FORM FINDING AND UTILITY-BASED OPTIMISATION

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Summary
In structural principles and designs materials are utilised for structural purposes and the properties of the materials are studied, tested and even developed regarding e.g. structural behaviour and architectural features. There is a steadily ongoing process of refining and developing the use, utilisation and properties of materials for the design of structures of all kinds. However, different objectives can be applied and different aims are taken as points of departure in the optimisation work, depending on the aimed at result, and energy, material and resource consumption should be regarded no matter what the aimed at use is. The question of how to optimise is also crucial in relation to managing and spending of financial and, not the least, natural resources.

This paper treats in brief and exemplifies results of optimising efforts with different aims, optimisation for the sake of a rational production of complex multi-layered systems, form finding for the sake of structural efficiency of systems with reduced complexity and construction of architectural symbols and functional structures. Referred to are examples of timber structures for different purposes and some examples are given from the area of plate-based timber construction. Discussed are also other materials and structural efforts, since the basic approach to design factors and features, and to environmental issues, concerns all types of construction. Factors decisive for the rationality – and for which rationality that is the most suitable one to strive for in each case – are e.g. material quality, technological state and efficiency of the production line, speed of production, produced volume and type of architectural-structural interaction.

Keywords: Optimisation, form finding, architectural utilisation, material capacity, resource and production efficiency

1. Introduction
Optimisation is often used as a positive term denoting the increasing of structural efficiency, but there are different ways of optimising a structure or the use and utilisation of a material, depending on the preconditions and/or aimed at function and/or effect. One case of optimisation occurs when e.g. the structural capacity and utilisation of a certain material is taken as a point of departure for the morphological process. Computer aided modelling and form finding can be seen in the development of computer-based tools and their applications and resulting designs, e.g. ESO, Evolutionary Structural Optimization [1]. The result of this type of process may differ very much from an optimisation process relating to the production process or production line. In most cases these aspects depend on structural context and, in the end, on economical prerequisites for production.

Structural efficiency, architectural adaptation, material utility, economical reasonability and level of innovation may differ very much from case to case. The question of how to optimise can be given different answers, answers, which – like the relation between architectural and structural design – have varied through history. Still the optimisation of the system/structure and architectural form in each case, regarded from its current context, may be judged as fulfilling the necessary/prioritised demands. Good structural and architectural design should of course also seek this very type of optimal reply on the questions put from our ever-changing society.

Production rationality, long-term economy, structural efficiency, architectural adaptability and functional utility are all different factors, which can be used to steer and determine an optimisation process. These factors are fully reasonable to focus on in the design process, but since the production in the construction sector still in most cases is project-based, the preconditions vary to a large extent. It is therefore reasonable also to study which factor that in the best way answers to the current preconditions, from case to case.
2. Phases and Focus in Design Work

2.1 The Potential of Conceptual Design

In the development of structural methods and technology, planning tools and material utilisation, currently almost anything is possible. In an affluent society with strong economy we can utilise all and every resource to obtain an endless row of variations. This is indeed a fascinating challenge and a tempting task to indulge in. But it is important to bear in mind that the utilisation of Earth's limited resources does have an end.

The efforts to reach extreme capacities have tempted man throughout time. The American architect Lois I. Kahn was active at the University of Pennsylvania, where he worked together with the French engineer Robert Le Ricolais from the late 1950’s. They were taking opposite attitudes in their approach to construction. Kahn could be described as an earthbound phenomenologist, and may be quoted as saying “When you have a room, something happens, the building program opens by itself.” Le Ricolais was engineer and rationalist and could be quoted as saying “Zero weight, infinite span – You know it can’t be done, but at least it’s a limit that we could try to go to.” [2] Zero weight and infinite span is the utopic goal of material minimisation. By refining a structure all the way to that extent it would be utterly efficient, from a technical point of view. But if technology and materials would be possible to take that far, the structure would probably be so expensive that it would be impossible to afford, at least more than once. For gigantic structures to resist tsunamis in Japan steel has been modified at nano level to stand the extreme forces in so far not yet seen scales of structures, which is a way to deal with structural challenges but not necessarily a way to sustainability.

![Fig. 1 King and queen post in a sketch by Le Ricolais (left) and a 19th century Polonceau truss in Flyinge, Sweden (right).](image)

Nature often ends up in a balance between structural capacity and resource economy. Le Ricolais studied and commented on natural phenomena like soap films and buckling performances of columns and beams to find orders for construction in the order of destruction. In an article he stated, “The time is not too far distant when to use steel as a compression member will be as unthinkable as to use concrete for tension.” [2] He addressed the replacement of bending in a beam by tension in the lower part and compression in the upper part, explicitly shown in a king and queen post and theoretically he opened up for refining the tasks for different structural members (Fig. 1 left) and which touches upon the subject of tensegrity.

