Integrated design with Form and Topology Optimizing

Uffe Lentz

The topic of this paper is to describe the ability of 3D CAD systems to integrate designers and engineers into a simultaneous process developing a functional and aesthetic concept in a close and equal interdisciplinary process. We already have the Finite Element Method, FEM systems for analyzing the mechanical behavior of constructions. This technique is suitable for justifying design aspects in the final part of the design process.

A new group of CAE systems under the generic term Topology optimizing has the potentials to handle aspects of conceptual design and aesthetic criteria. Such interactive design tools do not eliminate the designer, but the relationship between the designer and other professions and the professional consciousness of the designer will change. It is necessary to develop common ideas able to connect the scientific and the artistic fields. The common aesthetic values must be clarified and the corresponding formal ideas be developed. These tools could be called "Construction tools for the intelligent user" (Olhoff, 1998) because the use of optimizing is based on a profound knowledge of the techniques.

Keywords*: Form, Topology, Optimizing*

History

Looking back at the digital development for the past 15 years, we have in our profession two dominating technologies. CAD and CAE. Roughly they have been used separately in each profession. The eCAADe abbreviation expresses some of the digital dream of integrated design tools in a collaborative computer system to be used in all stages of the design process. The dream is closely connected to the idea of one single 3D model, 'owned' by an architect. The CAAD system, operated by an architect should be able to:

- Develop continuously during the design process
- Visualize all relevant architectonic aspects of the model and the surroundings
- Simulate and calculate all functional and mechanical behavior
- Automate the creation and the construction of building components closely linked to the component industry
- Integrate all relevant data from the surroundings in GIS
- Contain all information created and collected during the design process relevant for facility management.

Through the years this dream has been pursued in a large number of research projects, which have achieved many results, presented to us at this conference. Often we have dreamt of retrieving lost terrain from competing professions.

There are obvious reasons why further integration between the professions offers resistance: The building as one unique object bound to a specific location, professional traditions and the organization of the building industry.

In other areas of design and production, that don't have these traditions and bindings, we can observe the clearest examples of such an integrated design process: in the airplane and car manufacturing industries and the naval industry. Generally speaking it is found in industries dominated by heavy investments and in areas where the engineering aspect is predominant.

The dynamic of these industrialized sectors is their ability to integrate designers and developers in cross professional teams working in a concurrent process, causing an effect of synergy because of the close collaboration. Architect are traditionally placed in the gab between the technical and artistic area, but the scientific development in the technical professions is far ahead the equivalent knowledge and methods in the architectural education and profession.

CAD modeling in the old days

The "old" 3D CAD systems of the early eighties were totally dominated by various extrusions, - adding heights to geometric shapes along different directions and paths, combined with the use of parameters for rotation and scaling at different stages of the extrusion. The tool gave designers the ability to predict and create form of such complexity that it would be almost impossible to produce them with the traditional geometrical tools, e.g. ruler, pair of compasses.

Boolean operations became available and sufficiently reliable, geometrically speaking, in the mid eighties even in relatively cheap modeling systems. In combination with extrusions it was possible to create very complex geometry, although it was very difficult to edit in the resulting shapes and points without disturbing the formal topology of the design.

A static world

Traditional modeling, seen as unique work (of art) is quite accordant to the way we regard architecture as being a product of static qualities. We regard it as a complete and enclosed product, not to be altered by changes or additions.

In that respect one could say that our professional standpoint is parallel to that of the renaissance architect Leon Battista Alberti (1444-1472). He outlines in his "Ten books on architecture" the definition of the perfect building:

> *"…a rational coherence of proportions of all parts of the building, where every part has its own unique distinct form and size and nothing can be added or subtracted without destroying the harmony of the whole ..."*

Our profession regards, according to this viewpoint, the building as being the perfect and complete solution, hopefully situated in a permanent historical framework, only subject to the force of gravity on the horizontal plane.

Euclidean geometry and the understanding of architecture within a cultural context seem to converge. In general we disregard the abundance of dynamic forces as one of the few professions, both the very real forces affecting the architectural space such as pressure of traffic, changing functions, new communications, materials, constructions and in a more virtual form of rapidly changing social, economic and cultural structures (Greg Lynn).

Alberti can not be a valid theoretical foundation to our profession any longer. Considering the structural changes in production of buildings it becomes still more difficult to see the product as a harmonized work, where all parts rest in a perfect balance. To days architecture is made of components and elements. The adaptation and assembly of replaceable components rapidly renewed or removed according to varying demands and forces in the urban structure is a relevant architectural problem but not familiar to the way architects normally works.

