LINKING PARAMETRIC DESIGN AND STRUCTURAL ANALYSIS TO FOSTER TRANSDISCIPLINARY DESIGN COLLABORATION

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Abstract. The investigation presented in this paper focuses on the following questions: How can engineering and architectural expertise guide a process of digital optimisation and add structural 'awareness' in real time to aesthetic considerations (or vice versa)? How can building geometry be set up computationally in order to render it 'sensitive' to structural input? Which tools are required to foster this interaction?

The authors of this paper form a team of researchers and practitioners from architectural and engineering background who combine their efforts to address the issue of interconnecting design intelligence across disciplines and advancing work methodologies in practice assisted by academic research. A live case study project is presented as a test scenario in order to find answers the above questions.

1. Introduction

Removing engineering and engineers from the design process has gradually separated architecture from the general technological knowledge of culture. (Robbin, T., 1996)

Although working on common projects, architects and structural engineers are inherently concerned with different theories and objectives, using different measures and tools to reach their goal. This current status is mirrored in the software solutions used by these professions. Analysis and optimisation tools are dedicated to facilitate services and provide decision support to individual specialist, but at the same time, they have little to no capabilities for interfacing design intelligence across disciplines. (Chaszar, 2003; Malkawi, 2004)

This paper investigates linking architectural design closer to structural optimisation through streamlining the connection between flexible (parametric) modelling, structural analysis and optimisation. The authors combine the use of ready-made applications for parametric design and engineering-analysis with a custom-developed optimisation and code-checking tool to foster the collaborative process. By doing so, challenges and potentialities to the modus operandi of architects and engineers arise and current models of interaction between the two professions are scrutinised.

The research presented here has been carried out in a collaborative effort from researchers at the Spatial Information Architecture Laboratory (SIAL) at RMIT University in Melbourne, Australia and practitioners from Arup Engineers in Melbourne and Sydney. Two main goals were defined by the collaborative team: The first was to provide designers with close to real-time structural feedback in the design process for decision support. The second was to integrate engineering intelligence in the morphological generation of a project in a concurrent, transdisciplinary fashion rather than using it to facilitate the construction of a pre-given idea. This was done by investigating heuristic strategies for both professions to examine the interconnectiveness of their design methods and the exchange of data in a concurrent design process. The terminology *transdisciplinary* describes a work-method which aims at sharing knowledge gained during production in collaborative teams and which transforms disciplines involved by making that knowledge subject to social accountability and reflexivity. (Gibbons et al, 1994)

2. Background Research

The definition of 3D computer models as flexible design templates for the creation of alternative design solutions through parametric design is an effective method for opening up a dynamic information flow between various members of an architectural project from the conceptual phase to production (Burry, M.C. 1999; Hensel, 2006). In recent years, a number of designers and design researchers have investigated the possibility of linking parametric design with engineering analysis and optimisation processes to allow for a concurrent work methodology across disciplines.

The work on the parametric bridge (Maher and Burry, 2003) illustrates how a predefined set of fabrication constraints can be the driver for parametric alterations for iterative shape optimisation. In the bridge project, results from the built-in structural analysis package of the parametric software were compared with the analysis tools used by the engineers working on the project. Target values were used to drive the shape-optimisation of the bridge through a dedicated tool (Product Engineering Optimiser).

Optimisation tools can address a variety of tasks depending on specific project requirements and the design overall progress. As described in *Structural Systems Optimisation Techniques for the Building Industry* (Baldock, 2004) a distinction is required for several structural optimisation tasks between *size* (member sizes & cross sections), *shape* (geometry & size of a fixed topology), *topology* (for a structural system layout) and *functional layout* optimisation.

In this context, the application of the stochastic shape optimisation software EifForm with the parametric tool Custom Objects (Shea, Aish and Gourtovaial, 2003) has shown that, by combining the two, a rich array of solutions can be found for complex design problems and unexpected structures could be generated. The upgrade of the role of the computer from being a design assistant to being a design generator is possible through a tight link between associative geometry, structural performance evaluation and structural optimisation.