The first quote of Le Ricolais above is an extreme definition of lightweight structures. In long span structures the dead load of the structure becomes important for its behaviour. Palaeontologists have discussed that some species of dinosaurs reached the limit for the size of living creatures on this earth. The magnitude of Earth's gravity decides how big our bones can become. The bigger a structure or a skeleton becomes, the heavier its structural members/bones have to be to be able to carry its own weight. There is a limit, where the structure cannot grow more without collapse, unless bending in its members can be transferred into tension and/or compression. The challenge lies in the design of a structure as light and statically efficient as possible, “[…] the more stiffness it produces from least weight the better” [3].

But lightness is not a pleasing one-way lane without problems to deal with; the lighter the better is not necessarily the case. Light structures easily become unstable and they often deform to a certain degree before they take loads. Tension structures, which may look slender and light enough, also demand heavy anchoring systems or abutments to manage the forces they will be exposed to. This makes the entire system quite heavy and also expensive. Reduction of material
also places high demands on the design and structural detailing, which have to provide more efficient and precise performance. Le Ricolais stated in a paradox that to build light is the art of making a light structure with big heavy members. A similar paradox is to be found in the relation between structural engineering and architecture, where structural engineering deals with the structural realisation, whereas architecture to some extent deals with the experience of the structure, which may be quite different. The experience of a structure may be lightness even if the structural mass is heavy, and vice versa. The right optimisation of form is therefore not always evident and clear from the beginning. The way to optimise depend on the aimed at result. Is the result meant to look or actually be light, or heavy?

Erik Reitzel, former professor at the Royal Academy of Fine Arts and the Technical University of Denmark, has worked with structural form based on the study of failure patterns of materials and elements. [4] His work has resulted in several minimised structures and tension rod and cable-stayed structures. Buckling patterns as generators for the design has also been described by e.g. Yoshimura in the 1950's and other examples on this theme can be found where folding and buckling patterns are utilised to create structural members reinforced by form [5].

Means and needs may thus go hand in hand. In 1921 the Russian constructivist Karl loganson was the first to patent structures later called tensegric. He stated his credo as "From painting to sculpture, from sculpture to construction, from construction to technology and invention – this is my chosen path, and will surely be the ultimate goal of every revolutionary artist." [6] High-tech has become an expression, a style, associated with technical delicacy and visual, readable, more or less advanced technical solutions. It can be used as a visual means, but is based on the minimising of structures, increasing the demands on the performance of the remaining members. If mass is taken away, the joints still remain largely irreducible and the detailing becomes more apparent features of the overall design as for the architectural expression and visual impact. The high-tech potential of structural development has later on been followed by the design effects of computer aided design tools, resulting in what has been referred to as blob design or liquid architecture [7] (Fig. 2). This design trend shows different approaches, where the form concept may decide the exterior only and the structural solution decides the interior, or both outer and inner skin are defined independently by the computer model and the structural solution has to fit in the gap [8].

![Fig. 2 Night view and glass façade detail of Kunsthaus Graz, “the Friendly Alien”, Graz, Austria.](image)

In Kunsthaus Graz, designed by Peter Cook and Colin Fournier, the exterior form shows most ambitiously elaborated and eye-catching effects. The façade also works as advertisement for the housed activities. The museum interior shows few similarities with traditional museums for traditional painted art: the inner walls are curved and not suitable for hanging of two dimensional paintings, which results in utilisation of temporary screen walls when paintings are to be exhibited. Without additions the enclosed volume is, however, suited for contemporary conceptual art and spatial installations. It is symptomatic. As the relation between structural and architectural demands, inherited borders of traditions and fields of professional activities gets rather blurred, which points at the potential in converging lines or rather parallel, simultaneous and interactive processes of architectural and structural design work. Architectural and structural design work need to be
intertwined; from the then obtained range of varying factors — both necessary and less important — the choice of the steering one or ones may be made. Not the least is this important for the relation to and for aesthetical, environmental and maintenance concerns, issues sometimes treated as something not really affecting us or of importance, here and now.

