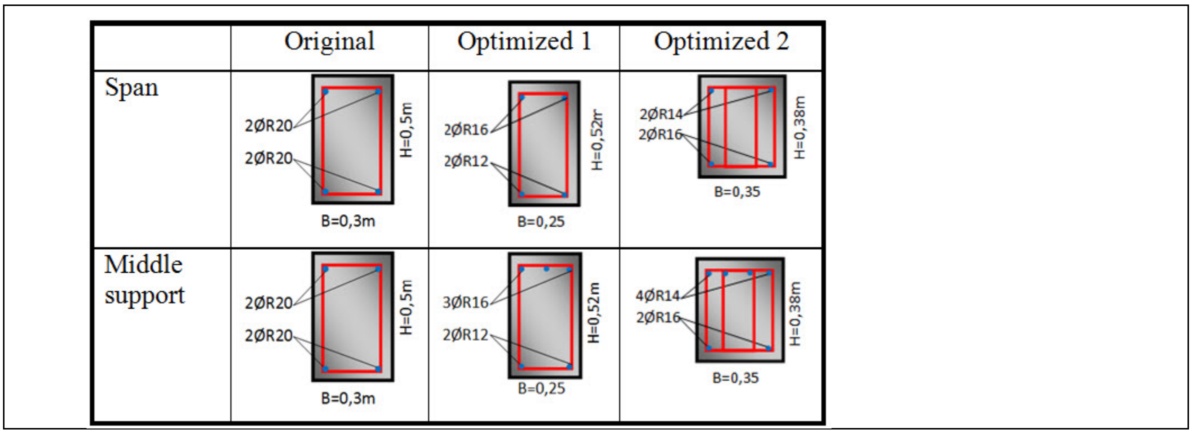

Fig. 6 Comparison of Reinforcement

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 Fig 6.
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 approximately 11%.

4 hours 30 minutes to achieve an 11% cost savings isn't necessarily efficient for an engineer who is designing a single beam for a single project. However, for a precast concrete manufacture to be able to take 4 hours 30 minutes to save 11% on a beam that will be used hundreds of times on a project, can offer real value to their clients.

Optimization Of Tendon Geometry Of A Post-Tensioned Concrete Bridge

This project involved the construction of a concrete bridge. The bridge was 46.54m long, and consisted of three spans (14.0+17.0+14.0) and two edge crossbeams. Construction stages with time effects are taken into account (creep and shrinkage of concrete). Pre-stressing is introduced by means of 10 tendons of Ls15.5-1860 material.

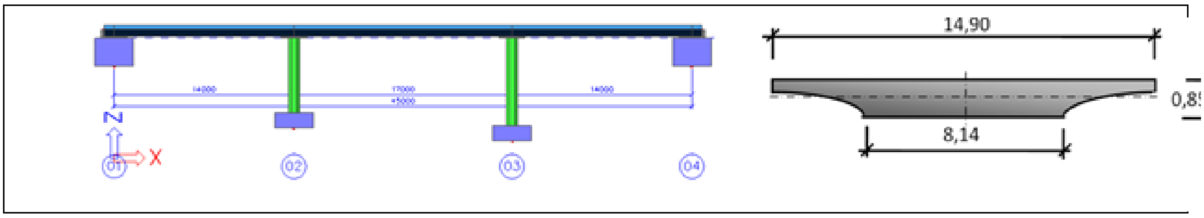

Fig. 7 Bridge Spans and Cross-section

Three different tendon shapes are used (see Fig. 8). The objective was to optimize the shape of the tendons with the aim of minimizing the total area of the cross-sections tendons.

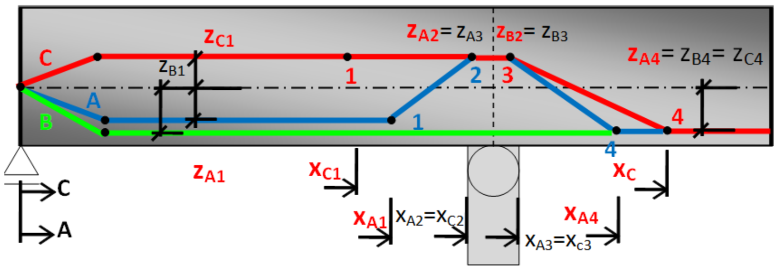

Fig. 8 Geometry of Tendons (Symmetrical Half of Bridge)

In this project the optimization was checked against the allowable concrete stresses. The Modified Simulated Annealing (MSA) method was used. This method found several optima. These optima were then manually analysed, and only some of them satisfied all of the checks required by the code (these check 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)			

Fig 9 Comparison of accepted solutions

The comparison of the accepted optima is illustrated in Figure 9. The optima discovered in Sol. 2 what the most optimum and produced a savings in pre-stressing steel of about 15%.

Fig. 10 illustrated the optimized layout of tendons is the following:

1. 6 pcs of 17-strand tendon with geometry A
2. 2 pcs of 9-strand tendon with geometry B
3. 2 pcs of 17-strand tendon with geometry C

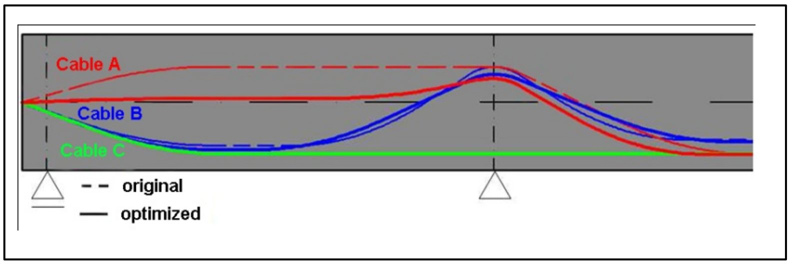

Fig. 10 Optimized Tendons

CONCLUSION

Engineering optimization is an active field of study. A simple web search will lead to numerous articles and papers. Implementing the technology is more difficult. There are few commercial structural analysis software programs that offer links to Engineering Optimization Tools (EOT). For this paper, Scia Engineer was the commercial software used. The EOT was developed by the Czech Technical University in Prague. And the link between Scia Engineer and the EOT was developed jointly. More information can be found by contacting Nemetschek Scia or Czech Technical University in Prague.

As an emerging computational technology, EOT has the potential to help engineers satisfy the owner's demands for cost reduction, material savings, compressed design/construction schedules, and environmental protection.

The computational technologies, as the ones described in this paper, are allowing civil and structural engineers to leverage the power of the computer to effectively run hundreds, or even thousands, of calculations to define optimal structural variants that best meet the designer's exact criteria.

This technology can give engineers new insights on how to best optimize a structural design. These insights can go beyond engineering. They can consider practical issues like constructability, manufacturing, safety and costs. These considerations would be impossible to discover practically by traditional analysis methods.

However, these optimizations must be weighed in terms of costs (cost to implement a new technology and time to run an optimization). Today, it is not practical to apply these methods to every project.

But, for the right project, the results can be considerable cost savings for the owner and increase productivity for the engineer. And, it offers those firms the possibility to offer new services and stand out from the competition.