White Paper

Optimal Design of Structures

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AutoDesign and Parametric Structural Optimisation Breakthrough technology in Scia Engineer 2008

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Content

Introduction

Most CAE software suppliers announce: "Our software helps you to make an optimal design of your structures". It this achieved in reality?

Broadly speaking if one claims optimisation of structures, in fact only a few chosen structural parts are optimized. A design engineer searches for the minimal size of the cross-section satisfying the design code, he/she tries to find the minimum number of bolts needed in a specific steel connection, he/she is searching for the minimum required area of reinforcement steel in a concrete beam. All structural parts are designed optimally, yet it does not mean that the whole structure is optimized for instance from the point of view of cost of materials, time of construction, price of labour, etc.

An optimal design of a structure is found when many design variants are tried out and compared. Everybody will agree, but how many times it is really done in the construction industry? Normally the designer works under the pressure of the client and there is hardly any time to study variants.

A typical example concerns a reinforced concrete beam. First the dimensions of the cross-section are preselected, then the internal forces are calculated and the reinforcement is designed, optimally of course. Yet who plays a little more with the depth and width of the beam to find an optimal price of the whole beam, which is composed out of the price of concrete and the price of steel?

Almost everybody is able to do it with existing software tools, it is only the question of testing of number of variants, comparing them and finding the most suitable one. In fact, this methodology may be realistic for small projects, but certainly not for real big projects. An experienced designer will certainly get closer to an optimum than a young starter.
Optimisation of systems

The research on optimisation is mainly lead by automotive and aerospace industries. The emphasis is mainly on the computational fluid dynamics domain and structural optimisation area, especially on the shape optimisation.
There are many mathematical methods, which could answer the needs of the construction and building industry. Normally the system has to be described with a number of parameters. Then one has to set the target of the optimisation – what is the goal, what should be minimized or maximized? And it is required to be able to calculate this goal from any set of parameters. If one does so, then one has defined what is normally "goal function" or "price function".
Once a set of parameters and the goal function are defined, one can use standard mathematical optimisation methods, it does not matter if we optimise the weight of a space shuttle or the traffic in the streets.

Five conditions for the optimal design of structures

Having powerful software tools for the design of structural parts and the mathematical methods for optimisation of systems being clear, why then is the optimisation of structures not widely used? The current CAE software systems are not equipped well enough for the structural optimisation. Which necessary functions should be intergrated? Five main conditions have to be fulfilled.

Condition 1

Functions for optimal design of specific structural members like a steel beam, concrete beam, steel connection, foundation block, etc. Usually the minimal dimensions, size or number are searched for. The member must satisfy the criteria of the appropriate code.

Condition 2

There must be a possibility to parameterise the structure. The designer has to decide, what is fixed in the structure and what can be changed – spans, depths, dimensions of cross-sections, thickness of plates and walls, loads ... Each feature which can vary must be able to be described by one independent parameter. Other dimensions can be dependant on parameters, creating an intelligent parametric structural model.

Condition 3

There must be a possibility to define the goal function. It can be the weight of required structural steel, the volume of concrete, the weight of reinforcement, but it can also be maximal displacement or anything else. The ideal situation is if the system is able to calculate one overall value like the price.

Condition 4

The software system must be able to evaluate the goal function for the specific set of parameters. It means that a function, which is able to read the set parameters and return a goal value, must be available.

Condition 5

The optimisation solver is needed. This is a tool, which generates the different sets of parameters, calculates the goal function, and finally proposes the optimal set of parameters.

With a CAE system equipped with all such functions, the way to the optimisation is wide open.

AutoDesign and Parametric Structural Optimization in Scia Engineer

Scia Engineer 2008 incorporates all needed functionalities described above. The implementation of the functionality needed for the 5 mentioned conditions above was done in 5 steps. For better understanding we use the simple word “AutoDesig”n for the first step of optimal design of the structural members. The word “optimisation” is used in step 5 – it means the entire solution for the whole structure.

Step 1 – AutoDesign

Steel and concrete members can be designed optimally. Optimisation of steel-cross sections is common practice since many years; the optimal design of reinforcement was made available more recently. Also several steel connections may be optimised. The design of the minimal needed reinforcement in plates and walls is available. Scia Engineer also allows defining all needed member optimisations, remembering them and repeating them after the change of the input data for a structure.