2.2 After the Conceptual Design Phase

In the conceptual design phase anything is possible. But after the conceptual stage an important question must be asked: what is the main reason for producing this structure? Russian constructivists like Vladimir Tatlin created impressive visionary designs of which several remained as drawings. These designs have been displayed as architectural design closely related and often associated to art, and has also influenced artists in the 20th century art history. The French engineer Gustave Eiffel designed the Eiffel tower as a temporary structure for the big exhibition in Paris in 1889. It became so appreciated that it was kept as a landmark, even though its structure continuously demands laborious maintenance. Roller coasters are enjoyed all over the world and the structures most appreciated are constructed in timber, because of the soft, smooth experience of the undulating track while running it (Fig. 3). The maintenance of the structure is rather laborious and costly also in this case. Bolted joints must be checked meticulously every day, to secure the track width on top of the timber structure, which shows moisture-induced variations in measures. But for the sake of a nice smooth ride this is by the contractors regarded as fully acceptable.

Fig. 3 External and internal view of the roller coaster Balder, with structural design by Gerhard Stengel, in Gothenburg, Sweden.

Discussing Le Ricolais it can be noted that several of his designs were structural visions. As such they reached far, but they were, at least at that state, often too extreme to realise in practice, thereby showing a kinship in attitude with Tatlin and his colleagues. The full value and gains from such efforts are not realised until a practical use is found and the vision applied. Le Ricolais nurtured a vision about going into a stiff hollow rope to obtain his vision about zero weight, infinite span. This issue has been further treated and also further concretised e.g. in works where the hollow rope is composed as a tensegrity assembly [9]. In cases like this there is a structural solution, which has not yet found its application in practice, the question matching its answer. In a similar way, new art-related research, with the freedom of digital modelling, in architectural form and conceptual process creates forerunners that inspire, develop and revolve the building related evolution. Structural visions like those of Le Ricolais tempt engineers to continue searching for new structural solutions and development of structural principles, even if initially the practical use of them is not made clear. Visions and an urge to strive for novelties in design and form, play an important role in the development of the society. The functional utility, the realistic maintenance and the resource economy must, however, come into the picture, and not too late.
The tie between architecture and structure has in some respects grown stronger during the last decades, in the quest for new styles, freed from the structural shapes of past times. The striving for unique features tends to lead to, by current standards, extreme structural solutions. The lowest common denominator is the material. The material that is chosen for the structure will decide the architectural characteristics of the created room and the engineered characteristics of the necessary structure. The choice of material, the joining technique, the structural concept, the structural design and the design of the detailing are of particular importance for the quality of a structure. Rational relations between material cost and action, i.e. architectural goal, functional and structural demands, and between material cost and total cost are crucial for a fruitful result in line with sustainable resource utilisation. Knowledge about materials and what they can do, their properties and what one can use them for and how, is decisive for the result of both architectural and structural practice.

Another factor decisive for construction and design development is, of course, the means and volume of production. The sub factors to regard are then utility, production efficiency and economic repetitiveness and adaptation to surrounding contexts. A unique object often allows more unrestricted spending, or at least a more generous financial situation. Production can be allowed to be more costly, material utilisation more demanding to reach and construction means more complex. A big roof structure erected only once does not need the same trimming of the production line – even if it may show it – as a stock design for a roof structure for repeated construction (Fig. 6). There is also a decisive difference between e.g. a structure with a large span where the main task is to span, cover and transfer loads to the abutments, and a structural system designed for multi-storey apartment blocks (Fig. 4), where the range of demands and needs from the end users are not as purely structural, but where load-bearing, lateral stability and foundation solutions are to be combined and co-ordinated with installation systems for heating, water and ventilation and with functional layouts, interior values of a liveable environment and last but not least with a slimmed production line and logistic system to keep production costs competitive in series production. In both cases – large span roof and high-rise apartment block – it is a question about optimising the material in construction. There is a big, important and interesting difference, though, between the referred to roof structure designs aiming at structurally optimised utilisation of the materials, the apartment blocks aimed for rational pre-fabrication in series production and e.g. a roller coaster. In the first case the material utilisation can be said to be optimised for structural performance, whereas in the second case the material utilisation can be said to be optimised for efficient production and in the third for a utility effect.