3. Research Methodology

A live project has been chosen to allow the authors direct exposure to an actual design problem with a high level of complexity. The project (a stadium roof structure designed by Cox Architects in collaboration with Arup Engineers) was in an advanced stage of schematic design at the commencement of the author's involvement. Working in this advanced design stage facilitated design input during the project's transition from the pre-ideation to the production phases. The authors were confronted with several unresolved design aspects which required optimisation in regard to structural stability and manufacturing constraints.

The project team has expressed their interest in being able to create slight variations in the geometry of the project to run structural analysis and code-checking in order to better understand the behaviour of the distribution of loads, the overall tonnage and the member sizes required. In order to address these issues, a precise definition of the type of analysis required was communicated amongst the team of architects and engineers in the beginning. 'Suitability' rules were defined by all involved, which put architectural and aesthetic considerations in relation to structural performance by setting up flexible design variables in direct relation to parts of the geometry which had a strong influence to structural behaviour. This basic configuration required input from both architectural as well as structural engineering expertise.

The immediate goal of the project team was to find an optimal shape of the roof structure which should be aesthetically pleasing, structurally sound, dividable in easy manufacturable entities and as light-weight as possible. The automation of geometry updates, data transfer, structural analysis and code-checking was expressed as a long term goal by the research team [figure 1]. The idea of an intelligent feedback loop guided through 'suitability' rules assisted by the storage of geometrical and non-geometrical information of the stadium roof in a database was discussed.

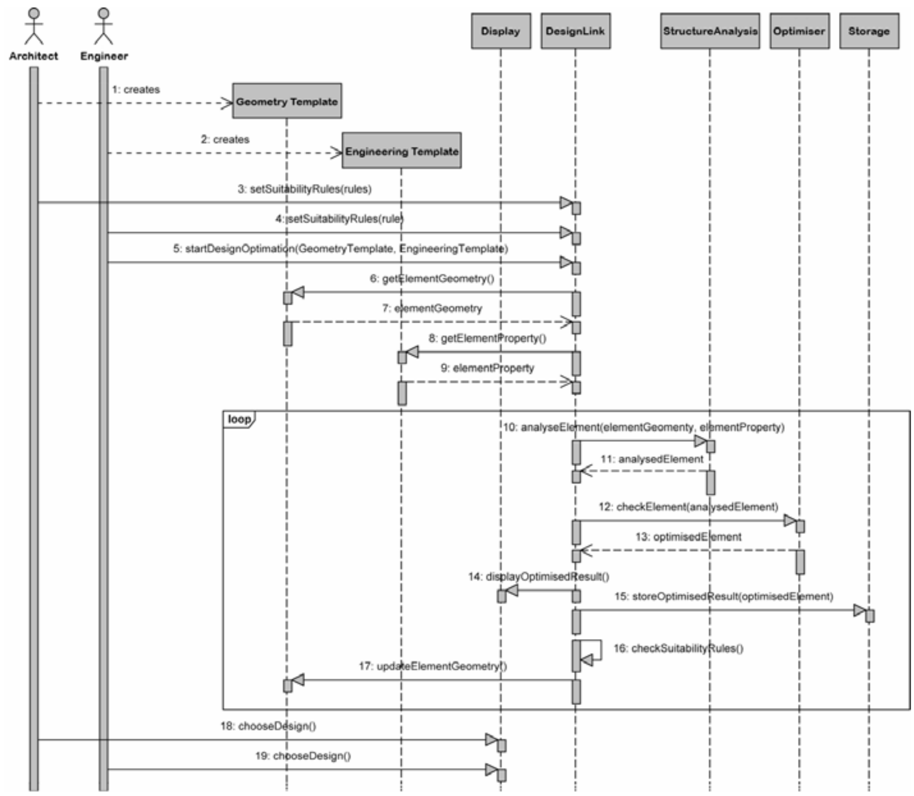


Figure 1. Proposed Process Flowchart, UML diagram

4. Project

Once the principles for the link between the flexible design parameters and the structural optimisation requirements had been defined, the authors created a flexible 3D model in the parametric design tool Catia which allowed for varying the main stadium roof sweep and the sweep of the individual shells of the stadium roof through simple numeric input of a curvature ratio. The range of change for the overall sweep was defined by the 'high-ball line' – a minimum height for the roof in accordance to the field of vision of the spectators towards the pitch – and by structural considerations where a sweep of approximately 1:15 (height to length) was desired. In addition to that, the architects wanted a strong articulation of the individual shells comprising the stadium geometry [figure 2].