Step 2 – Parameters

The parameterisation of the structure is a basic feature of Scia Engineer modelling. Almost any entity, any feature of the designed project can be defined by a user defined parameter. Parameters are assigned to variables, starting from dimensions of structural members and cross-sections, loads and masses, over the time of pouring concrete, up to for instance the diameter or cover of steel reinforcement.

Step 3 – Input/Output XML interface

Scia Engineer has a general data XML interface, which allows modifying structural data from "outside" and also reading any needed value for a project. In a XML document the user defines what design values should be incorporated, what is in the list of input parameters. All ESA output documents are live, refreshable when the project is changed and recalculated. Then the XML document can play the role of the goal functions without limitations.

Step 4 – ESA XML solver

Scia Engineer also operates in the "hidden" mode. The project may be modified from outside of Scia Engineer, the calculation process can be launched from the outside of Scia Engineer, all defined documents may be refreshed and updated from outside and finally all values in the document can be read from outside. For that purpose we have an extra application ESA_XML.exe, which is easy connectable to any external software application.

Step 5 – Parametric Structural Optimisation

The simplest optimisation solver is the one that generates all possible sets of input parameters and calculates a goal function from all of them. Then the minimal (or maximum) goal value is found with the optimal set of input parameters. This operational mode is simple and reliable, in theory they call it "brute force". If one calculates all possible variants, then one definitely finds the optimum. The only problem is that for systems with many parameters, the number of variants increases dramatically. This kind of "batch optimiser" is now available in Scia Engineer. The user only defines limits for his parameters and the step of variation for the parameters. All variants are calculated and diagrams of the results are generated within the spreadsheet Excel.

The last step in optimisation is the real optimisation solver. Such a solver needs the same input as the "batch optimiser" – with limits and steps for the parameters. But in this case not all variants are calculated, only a few variants are "tipped"; from the results of the goal function the optimal set of parameters is derived. The magic of the quality of this solver is how good they are at "tipping". The better the solver, the least calculation of variants is needed.
SCIA co-operates with the Prague University of Civil Engineering on this research topic. It is planned to have the university optimisation solver connected to Scia Engineer. The solver uses a stochastic algorithm of "Simulated Annealing" based on general genetic algorithms. It enables also potentially multi-parametric optimisation, what means that more result values can be controlled. The method guarantees finding more "optimal" solutions, because it searches for local extremes, which have a sense from engineering point of view.

Practical examples of optimisation

One distinguishes 4 different types of structural optimisation:

- Topology optimisation, which means finding a structure without knowing its final form; it means that members or FEM mesh parts will be removed/added during calculation of the variant solutions
- Shape optimisation: the topology of the structure is known a-priori but there can be some parts in which e.g.high stress can cause problems, thus shape parameters will be optimised to minimize stresses.

- Size optimisation: a structure is defined by a set of sizes, dimensions or cross-sections; these are combined to achieve the desired optimal criteria.
- Topography optimisation, which means searching a proper shape of a structure (e.g. tent, membrane, bridge).

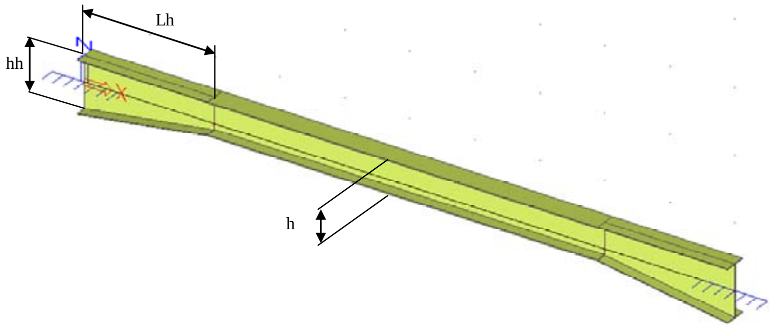
Many examples of structural optimisation are manifest by present in the daily engineering practice, a few are mentioned here:

- searching the optimal relation between stiffness of beams and columns
- finding the optimal thickness of concrete slabs
- determine the optimal dimensions of concrete beams
- finding the optimal shape of a post-tensioned tendon
- optimisation of the position of foundation piles
- sensitivity analysis of the subsoil parameters
- designing the least cost steel connection
- minimizing the weight of a steel structure for a previously defined type of frame
- searching the optimal definition of bridge spans
- finding a maximum carrying load for a crane under various geometrical positions
- …