Cyberworld

The image of a static world consisting of simple forms and harmonies is gradually changing to show a dynamic space with a complex interplay between compounded forces and suspenseful fields.

This can be regarded in use of virtual or real spaces in other professions. Their methods, tools and data are complex and dynamic to such extend that they need 4 dimensions to look at the results of the analysis simulated in computers:

- GIS systems visualize geographic related social, economic, historical, functional relationships in complex 3D representations of densities and distribution.
- Sound evaluation programs are used to analyze and represent the invisible sound image in 3D CAD models.
- Navigation systems are used to overview Cyberspace. 3 and 4D representations brings architectural metaphors to cyberspace.

In modern CAD systems we meet new tools involving time, forces and tensions. They are developed in the area of show business, movie industry, game making and entertainment. Architects regard them worthless, but they are pointing at new ways to work with dynamic shapes in a 4D world.

- "History" of the design process integrated in 3D objects, where design parameters and actions can be modified from the birth of an object to the present stage of the design.
- Spline curves like a spacecraft traveling amongst planets in a field of gravity constantly affected by changing weights.
- Blops, like clouds of material, defined by mass and point of gravity. Interaction between the clouds will create "places" where particular circumstances are sufficiently represented.
- Voxels - totally different to traditional polygon geometry. A map of pixels, where each pixel has a color and a height. This will allow much more detailed graphics, and it make it possible to "add and remove" material dynamically across borders of objects and materials.
- Particle systems giving entities vectorial properties before they are released into a CAD space differentiated by gradients of force
- Bone kinematics, interactive mechanic simulations.
- Inverse kinematic animation where the motion and shape of a form is defined by multiple interacting vectors that unfold in time perpetually and openly.

Optimization

From the simplified world of ideal geometric proportions CAD systems begin to integrate potentials to let constructions develop over a time span, the same way as nature has evolved optimal design.

Designers can reach "the best possible" solution evaluated according to design criteria and demands in the same way as naturally selection leads to "the best possible construction".

Regarding a passenger airplane the optimal solution could be described by at least 3 criteria:

- less possible weight according to a given load ability,
- highest possible aerodynamic lift and
- long safe life span.

Each of these criteria has an optimal expression. A long life span will probably be the demand that draw a limit for the weight, because strength and life span normally decreases when the use of material is reduced. In contrary aerodynamic and weight do not have similar coherence. A traditional "trial and error" process has made it possible to balance the individual criteria against each other.

Figure 1 (bottom right).

Figure 2 (top right).

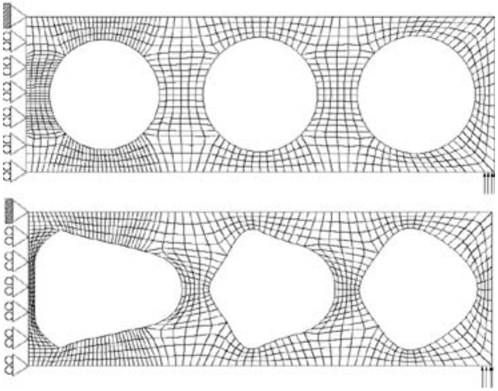
The appearance of the FEM-method for computer simulation and calculation of the stiffness, strength and stability has been an important step to optimize design. Nature's constructions are created by evolutionary processes. In the same way humans have always aimed at optimal constructions, characterized for centuries by gradual improvements of existing constructions.

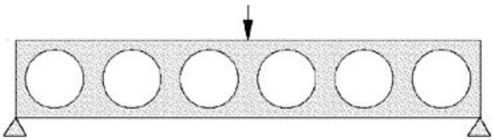
FEM methods made it possible to do very efficient simulations of constructions, after which the results were compared with the design criteria. This process was to be continued until the demands were satisfied, if possible. There are many similarities to the natural development. The problem is, that there are so many parameters involved in e.g. airplane construction that it is impossible to test or estimate all connections in an "if-then-else" process (Olhoff)

Mathematical programming methods based on iterative use of FEM calculations made the Form Optimizing break through. Supplied with design sensitivity analysis and optimization. With these methods it is possible to achieve a process where the "best possible" solution is constantly approached.

