Structurally informed decision-making by means of Data Visualisations during the Conceptual Design Phase

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Abstract
This paper presents a new approach for comparing different structural design alternatives based on data visualisation in the conceptual design phase. The aim of the proposed methodology is to focus on the overall structural behaviour and to include non-numeric architectural parameters. By having the information of all different design proposals at hand, the designer is able to make informed design decisions. Previous research will be discussed in order to introduce this new approach. Illustrated with the cases of a gridshell and bowstring bridges, it turns out that the use of data visualisation and dashboards enriches the design process and that the informed decision-making process is facilitated. What is presented in this paper is part of ongoing research and is focusing on the concept of the new approach and its research context. To have a clear understanding of this research context, an overview of terminology, difficulties of the current design process, and research topics with similar goals are discussed.

Keywords: Structural Design, Performance Aided Design, Conceptual Design, Data Visualisation, Design Decision-making, Dashboard Approach

1. Introduction
Quite often the design of a structure is based on a shape imposed by the designer or architect. The structural behaviour and efficiency is only considered in a second phase, in which the geometry is subjected to finite element calculations and in which the results are analysed. If the results are not satisfying, the design is changed iteratively. If design modifications are made in the geometric modelling tools, those changes need to be remodelled as well in the engineering tools, an approach which is time consuming and can lead to errors (Verbeeck, Loos, et al. [24]).

It is clear that optimizing structural shapes is a field in itself, but the question in the early design phase is to estimate the impact of different structural topologies and to explore the design space freely (Verbeeck, Loos, et al. [24]). In the presented new approach, different design proposals are generated and structurally analysed. By the use of data visualisations and dashboards, the informed decision-making process is facilitated because all structural and architectural information of different design proposals is present in a comprehensive and global overview. The approach is aimed to offer the experienced (structural) designer a synthetic view of the whole, whilst not reducing the structural behaviour to a single number, such as maximal internal forces etc.

Before introducing the new approach, an overview of the current design processes and the shortcomings they exhibit, will be discussed.
2. Conceptual design

2.1. Design process

Currently, a succession of different steps exists in the building industry, from the very beginning till the completion of a construction or building, and each phase requires a specific set of skills and expertise. The very first step, the design process, is in general divided in four successive phases: conceptual design, schematic design, design development and construction documents (American Institute of Architects [2]). During the conceptual design phase, designers are exploring the design space through design alternatives. Different concepts and geometries that fit within the requirements and the architectural ideas are generated. Base principles, reasoning, argumentations and/or justifications can be set as requirements (Rolvink et al. [18]).

The conceptual design is achieved by an incremental learning process consisting of the generation and evaluation of a set of design alternatives (Wang [25]). The nature of these processes is divergent and convergent respectively. Selecting the most promising design proposals accompanies this evaluation process (Liu et al. [9]) and the practice of comparing design alternatives is of great importance in this selection procedure as it helps the designer in checking if the design fulfils the requirements (Woodburry and Burrow [26]), whatever these requirements are.

2.2. Integrated design

The conceptual design phase is of great importance in the overall design process since the design conception highly influences the architectural requirements (Turrin [20]). Important design decisions, such as the building’s overall geometry, are therefor made during this conceptual design phase (Hsu and Liu [5]), and is traditionally carried out by architects without the input from structural engineers (Clune et al. [3]). After the conception phase, engineers are asked to analyse the imposed design and they have to propose a structural solution that fits within the conceptual design. This means that the structural considerations are often subservient to the conceptual – fixed – design and rarely have an impact on the general design (Macdonald [11]).

However, it is known that the overall geometry is an important factor for a structure’s performance (Allen and Zalewski [1]). Hence, it would be better to take the structure’s geometry and its structural behaviour into account during the conceptual design phase of a building or construction. The combination of the architectural design with other disciplines such as HVAC, structural design, construction management etc. is called ‘integrated design’. An integrated structural design approach results in better structural performing solutions. Hence, fewer resources will be needed to satisfy the same boundary conditions, resulting in a direct ecological benefit concerning required energy and mass (Mueller [14]).