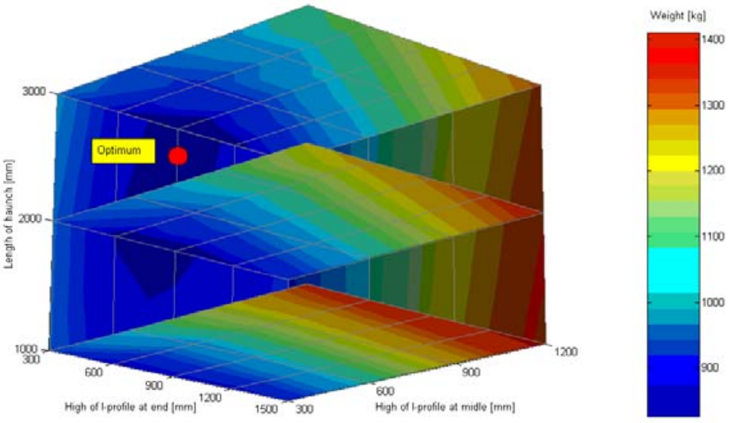
To explain the discrete parametric batch processing in Scia Engineer a few illustrative examples are outlined.

Example 1 : Optimisation of the length and depth of a haunch of a tapered beam

Consider a steel member with haunches; the beam is composed of I-welded sections. The depth of the beam in the middle and at the ends plus the length of the haunch is parameterized. The flanges and the web thickness are AutoDesigned in each step of the optimisation process.



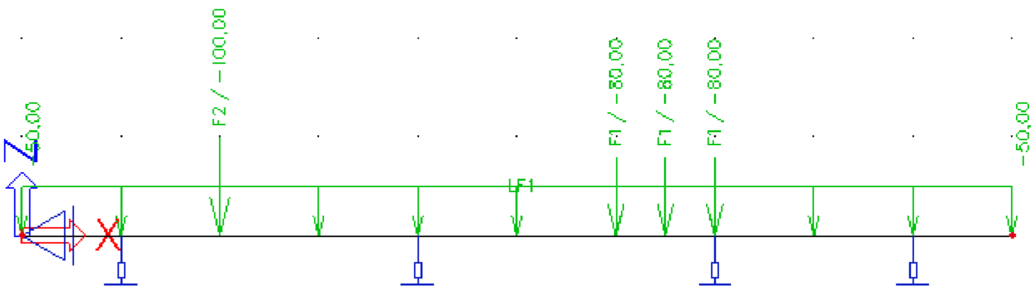
One finds that all variants satisfy from the point of view of code provisions, yet the weight is varying in a quite wide range.



An optimal shape of the tapered beam was determined.

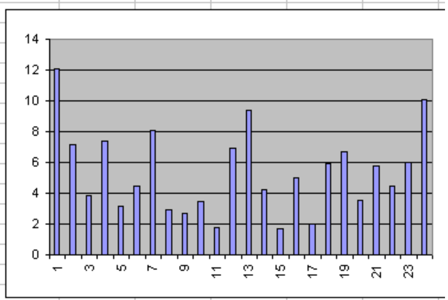
Example 2 : Optimisation of the position of piles.

The user has to design the foundation beam supported by piles. An ideal situation is when the reaction force in all piles is the same.

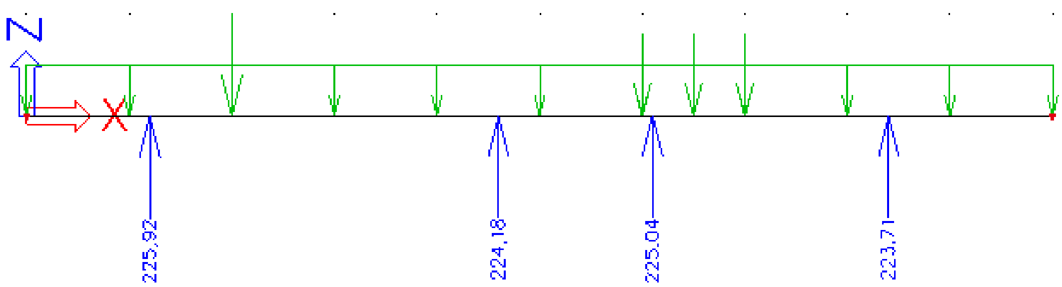


The user can set the limits to move the supports, each variant is calculated and reactions are evaluated. The goal function can be a simple formula, which calculates the sum-of-squares of deviations from an average value of reaction.

