

Design Using Evolutionary Optimisation and Associative Geometry

Architect Engineer interaction

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Abstract: This paper describes the usage of parametric design and evolutionary optimisation techniques in architect-engineer collaborations. It discusses the apparent challenges in setting up a trans-disciplinary working-platform that cuts across profession-specific boundaries and negotiates between the otherwise distinct work-methodologies through the use of intelligent CAAD applications. Two approaches to architectural form finding have been combined in this research. The first, parametric design, uses a proprietary package as a key element to the organisation and reorganisation of architectural design. By doing so, it is providing it with intrinsic flexibility allowing designers to go beyond form and accommodate performance data for versioning. The second, ESO (Evolutionary Structural Optimisation), is an engineering tool based on the use of finite element analysis (FEA) capable of optimising the formal geometry of an object to obtain minimum volume under even stress-distribution through an iterative design process. In undertaking this research it became apparent that different levels of resolution need to be addressed in the form-finding process in order to investigate the full potential of the interactive use of parametric design and evolutionary optimisation. The case studies reflect this diversity and demonstrate more successes, limitations and future challenges within the transdisciplinary, collaborative effort.

1 INTRODUCTION

‘Intelligent application of CAAD-CAM techniques allows us to design in a fashion that privileges variety, complexity and local responsiveness over standardisation, repetition and tight spatial disciplines characteristic of the industrial age’ (Mitchell 2002).

High level CAAD tools offer architects and engineers a wider spectrum of liberties and choices during creative and analytical form finding processes. Both professions individually have embraced new technologies to add a component of flexibility to

Design Using Evolutionary Optimisation and Associative Geometry

their work-methodology facilitating the creation of more daring, non standard design solutions. Software packages for simulation and analysis purposes have shifted the architectural domain over the past few years towards knowledge-based design, allowing checking of particular elements of design in regard to performative aspects (Eastman 1997). There is a preeminent question related to this subject. Can these tools be used as interfacing applications to enhance the morphological development of a design from the early stages on? Furthermore, in order to profit from new possibilities provided by CAAD on a practical level, we need to overcome the divisions that have gradually separated the discrete professions involved in the building process over the past decades, and synergise our efforts collaboratively towards a more streamlined work methodology. We know from the past that the human mind is capable of such thinking. As illustrated by the work of Antonio Gaudí, (Figure 1) the synergetic interplay of architectural expression and structural optimisation can generate a formal poetry that reaches far beyond the possibilities of each discrete profession. This is what gives us confidence. We are learning from the past 'conference theme' to generate tools and methods for the future (Figure 2-4).



**Figure 1 Passion Façade Figure 2-4 Passion Façade ESO model
A.Gaudí drawing (reproduced from an image supplied to Mark Burry by the
technical office of the Sagrada Familia church).**

This paper focuses on two questions, firstly, how can design be structured; which are the most satisfying interfacing methods to obtain useful performance data in an architect - engineer collaboration? Secondly, what level of reorganisation is required for fostering the synergetic effect gained through the common use of CAAD/CAM applications by architects and engineers? In order to answer these questions, trans-disciplinary research has been undertaken on the basis of two case studies: The Beijing Biennale project and the Melbourne Docklands tower.

2 LINKING THEORETICAL RESEARCH TO PRAXIS

The collaboration between architects and engineers which enabled the research for this paper is based on the setup of the 'Innovative Structures Group' at RMIT University in Melbourne, Australia. The collaborative group consists of researchers from SIAL (Spatial Information Architecture Laboratory) and the Civil Engineering faculty at RMIT as well as experts from praxis of both architectural and engineering background. The group meets on a regular basis to explore and discuss new means of linking academic research to everyday praxis through a series of case-studies and actual building projects. Intensive one-on-one sessions between architect and

engineer complement the collaborative effort. As a former associate of a high-profile European architecture practice, the lead author has gained empirical insight into the difficulty of ‘modernising’ working-methodology of collaborative environments in the building-process. In the course of various collaborations with renowned international consultants, it became evident that the potential of 3D CAAD is not yet efficiently utilised to channel the knowledge of diverse disciplines into one synergetic outcome. The possibility to embody aspects of structure or constraints in the morphological creation of a single 3D design environment was seldom if ever explored. SIAL, as part of the ‘Innovative Structures Group’ is a very unique institute that insinuates itself in practice and is therefore the ideal base for investigation in this matter. Rather than being drawn together, digital design at times seems to have the opposite effect: *‘The numerous individuals with specific expertise in discrete areas of knowledge have led to an unprecedented fragmentation of the building design/construction industry.’* (Harfmann and Bauser 2003).