2.3. Computer Aided Conceptual Design and the lack of structural input

Unfortunately, an integrated design approach is rarely applied in practice nowadays. The reason for this is the very sequential design process in which the engineer’s work is often subservient to the architectural design decisions (Macdonald [11]). Turrin [20] states that the lack of structural input in the conceptual design is a direct result of the limited selection of considered requirements. They are mainly based on issues of visual and functional aspects, disowning a whole range of other types of performances and leading to post-engineering processes (Turrin [20]).

Furthermore, the specificity and characteristics of the software applied by architects and engineers further hinder the integration of structural considerations in the (early) design phase (Clune et al. [3]). They are either suited for the first architectural conception phase or for the structural calculations done afterwards. Architects use geometrical modelling tools that stimulate the exploration of the design space and creativity, mostly without considering structural performance. Geometrical scripting approaches like parametric modelling are gaining importance in the current design practice. A well-known design
tool is the plugin Grasshopper (Fig. 1) for Rhino3D, in which parametric design scripts can be created intuitively. The use of parametric modelling allows designers to explore the design space in a renewed way. Instead of designing based on intuition and by using traditional methods, parametric modelling allows designers to explore complex geometries based on a definition or script.

Although it might seem that parametric modelling only eases and widens the creativity and exploration of the designer, the design space is narrowed to the definition of the particular parametric script. Harding et al. (Harding et al. [4]) suggest that the design method of parametric modelling may have benefits if the building or structure’s topology is already known, but that the top-down method of generation may hinder the conceptual design phase. Indeed in the first steps of a design, the designer possibly wants to explore the design space without any topological limitations.

Figure 1: Parametric design environment of Grasshopper. Data and geometries can be scripted by linking components (designcoding.net 2016)

Engineers on the other hand use tools for structural calculations, in example finite element analyses. As stated by Rolvink et al. [17] the current tools for the structural engineer are meant to use at the end of the design process in which there is need for analysis or documentation, rather than making design decisions. In addition, most engineering tools are not developed for the early design phase in which a lot of design decisions are still open. Instead, the computational tools for structural design and engineering require very specific information and input which is not yet available in the preliminary design concept (i.e. exact dimensions of elements, material properties, exact load cases etc.) (Rolvink et al. [18]). In addition, the results generated with a finite element analysis software can in general only be checked case per case, making it hard for the structural designer to compare design alternatives (Verbeeck, Loos et al. [24]). However, as discussed before, the intrinsic process of the conceptual design phase consists of comparing design alternatives. In the next paragraphs, some methods and tools that include structural considerations in the conceptual design phase are discussed.

3. Integrated methods for structural conceptual design

There are currently only a handful of tools that enable designers to bridge the gap between architectural and structural considerations in the first design steps, all with their specific focus, complexity, user interactivity and required technical background. Each of the existing structural design tools has its own goal and is very suited for a specific use. In what follows, the main categories of ‘structural’ design tools will be listed and their advantages and drawbacks will be discussed briefly.

3.1 Graphic statics

The principle of graphic statics is a useful structural design tool. The books ‘Economics of construction in relation to framed structures’ and ‘Die graphische Statik’ from respectively Bow (1873) and Culmann (1875) are fundamental references and the method has been used till the 1960s for both design and analysis of constructions. ‘Graphic statics’ is a graphical technique that enables the structural designer to visualise the behaviour of truss structures and to anticipate on it. Recently there has been a growing interest in this topic because it eases the interaction with the designer when implemented in a digital
design environment. In example, eQUILIBRIUM is a digital learning platform where graphic statics can be explored interactively (Van Mele, Block et al. [21]). Figure 2 shows the reciprocal graphic statics diagrams: form and force polygons. These show respectively the geometry and the internal forces of the truss system. However, some drawbacks are linked with this interactive method. The main drawback is that it is generally only applicable on statically determinate structural systems and that it is hard to easily extend towards three-dimensional systems. Furthermore most digital graphic statics tools work on preset examples and do not allow for having feedback on a design problem presented by the structural designer (Mueller [14]).