L1 [m]	L2 [m]	L3 [m]	L4 [m]	R1 [kN]	R2 [kN]	R3 [kN]	R4 [kN]	R [kN]
1,1	4,6	6,1	8,2	217,397	221,908	225,697	233,858	12,083
1,1	4,6	6,1	8,3	219,58	223,745	226,094	229,441	7,18
1,1	4,6	6,1	8,4	221,58	225,586	226,678	225,015	3,812
1,1	4,6	6,2	8,2	219,897	223,372	225,472	230,119	7,402
1,1	4,6	6,2	8,3	222,036	225,238	225,811	225,776	3,127
1,1	4,6	6,2	8,4	223,997	227,104	226,342	221,418	4,443
1,1	4,7	6,1	8,2	220,634	222,376	224,541	231,309	8,102
1,1	4,7	6,1	8,3	222,825	224,165	224,958	226,913	2,961
1,1	4,7	6,1	8,4	224,833	225,964	225,556	222,508	2,675
1,1	4,7	6,2	8,2	223,167	223,803	224,279	227,611	3,436
1,1	4,7	6,2	8,3	225,314	225,623	224,637	223,286	1,797
1,1	4,7	6,2	8,4	227,283	227,448	225,183	218,946	6,896
1,2	4,6	6,1	8,2	221,671	220,56	224,111	232,517	9,368
1,2	4,6	6,1	8,3	223,888	222,369	224,484	228,119	4,222
1,2	4,6	6,1	8,4	225,921	224,182	225,043	223,714	1,688
1,2	4,6	6,2	8,2	224,201	221,999	223,874	228,786	4,992
1,2	4,6	6,2	8,3	226,373	223,836	224,188	224,463	1,966
1,2	4,6	6,2	8,4	228,366	225,673	224,695	220,126	5,942
1,2	4,7	6,1	8,2	224,954	220,993	222,953	229,96	6,673
1,2	4,7	6,1	8,3	227,179	222,753	223,345	225,584	3,543
1,2	4,7	6,1	8,4	229,219	224,523	223,918	221,2	5,772
1,2	4,7	6,2	8,2	227,516	222,395	222,678	226,271	4,45
1,2	4,7	6,2	8,3	229,697	224,185	223,011	221,967	5,963
1,2	4,7	6,2	8,4	231,697	225,981	223,532	217,649	10,084