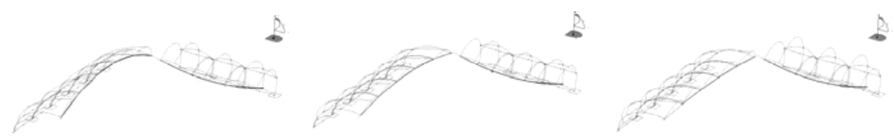


Figure 2. Parametric variations in roof curvature definitions.

A custom developed script running within from Catia has been applied to create a lattice representing the centre-line of steel members for subdividing the individual shells of the stadium roof [figure 3]. Several options for the density and rotation of the grid could be generated and they updated the structural layout automatically once the boundary curves of the shells were altered.

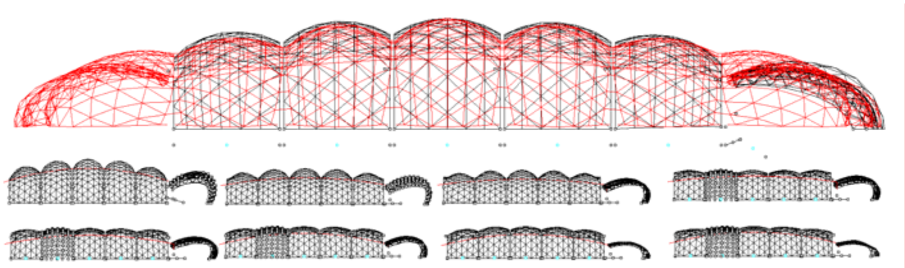


*Figure 3.*Elevation of variations of the stadium grid.

Results from the flexible model have been exported from Catia (via Rhino) to the structural analysis packages GSA and Strand in dxf format. Geometry updates could be generated and read into GSA/Strand within a timeframe of 5-10 minutes [figure 4]. Loads cases and restraints were transferred from the basic GSA/Strand setup without requiring manual input as long as the amount and logical definition of nodes and elements did not change. The engineers were then able to run a code-checking application (the 'optimiser') over the model. Once the optimisation was completed, the software displayed detailed assignment of member sizes, associated with varying colours which directly corresponded to stresses in those members [figure 5]. The results generated by the optimiser could be put out as an excel spreadsheet and visualised in graphic tables as a by-product of the optimisation process.

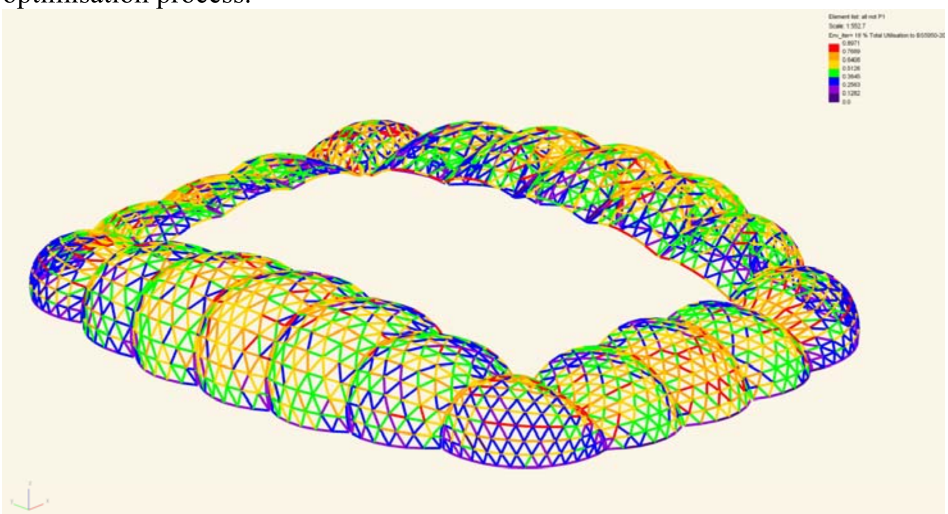


Figure 4. Stadium roof stress distribution diagram.