This rational process of construction requires that all the demands of the problem can be expressed as criteria functions, to be evaluated according to the design of the construction. These criteria functions can be weight, stiffness, strength, stability, life span etc. The next step is to introduce design variables, describing the design in areas where the designer wants to have the freedom to make changes. These variables can represent shape, thickness, material parameters (C)

From the FEM-analysis and the calculated gradients resulting from the sensibility analysis it is possible to predict how the criteria functions of the construction varies according to small changes in the design. An optimizing routine calculates a new design slightly better than the previous. Step by step the construction process will lead to the optimal solution. The natural evolution is compressed from millions of years to hours.





Form and topology optimization

There are two methods for optimization. Form optimization always lead to a solution with the same topology as the conceptual basic design. Topology optimization has only been developed in the last decade. The topology of a construction is understood as the superior concept, the configuration and the relationship between sub components in a construction. It is possible to combine the methods to obtain an optimal topology and an ideal geometry.

In the following example both methods are used (Rasmussen, Lund and Birker).

The supporting beam in an AirBUS passenger plane is to be optimized to reduce weight. The example is developed at University of Ålborg in a CAD-integrated tool, CAOS for structural form optimization.

Figure one shows the actual structure. The beam is supporting the floor in the passenger cabin. In the optimized structure the top and bottom of the beam has to remain plane. The intention is to reduce weight without loosing any strength.

In figure two only the half of the construction is shown because the construction is symmetrical.

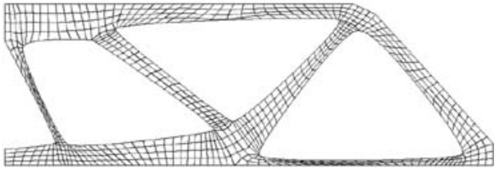
The shape is divided into finite elements and the material around the holes has been strengthened without changing the original shape.

Next step in a traditional FEM analysis could be to allow the shapes of the holes to change. The shown modification reduces weight with 5% using Form optimization.

The rather poor result leads to the suspicion that the basic topology with 3 holes is a wrong starting point for an optimal construction.

Topology optimization will allow a more ideal distribution of material regarding a weight reduction. The holes make up 56 % of the total surface. If this ratio is kept, the material will be distributed into a new topology show in Figure 3.

Each element is filled with a little "blob" of material according to the density. The designer can manually decide an acceptable porousness. In this case the design decision is to simplify the lattice. It is decided to make 2 holes in places where the structure seems weak. After optimization of the topology is possible to repeat a form optimization. The costs in production are probably lower and a lattice will allow installations to go through. The upper right corner has no influence to the strength of the construction.



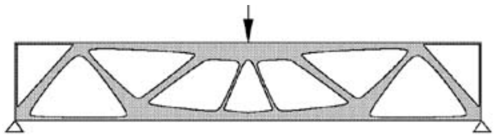


Figure 3 (bottom left)

Figure 4 (top left). FEM model of the new form optimized topology.

Figure 5 (middle left) The final new construction. The volume is reduced with 42 %

Conclusions

Integrated design

The knowledge and methods from several professions has to be integrated in the design process and in education.

Architectural form is unity and can be achieved only by someone who is familiar with all elements that make the design and who is in a position to co-ordinate and integrate the elements in a series of stages to achieve the desired goal

The artistic design process will decrease, and the conceptual design will increase, become detailed and technical aspects have to be more clearly defined.

The role of the designer being the one to decide the way things are to be - is moderated and replaced by someone who do not focus on the design object, but on the analysis of reasons for design (Dyson)

References

Alberti, Leon Battista (1404-1472). “De Re Aedificatoria Libri X”

Dyson, Mark. Danish Technical University, Energy Vision, Concurrent Systems in Performance Building Design, www.energyvision.cjb.net

Lynn, Greg. Columbia University, New York, “Animate Form”

Olhoff, Niels, Professor, University of Ålborg. “Design of optimal constructions”, Naturens verden 1998, p346

Rasmussen, Lund and Birker, Institute of Mechanical Engineering, University of Ålborg, Collection of Examples, CAOS Optimization System. ISBN 87 89206 18 5

Notes

[A] Rasmussen, John. , Institute of Mechanical Engineering, University of Ålborg,

[B] Sigmund, Ole. Associate Research Professor, Department of Solid Mechanic, Technical University of Denmark

Uffe Lentz
Aarhus School of Architecture
Dep. of Communication Design
DK 8000 Århus C
Denmark
uffe.lentz@a-aarhus.dk