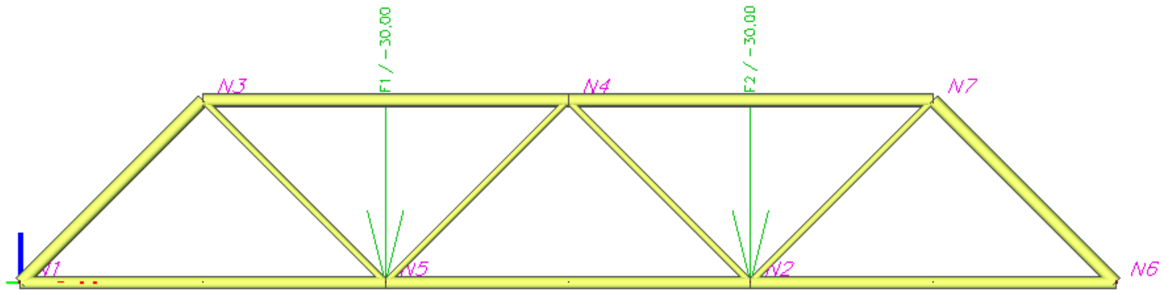


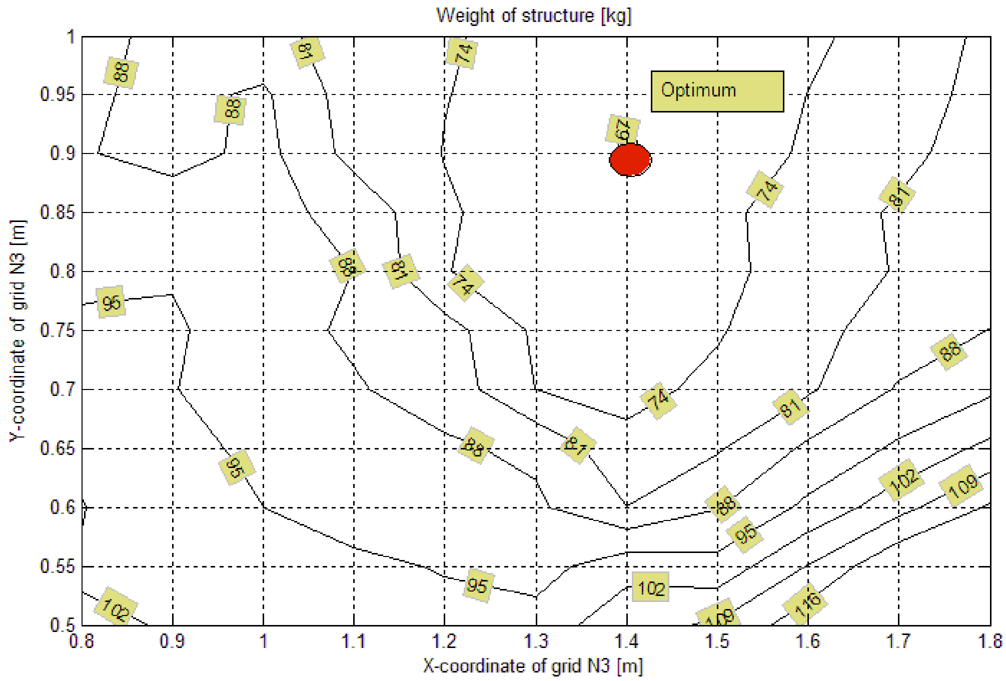
When we minimize this function, all piles are loaded with the same force.



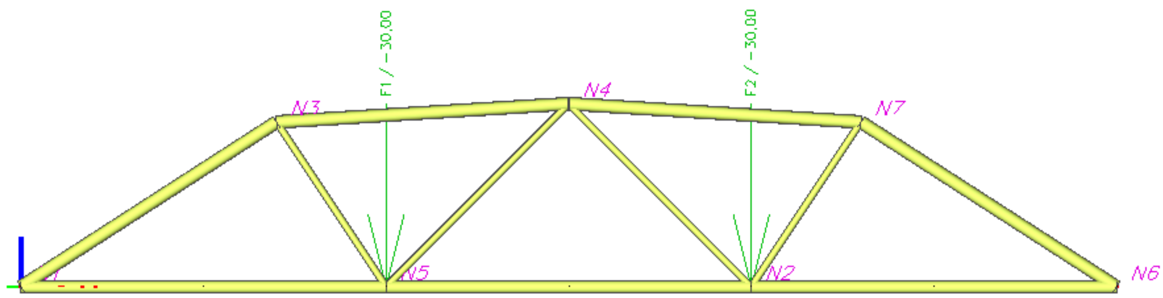
Example 3 : Shape optimisation of the simple frame

The shape of the simple truss beam is investigated. Parameters are the coordinates of nodes N3, N4 and N7 duly respecting the symmetry. The goal criterion is chosen i.e. minimum of weight.





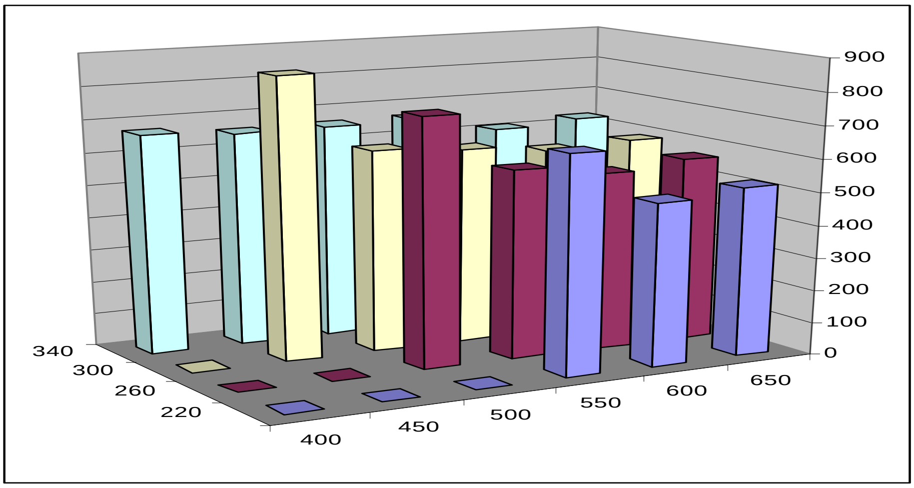
The optimal shape of the structure is like this :