3 STRUCTURING DESIGN FOR PERFORMANCE OPTIMISATION

In his essay on *‘Computing the Performative in Architecture’*, Branco Kolarevic stresses that many tools for performative can offer ‘high-resolution’ data regarding their particular domain, but are seldom capable of cross-referencing manifold input from other design, and building related components. *‘Determining the different performative aspects in a particular project and reconciling often conflicting performance goals in a creative and effective way are some of the key challenges in this new approach to architecture.’* (Kolarevic 2002). Through two case studies of increasing scale and complexity, we have learned that one way forward in resolving this problem is to apply different levels of resolution to the use of performance data when creating an interfacing application which communicates between the otherwise distinct design-criteria. To avoid an over-constraint model in the early design phase, it is essential to define a limited range of parameters that interact to generate performance data in a low-resolution approach. Selected according to the designer’s priorities, this initial data can serve to evaluate a number of basic outcomes in the morphological part of the form-finding process while referring to performative aspects. Proceeding to a more detailed level of design, more specific sub-categories of design-parameters can be applied to gain knowledge about particular design aspects in a high degree of resolution.

3.1 Parametric Design and Evolutionary Optimisation

Parametric design uses stable characteristics, *‘... providing a syntax to the description of unstable representations of form’* (Burry 1999). Designing the design through parametric values becomes a crucial aspect to associate variables, relations and dependencies to geometry and structuring the design process. Instead of deciding on a pre-given shape, an architectural model can be kept in a fluid state

Design Using Evolutionary Optimisation and Associative Geometry

allowing for intuitive alterations according to feedback of performance data from other performance-related factors. A step away from 'formal' architectural design for representation purposes towards an intelligent 3D model receptive for variation and change is essential. Multiple solutions can be analysed and selected according to the preference of those involved in the design.

There are advantages gained through the use of evolutionary optimization processes, for instance the fact that '*... controlled evolution can be formulated as a general purposed problem solver with ability similar to human design intelligence but with a magnitude of speed and efficiency*' (Frazer, 1999). Evolutionary design can incorporate a specific design-intent through generic algorithms that are applied to complex tasks and can produce unexpected outcomes in an automated process. An evolutionary process for optimization allows for multiple considerations of even conflicting design criteria. In the case of structural optimization, a generic algorithm based on multiple considerations will lead to an outcome that is required by at least one, and possibly all performance criteria. (Xie and Steven 1997). This is not only a basic property of structural optimisation but also makes sense for other types of performance-optimisation. At the same time, it also shows that the integration of multiple considerations in this optimisation can never lead to 'one optimum' solution gained through an automated process, but will always leave a margin of choice to the designers in order to define their priorities intuitively.

By setting up an architect - engineer collaboration through the integral use of parametric design and evolutionary structural optimisation, a morphological development of form takes place through parallel interaction of architectural and structural constraints. It became apparent in our research that optimised results gained through this approach have the potential to display unexpected outcomes and will always incorporate a sound structural solution no matter what programmatic alterations get applied in the versioning process. Proposals obtained in the generic optimisation process can easily drive alterations of the parametric template-model through analysis and feedback.

4 ARCHITECT – ENGINEER COLLABORATION

A synergy effect where architects and engineers strive for a combined authorship in the morphological composition of forms can only be gained through the application of high level CAAD tools if both learn how to adjust their tools and skills accordingly. This is sometimes difficult, as an ambivalent relationship can be detected between many architects and engineers based on misconceptions and a lack of knowledge about the other profession and concerns about protecting their own domain. '*With a better understanding of structures and materials, architects would be able to get far more out of the engineers with whom they work, and to do so without feeling that they are giving away advantages to the opposition*' (Addis 1994). As both aim at achieving diverse objectives and operate with substantially different skills and work-methodology, it is not surprising that their way of using CAAD tools does not automatically result in a streamlined collaboration.

It has become apparent during our research, that one of the initial difficulties in the architect-engineer collaboration is a lack of knowledge about what to expect from each other. This condition resulted in the challenge that the trans-disciplinary design team first had to get accustomed to the method of design and analysis as well as finding common file-exchange formats of all partners. Diverse methods of structural analysis-according to the purpose of investigation, ask for different organisation of an architectural 3D-model (either network, surface or solid). These differences are highly influential, not just for the formal setup of a common 3D model, but also for the choice of parametric constraints and dependencies.

A way forward in resolving this problem can be seen in studies about the integration interfacing CAAD tools in trans-disciplinary design (Rosenman and Gero 1997, Eastman 1997), which point in the direction of applications allowing multiple design views and models for collaborative design. One single 3D model appears insufficient to incorporate all functional and organisational aspects of different design partners. A central environment, capable of hosting separate descriptions of the same design element, allowing custom views, access and updates appears to be the right way forward. In order to provide the correct basics for such an environment, non-geometrical data needs to be linked with geometrical properties.