The optimiser is a custom-developed application that has been developed within Arup. In contrast to the traditional engineering method of deriving member sizes for stressed elements from tables and charts, it allows to evaluate the most appropriate member size of each structural element individually. A computational algorithm is checking several load-conditions for each member and assigns the appropriate member size given a specific material. This procedure is instantiated as an automated process and can be applied for complex structures with a high amount of members to be checked.

By assigning the member size required instead of a standard size derived from a table, tonnage could be reduced. Once a complete set of members was optimised, results were grouped according to production constraints. Results from the optimisation process were obtained within a timeframe of approximately 30 minutes. This assisted the research team in their effort to narrow the gap between evaluating

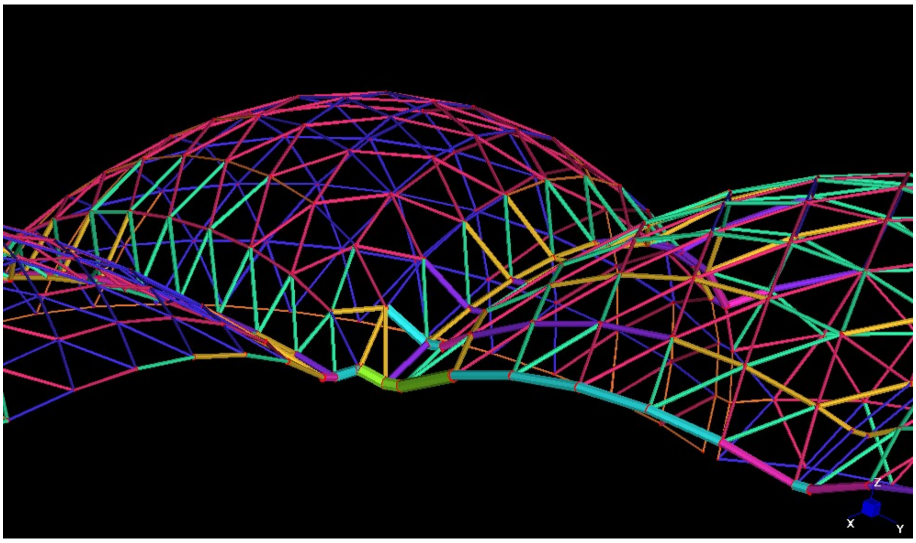
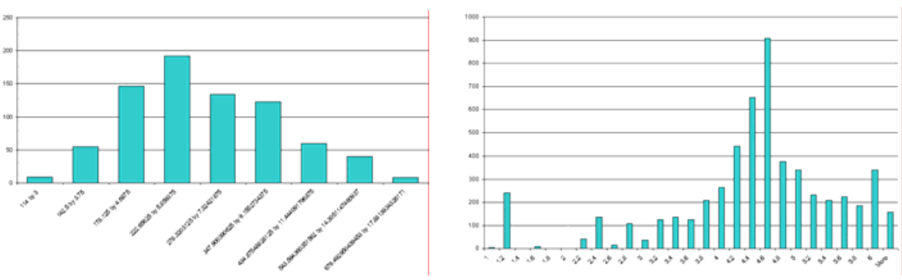


Figure 5. Detail of roof, optimized member sizes.