Figure 2: eQUILIBRIUM, an interactive online tool on graphic statics. (Van Mele, Block et al. [20])

3.2. Form-finding and optimisation algorithms
The last main category comprises the various form-finding definitions and optimisation tools. The geometry of a form-found structure is univocally determined by the applied form-finding load and structural principles (i.e. tension-only, compression-only). Familiar examples are compression-only shells, tensile membrane and cable net structures (Fig. 3). These algorithms offer the structural designer a method to obtain highly performant structures, however architectural qualitative or subjective parameters are hard to include. Form-finding does also not help exploring the design space since the structural topology is mainly defined by the form-finding method. As Mueller states it: “Unlike the human design process, optimization on its own cannot handle unformulated objectives and constraints” (Mueller [14]).

Figure 3: Framework developed by Van Mele, De Laet et al. [21] for form-finding tension structures with elastically bent, linear elements, integrated.

3.3. Real-time (numerical) structural analysis or feedback
Other tools are based on real-time numerical structural analysis. Changes of the geometrical and structural parameters can be understood immediately. A well-known example of this approach is the Karamba tool that can be used in Grasshopper. Karamba provides finite element analyses and enables
to calculate in real time the internal forces and deflections of spatial trusses, frames and shells (Preisinger [16]) Real-time numerical structural analysis might help to make structural design decisions in the design phase. This kind of tools however are often still a feedback-only way of integration.

More and more parametric design tools are including solvers to perform optimisations within the parametric model. However, one must keep in mind that this process of optimisation only acts within the scripted typology or parametric model, probably resulting in a sub-optimal solution. This creates the ‘illusion of optimal design’ (Harding et al. [4]). Furthermore, all in- and output parameters of such an optimisation within a parametric design environment needs to be expressed quantitatively. Though, qualitative parameters such as aesthetics, social impact, iconography etc. are as important for an architectural design (Harding et al. [4]).

4. Informed decision-making during the conceptual design phase

Performance oriented architecture searches for well-performing design solutions. Yet, one must admit that – within the field of structural engineering – one often puts emphasis on the structural performance only, resulting in mono-disciplinary investigations. Turrin [20] describes ‘architectural performance’ as “the capacity of a building to fulfil the architectural requirements, in relation to human needs and environmental factors”. It speaks for itself that a designer may not be restricted to the use of just quantitative or just qualitative parameters only to define a well-performing design but that a performance based design should ideally include as many disciplines as possible. In addition, the designer should have enough information about the different design alternatives and all considered parameters.

In the previous section, the lack of blending subjective architectural parameters with structural quantitative parameters in the conceptual design tools has been discussed. Currently these integrated methods/tools for structural conceptual design do not allow looking for structurally well-performing structures and designs that meet an architectural concept at the same time. In other words it is hard to search for well-performing structures that comply with both quantitative and qualitative needs in a user-friendly manner with the current ‘integrated’ design tools. These tools can also not be used as a general method applicable for all kind of structural typologies. Still it is desirable to explore the conceptual design space over a whole range of typologies, structurally or parametrically.

In order to integrate the non-quantitative parameters in the conceptual design method, there is need for a designer-interactive structural design approach that puts emphasis on exploration, the allowance for a plurality of design options, structural performance, comparison and user-interaction, as suggested by Mueller [14]. The designer will only be able to easily compare different design alternatives when he/she has all information of all different design proposals at hand. A structured manner of comparing is therefore needed.

5. Focus on data visualization for making informed design decisions in the conceptual design phase

The authors suggest that the use of data visualization in structural design is worth to investigate. It enables designer-interactive structural design in which the data visualizations help the designer to make informed design decisions. In addition, it should be possible to compare design alternatives of different typologies.

5.1. Data visualisation

Data is currently generated at very high volumes and the generation rate is still speeding up. The exploration and analysis of these vast volumes of data is increasingly difficult. However, information visualization and visual data mining often helps to deal with a lot of information. The advantage of visual data exploration is that the user does the most important part: he is directly involved in the data mining and interpretation process (Keim [7]). Joyce [6] states that data visualization is the link between
graphic design and quantitative information. In addition, the discipline of data visualization searches for the cognitive understanding and interpretation of graphical figures by people (Joyce [6]).