![Fig. 4 Social housing project by Hubert Riess in Vienna, Austria, constructed with plane elements (left) and prefabricated volumes for a student apartment block by Rolf Bergsten in Stockholm, Sweden (right).](image)

### 2.3 The Steering Factors

Basic prerequisites for all built structures are thus material properties and available technologies, methods and tools. The structural properties referred to in several contexts have steered and still steer the design features of the produced objects. Today, however, development has provided the field of construction with numerous efficient tools for design, calculation, simulation and production, and almost anything is possible to obtain. Simple and swift generation has brought us capacity to define complex forms, and technological development makes them realisable though not always...
really affordable [10]. There are both vast possibilities and potential problems in this situation; when anything is possible the aim may be unsatisfactorily set. The potential variability tends to become a steering factor in itself pinpointing the wasting behaviour and man’s cul-de-sac relation to natural resources. Here projects like the Denver International Airport designed by Horst Berger, show interesting features of influences of environmental and energy related concern and efforts on an object where the structural design is the architectural and vice versa.

The context, built and environmental, plays a sometimes vaguely recognisable role as a steering factor. It is a matter of trend whether a constructed addition should melt anonymously into the existing context, or stick out. A project like the museum extension at Kunsthau Graz sticks out as a representative of the blob design trend. Contrasting to this are e.g. some of the nominated proposals for the extension of the City library in Stockholm, which was originally built in 1937: some of the proposed designs for its addition are dug into the nearby hillside. In Copenhagen the Royal library was in 2003 extended through the addition of the so called “Sorte diamant”, the Black diamond, a black mirroring box contrasting to the original 19th century brick building. At about the same time the extension of the Royal library in Stockholm, Sweden, was dug down into the ground leaving only a sloping glass roof over the entrance stairs visible.

3. Development of Material and Technology

3.1 Structural Efficiency with Natural Capacity

The design, structural and architectural features of timber has followed and been developed along with the development of tools for cutting, sawing, planning and jointing the material. Structural capacity and spans have increased stepwise with developed means and technology. A brief overview of the timber building history reveals how decisive the material and the material properties have been for the properties of the result. Fig. 5 shows the Lejonström bridge in Skellefteå in northern Sweden, a timber bridge constructed in 1737 and still remaining in good condition: its wooden deck has been exchanged over the years but the main structure is intact. The bridge has been in use continuously since its construction and has stood the change to the much increased loads caused by the appearance of car traffic.

Glulam arches have come into use since the 1920's but when the Lejonström bridge was constructed this was not yet an alternative and the spans along its 218 m length were constructed based on the physical properties of raw timber, treated with the available tools. With the prerequisites of that time the form was optimised for the required spanning task across the Skellefte river.

Fig. 5 The Lejonström bridge constructed in the 18th century, Skellefteå, Sweden.

3.2 New Material Development Leads to New Form

Through history it is evident that the development of new materials and the efficient production of them very quickly will be utilised for new efficient structures and new architectural form. A very obvious example is the development of industrial production methods for iron and steel and the applications in the Polonceau trusses in the big railway stations in Paris. The Polonceau truss type was designed to utilise steel in tensile parts and cast iron in compressed parts, utilising the materials as effectively as possible. Iron, manufactured in an industrial way from the end of the 18th century is a material with very little tension capability but good compression strength. It was through the first half of the 19th
It can very clearly be seen that the newly developed steel was used only where it could be economically motivated. In another example, an equestrian hall at Flyinge in the south of Sweden (Fig. 1 right), designed by the military engineer Fredrik Blom in the mid-19th century, the compressed upper member is made of timber and the lower member of steel. It is a good example of optimisation with respect to material cost. Timber also came into use in posts in other trusses of similar design, with obvious parallels to wooden trusses in ancient Rome.

The Polonceau principle show similarities with the conceptual truss design of Le Ricolais mentioned above. It has shown suitable and rational for relatively large spans in low cost designs. The principle is based on optimised utilisation of materials and members and in recent projects the principle has been further developed and combined with timber plates, as described earlier by Falk [11] (Fig. 6 left). These plate-based truss structures are to be found in different designs. The latest example of a cable-stayed roof structure in Sweden is a storage hall in Uppsala, finished in 2007 (Fig. 6 right).

Another early example of how a newly developed material was used to achieve wanted architectural results is the "Skeppsholmen" bridge in the centre of Stockholm, constructed in 1858 (Fig. 7). This bridge is interesting for two reasons. It is a very well designed bridge from architectural viewpoint. It is also a very early truss structure utilising steel members produced through the "puddle process" which was a very interesting development step in the history of industrialisation of steel manufacturing.