After the generation of each variation of the geometry in the Catia model, the coordinates were exported to the structural software for buckling analysis. These results were then taken as basis for running the member size-optimisation and solutions of the optimisation process were read out from a spreadsheet to a graphic display. The authors were able to analyse the effects of varying the curvature coefficients in the variation in member length, member sizes and overall steel tonnage. The information at hand provided essential decision support for determining the direction of which to alter the curvature sweeps of the stadium. Informed by the knowledge visualisation from the graphs, coarse resolutions for the stadium roof geometry were looked at initially and then refined over time [figures 6,7].



Figures 6,7. Graphs displaying member-size groups, tonnage per group and required steel-member length.

5. Critical Analysis

During the first three month of the development and testing of the parametric model, the authors encountered difficulties due to ongoing external changes in the stadium geometry. In this stage, a series of design parameters which were assumed fixed, had to be altered and consequently the flexible model had to be updated constantly. These changes were required due in aesthetical, legal or financial considerations and included inter alia a revision of the main grid of the project, an alteration in the position of the main roof supports and the variation of the extent of the roof cantilever towards the pitch. In most cases, the changes could be accommodated in the Catia model, which lead to an increasingly 'flexible' setup. At the same time the complexity of associative dependencies got increased which had its effect on the hierarchical organisation of design parameters within the Catia file.

As much as the increased shift from fixed numerical coordinates to a more associative geometry allowed the authors to get a better understanding of the 'design intent', it proved a difficult task to accommodate changes in the parameter-setup 'on the fly' in particular when tight deadlines for submission were involved.

At one point in the setup of the parametric model, changes required by the design team were of such a disruptive nature that the parametric model could not cope with their inclusion. The 3d model consequently fell apart and parametric integrity could not be re-established in the original model.

Lessons learned from this experience lead to the insight that the setup op one all-encompassing flexible model, capable of accommodating any kind of changes to the geometrical setup of a project is not advisable. As the definition of alterable parameters responds to a clearly defined optimisation process, major changes are likely to interfere with the logical structure of the parametric model. The alternative approach is the setup of not one, but several flexible models that each can each address a particular aspect of the performance optimisation being sought..

In regard to increasing the transdisciplinary workflow and the aim for real-time feedback, the link between parametric software (Catia) and the structural analysis package GSA via dxf was inappropriate for facilitating automation in data transfer and hence real time interaction between architects and engineers. Direct output of geometrical information from the parametric model via a custom script offered a better alternative and has been facilitated by the authors through direct binary data transfer from Catia to GSA. The current duration of the optimisation process of approximately 30 minutes is depending on the complexity of the project and on computational processing speed.

6. Conclusions

By linking parametric design to structural analysis and optimisation, a tight information flow can be established between architecture and engineering intelligence. The setup of any such flexible model requires a priori input from experts of both professions to define suitability rules that guide the process towards a specific performance goal. The rate of success depends on the precise definition of quantifiable design variables across disciplines and the awareness of the extent of variations being sought. The implementation of this method is dependant on the progress of the project according to the design stages. In the case presented, it is not aimed at optimising changes in topology or an entire functional layout, but rather for member-size optimisation in an advanced stage of design with a direct link to production constraints.

From an architect's perspective, the immediate visualisation of structural feedback provided by the engineers proved very valuable to understand the effects of changes which might otherwise only be driven by aesthetic considerations. The opportunity of visualising and distributing results from structural optimisation in close to real time enables the transdisciplinary team to evaluate options and propose changes in a highly informed manner. At the same time, the graphic output of the optimisation results gives a clear impression not only of the intelligence the structural engineers are deriving from it but also allow the architects to gain insight in the work-methodology of the engineers, the tools being used by them, and the design constraints they are confronted with from a structural perspective.

7. Future Research

The authors continue their investigation in particular in regard to developing a more automated work-methodology. An application logic is currently being investigated for closing the information loop between geometry update and structural optimisation by introducing generic algorithms which negotiate between suitability rules to drive the design.

Acknowledgements

The authors would like to acknowledge the assistance of Alex Edwards and Tristram Carfrae as well as John Bahoric and Frank Gargano from the Arup offices in Sydney and Melbourne.

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