Nowadays data visualization is used a lot in all different kind of fields. Main reason is the availability of relative easy-to-use tools. Think of the well-known chart-makers implemented in MS Office. Also more complex visualisations can be found in a whole range of topics; in example the popular publications “Information is Beautiful” [12] and “Knowledge is Beautiful” [13] by Mc Candless. New tools are making the way for more user-interactive dynamic visualisations on the web. The new web standards implemented on modern web browsers and the relative ease of scripting these visualisations are making interactive data visualisations more accessible (Joyce [6]).

5.2. Applicability for structural conceptual design

In the paper “Web Based Data Visualisation Applied to Creative Decision Making in Parametric Structural Design” Joyce [6] states that the quantitative data output of structural analysis software is often shown in table format and that “this fits into current workflows where often engineers manually copy large tabular information into Excel spreadsheets, which are developed individually by the engineer to generate new tables and further calculations to summarize and digest this information.”

A possible way to compare different structural geometries is to model a geometry, conduct a finite element analysis with all load cases and run the code checks with optional optimisation to dimension and verify the structure. After the dimensioning, the structural models will have a clear output: the weight of the structure. Based on this parameter, one is able to compare different design alternatives. However, this approach might become very time consuming when wanting to compare a whole series of topological alternatives. Furthermore, an experienced structural designer will start to point compare structures: maximal normal forces, maximal bending moments, maximal deformations, etc. Yet this gives punctual information about peak performance, while neglecting the view on the overall performance and behaviour (Verbeeck, Loos et al. [24]).

This way of working is not appropriate at all for the conceptual design phase in which comparing various design alternatives (in example generated with a parametric design approach) is essential and in which informed decisions need to be made based on the overall structural performance and behaviour of the design alternatives (Joyce [6]).

This research however explores a new approach in which visualisations and representations ease the comparison of different design proposals in an early design phase. As mentioned before, the advantage of visual data exploration is that the user is interpreting the data himself/herself, instead of relying on algorithms. This enables the designer to make decisions in an informed way. The authors investigated the use of dashboards for structural conceptual design. By using the dashboard, the (structural) designer has all necessary information at hand to compare the structural behaviour of the various proposals. This facilitates the choice of a proposal that both satisfies the architectural and structural criteria. In concrete terms, the dashboard is a collection of graphs, representing structural information such as internal forces and displacements under a reference load (Verbeeck, Loos [10][24]).

In what follows, some specific case studies of the authors will be discussed briefly, rather than presenting a finished tool. The aim is to show the possibilities of interactive data visualizations applied for structural design.

5.3. Dashboard approach and workflow

In the paper “Enhanced decision making in the structural design process by means of a dashboard approach” (Loos, Verbeeck [10]), the authors investigate the use of a dashboard through which the comparison of bowstring bridges in an early design phase is assisted. Various bridge geometries are generated in the parametric design environment of Grasshopper (Fig. 4). Parametric modelling serves
the opportunity to quickly generate a variety of geometric models that can easily be implemented in the further workflow of the comparison tool.

![Figure 4](image)

**Figure 4:** Different design proposals of bowstring bridges that are subject of the comparison tool. Geometries on the same row have the same cable configuration, while the models in the same column have a similar bow shape.

In order to get structural feedback on each of the design alternatives, a finite element analysis is done. One single reference load case – representing the selfweight – and typical cross-sections are introduced. This load case and these cross-sections are identical for all investigated structural design proposals. This way a quick linear finite element calculation can be done, without the need for dimensioning all structural proposals. A certain error is initiated with the use of the reference load and general cross-sections, however the aim is not to have quantitative exact results while comparing all design alternatives, but to have a qualitative overview of the structural behaviour of all proposals. Based on the interpretation of this behaviour, the designer can make a well-informed comparison.

![Figure 5](image)

**Figure 5:** Some graphs of the dashboard in which four structural models are visible: MN-chart (left bottom), line graphs (right). By having interactive data visualizations, the designer is able to do well-informed comparisons.