The location of the bridge in the centre of Stockholm closed to the royal castle made the design task very delicate. The bridge should have a good architectural design without dominating the surroundings. During several decades in the early nineteenth century a new bridge from the mainland of Stockholm to the island Skeppsholmen was discussed and several designs were dismissed. Finally a proposal worked out of the engineer O.E. Carlsund and the major G. de Geer was accepted. The bridge should be as low as possible and the form should relate to other bridges in the centre of Stockholm like the "Riks" bridge in front of the castle, a well designed stone bridge with low pitched arches constructed in the end of the 18th century. The structural solution was to make the four main beams as continuous trusses, which even included the handrails as compression members. The truss work is built up of members of puddle steel joined together with rivets, on its lower part clad with steel plates to give the visual impression from a distance of the wanted arch form.
The bridge is a very good relatively early example of the utilisation of new materials to achieve high quality architectural result. At the end of the last century the bridge was threatened to be replaced by a modern replica, wider and constructed to carry higher loads. Wide spread opposition did, however, stop the demolition and the bridge is now renovated and a very good representative of architecture and structural form.

4. Architectural Possibilities of Structural Complexity

4.1 Guggenheim

A contemporary example of the approach chosen by loganson is the American architect Frank O. Gehry. His architectural designs are widely known and much appreciated for their sculptural effects and non-orthogonal forms. Gehry’s design work often starts with chaotic sketches, he deliberately approaches buildings as sculptural objects, which then are elaborated and transferred into structural engineering tasks [12]. The work is an iteration process between sketch and physical model, which is affected both by its resulting forms and by changes of the program. The work has in many cases resulted in complex architecture with advanced forms, which have been made possible to calculate and construct by specially developed computational tools.

The approach in the Guggenheim Museum in Bilbao, Spain, has resulted in a clad form, which does not reveal its inner structural build-up (Fig 8 left). The structure carries an advanced exterior face with undulating forms, clad with titanium sheets, and an interior enclosing a sequence of inner spaces not following or referring directly to the exterior. Both outside and inside it is a question of sculptural form rather than a concretised structure; the structure is designed to support the architectural vision without revealing itself. The structure exists in between the architectural surfaces.
4.2 Bird's Nest

The Beijing National Stadium, China, designed by the Swiss architects Herzog & de Meuron for the summer Olympics of 2008, is a project with another relation between structure and form than in the Guggenheim museum above. The steel structure shows an advanced superstructure supporting the exterior outline which forms the concept, architectural symbol, a dominant order in which the architectural function takes place as internal, intermediate spaces (Fig. 8 right). The entire structure is in its finished state displayed, visible through covering ETFE and PTFE membranes chosen for their translucent properties.

Whereas the structure describes the exterior and circumscribes the interior, two very distinct shapes, it represents itself as a very strong symbol of structural force. The structural system is based on rather simple but large structural steel frames \[13\]. To manage the span around the inner ring encircling the opening in the roof structure, the frames are interconnected in a tangential layout around the opening. The structure itself is the symbol and main architectural feature, for which it has also been designed. The function exists in between the structural elements.

5. Discussion and Conclusions

The ways to design and construct form and function of buildings are manifold and steadily able to render man a wider and wider flora of built expressions and structural realisations. Of importance here are interplay and prioritising between the steering factors. It can be seen that for the right architectural function the optimisation of other aspects might need to be limited and for efficient production, architectural variety or structural and material utilisation may need to be modified.

The given examples from different times and contexts represent different architectural and structural aims. With limited resources, like in the 19th century, it was important to use materials in the most efficient way and to take care of the architectural possibilities of structures and materials. During recent decades the architectural form has become more and more important, and we can often see buildings formed as sculptural objects rather than as architectural functions. The goal is not to save material and, mainly because of the development of computer-based design, just anything can be constructed. Guggenheim museum in Bilbao is one example of that view and the Bird’s nest in Beijing, is another. The mentioned recent examples of sculptural architecture have as their main aims to be widely recognised in order to sell something, in the case of Guggenheim museum, the city of Bilbao and in the second case, the Olympic Games in Beijing. In that respect they are highly successful and well motivated.

However, if this way to handle architectural and structural form would be more widespread it would not be in line with ecological aims. How much does it take to stick out, and do we need to, at any cost? It is important to vary the set and treatment of aims for construction actions, but the viewpoint of sustainability should be regarded and kept. In recent years the environmental issue has been of growing importance; it is immoral and not sustainable to use more resources than necessary. The awareness of how efficient use of structures and materials is related to architectural form and in the end to an ecological way of constructing is important. As important is that the equation of optimising efforts gives a sustainable result in more than one aspect. Studies of historic construction methods are fruitful and important, to learn what have been created with limited means. What do we optimise, why, and can we afford to do it again?
6. References