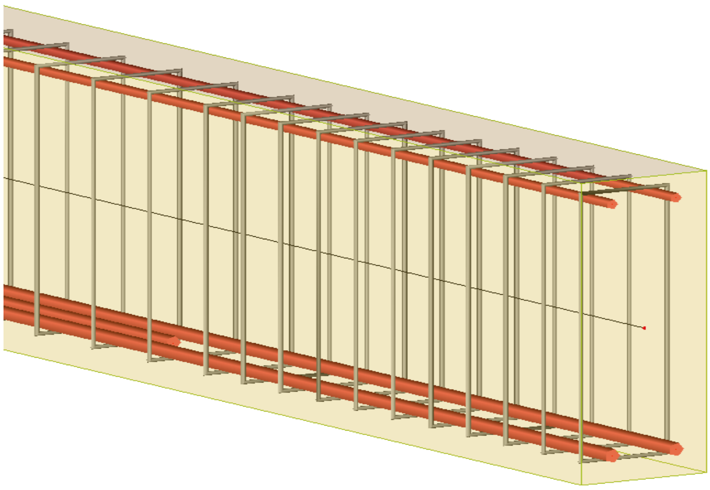
Example 4 : Optimization of the cross-section dimensions of reinforced concrete beam

The concrete beam of a length 8 m loaded with 50 kN/m is investigated. The depth of the cross section varies from 400 to 650mm, the width from 220 to 400 mm. The goal function is the price of a beam – this is calculated from the price of concrete and steel. The optimal shape of course depends on the price relations from country to country. In this case we use 150€ per 1m^3 of concrete and 2€ per 1 kg of reinforcement.

		Width			
		220	**260**	**300**	**340**
Depth	**400**	0	0	0	671
	450	0	0	860	658
	500	0	756	620	660
	550	663	578	602	662
	600	498	545	580	613
	650	520	569	592	629



The optimal shape of the cross-section was found 600x220 mm.



Ongoing research work

The Prague University of Civil Engineering has an extensive research program on optimisation. The research work is focused on algorithms, which are suitable for practical civil engineering problems, with typical discrete input functions (e.g. set of available materials, rolled sections or steel bars), together with a complicated dependency of the final goal function on those input variables. Moreover, as a structure must fulfil many various criteria, it is necessary to handle either multi-criteria problems or constraints, which are usually difficult to be described in close mathematical form. Several optimisation algorithms are developed, yet the optimisation of real life structures still demands a very large computation time. Methods that realize a breakthrough concerning this problem are based on numerical approximations, resulting in minimizing the number of calculations, and are called response surface methods. From artificial intelligence usually methods are used like neural networks, e.g. the so-called radial basis function network.
One of the advantages of the presented optimisation methods is, that they search not for the global extreme of a goal function, but for local extremes, and, therefore, more local extremes are found. Each of them has a meaning and it is up to the designer to assess those variants from the practical point of view, constructional aspects, a.o..

The other approach for handling high computational time is the approach of parallel or distributed computing. Most of the users of the SCIA software have a computer network, consisting out of PC's, which are in use during much less than 24 hours per day. Many hours during the day and definitely during the night they are either switched off or not really running computational tasks. So, algorithms that are able to use this free capacity will be very helpful. The scenario is as such: the designer - who is at a certain state of his design of a structure - defines ranges, limitations, demands etc. The optimisation algorithm runs overnight, and when coming to the office in the morning, he considers one or more variants of the designed structure, which were computed as optimal solutions.

Benefits for structural engineers

Optimal design of structures will change the design process intensively; a "dream of the future" is becoming reality. As mathematical methods are developing and speed of computers is increasing, optimisation will bring a completely new quality to the practical design process.

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