The outcome of these quick FE calculations is post-processed to gather the information of all models in a dashboard overview (Fig. 5). The interactive dashboard allows the designer to hide and show all structural proposals and their represented structural information individually in order to have all essential parameters for comparison and interpretation at one single place. The dashboard contains several graphs. The MN-chart (Fig. 5) displays the internal axial force and bending moment of all structural elements (bars) of the numerical model; each dot represents one structural element. The horizontal axis represents the bending moments while the axial forces are located on the vertical axis.
This representation gives a first understanding of the overall behaviour of the structures, each in its own colour. Also line graphs are included for a more detailed view on the distribution of the internal forces in the entire structure (Fig. 5). The axial forces and the bending moments are represented for both the deck and the arch, resulting in four different line graphs. For a more comprehensive discussion of the particular dashboard, the reader is referred to the paper “Enhanced decision making in the structural design process by means of a dashboard approach” (Loos, Verbeeck, et al. [10]).

This way of nuanced comparisons facilitates the choice of proposals that both satisfy the architectural and structural criteria, rather than looking for the strict structural optimum whilst ignoring architectural needs. The dashboard for bowstring bridges informed the structural designer well in the early design, however the visualisations remained quite linear and not appropriate for more complex structural geometries.

Another more complex case study by the authors deals with gridshells (Verbeeck, Loos, et al. [24]). The use of a dashboard approach for gridshells is investigated and the approach focuses mainly on the inclusion of all structural elements in the dashboard, instead of relying on maximal forces of only a few elements. Also here, all design proposals are numerically calculated considering one section for all elements and a reference (self-weight) load case. The internal forces and displacements of the various alternatives were sorted and plotted as a line graph (Fig. 6). This way, the structural designer gets a better insight into the overall structural behaviour of all design proposals and the distribution of forces throughout the entire structure. This first proposal of a dashboard was conceived static without user-interactivity. It shows clearly that interaction with the designer is important; displaying a bunch of graphs on top of each other is rarely easy to read and makes the interpretation hard. Nevertheless, the strength of this representation is that the (structural) designer can quickly make an abstract interpretation of the structural behaviour of all proposals. For a more detailed explanation on the used dashboard and the validation of the method, the authors refer to the published paper “Structural design by a dashboard approach” (Verbeeck, et al. [23]).

Figure 6: Dashboard with the represented structural information of nine different models. The axial forces, bending forces and displacements are included for all elements. This way, a lot of information can be visualized in a compact dashboard without the need for looking at tables and graphs at different windows of the finite element software.
6. Further research and conclusion

Part of on-going research is the use of structural ‘finger-prints’ that enable the designer to have a quick view on the structural behaviour of different design alternatives. Figure 7 shows the representation of two design alternatives of a gridshell structure, in different colours. All elements of the structural model are represented as dots and their positions are related with the internal forces under a reference load case, just as the regular MN-chart discussed above. However, when the structure contains a lot of elements, the chart can be used as a structural ‘finger-print’ by which the designer gets immediately an impression of the differences in structural behaviour of both structural models, based on the visual clustering and interpretation of point clouds. Model A is mainly working in compression and the bending moments are relatively low, while model B contains elements in tension and has a much larger spread of internal forces. In addition, the spread of dots gives the (structural) designer a preliminary insight in the needed cross-sections, as the chart enables him/her to get a quantitative insight into the internal forces of all elements.

![Image](image_url)

Figure 7: The idea of structural fingerprints, based on the MN-chart.

As a conclusion, it turns out that the use of data visualizations and dashboards for conceptual structural design is useful and worth to explore further. User-interactivity becomes very important when dealing with a bunch of design alternatives. The development of dashboards and the search for instructive graphs will continue to focus on the visualisation of the structural behaviour and performance. A further exploration of useful parameters for comparing, will be of utmost importance. The use of strain energy and stiffness as performance assessors within the use of data visualisations will be investigated on a variety of typologies. Till now, all case studies remained within a certain typology (bowstrings, gridshells), but the aim is to compare design alternatives of different structural typologies. By exploring over various typologies, the design space exploration is facilitated and not limited anymore to any assessment difficulties.

7. References