4.1 ESO in Creative Form-finding Processes

The ESO method was proposed by Xie and Steven during the 1990s. The basic concept of the ESO method is quite simple: by testing for redundancy/inefficiency, material is removed through digital sculpting from an oversized structure. The residual shape gradually evolves towards an optimum. At the end of the optimisation process, each component is indispensable within the structure. Since this method is simple in concept and effective in application, it has been applied to various aspects of optimal structural designs in the fields predominantly as civil engineering, product design and aerospace engineering. The method of ESO has already been extended to BESO (Bi-directional ESO), which allows new elements to be added or removal elements to re-enter the structure, going beyond reductive sculpting. This section of the paper focuses on the application of ESO in form-finding for complex structures by stress criterion.

First, an oversized structural geometry is created by a Finite Element Analysis pre-processor software (FEMAP) or imported to FEMAP from other CAAD software (CATIA in this research). The geometry model is then meshed to FEA model by FEMAP, considering material properties, load cases and constraints. Some of the elements could be assigned as non-design property, which always remain in the structure due to designer's demand. The FEA model file is the initial design of ESO. Following a finite element analysis the stresses of all designable elements are compared, and a small number of the most low-stressed elements are removed from the model. The removed elements have been inefficient for the structure to sustain loads. The modified model is then sent back to FEA and the second iteration begins. Most often, after 10-100 iterations we can obtain a very efficient structure, in which the material distribution has been optimized. During this process of evolution

Design Using Evolutionary Optimisation and Associative Geometry

various stress criteria could be applied. Von Mises criterion is widely used in most structures, if the material is suitable for both tension and compression. A principal stress based ESO method could be used to develop a tension-only or compression-only structure, e.g. concrete structure and cable structure.

The ESO method can be used both in conceptual design and detail design in engineering and architecture application. For a structural conceptual design, we can optimize the topology of the whole structure in order to distribute material efficiently, and in this way the structure weight and cost could be reduced. When using ESO for structural detail design, we can modify the shape of some part of a structure to reduce the so-called stress concentration. In this way, the optimized structure could be more durable.

4.2 ESO and CATIA in a Trans-disciplinary Design

Results of evolutionary processing through ESO require several hours of processing time, depending on the number of iterations. Various load-cases and setups lead to manifold optimised solutions that can be compared, analysed then offer a proposal for changing the original parametric template (Figure 5). Data transfer between the parametric model in CATIA and the engineer's FEA-based software (FEMAP) can either be facilitated through a meshing tool that links from CATIA into FEMAP through an ASCII database, or through export of the CATIA model in 'mdl' format to FEMAP.

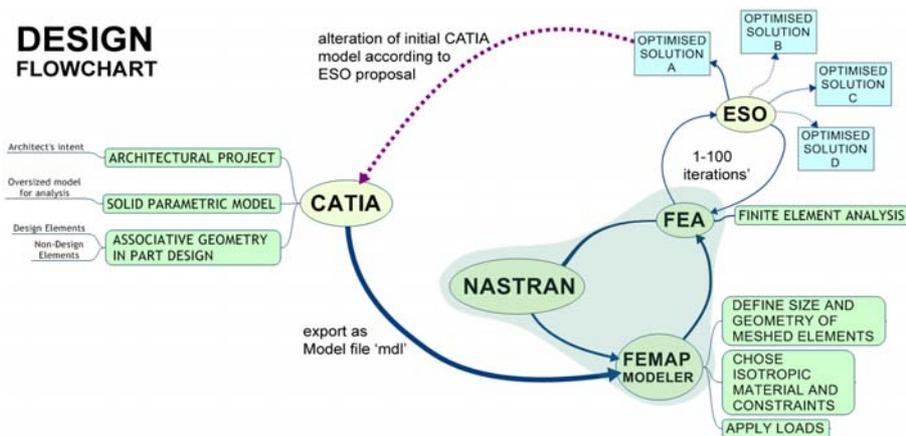


Figure 2 ESO Design Flowchart

5 CASE STUDIES

The project work shown in this paper will demonstrate parametric variables and production-related performance-data being associated during the early design phase in a selection of hypothetical and real applied practice-based research projects. It

will demonstrate the process from exploring the potential of parametric design to the usage of performance-related optimisation software and the interaction of the two. Specifically, the parametric software being used as part of this process is CATIA used in collaboration with structural engineers using NASTRAN's FEMAP as well as custom-developed evolutionary structural optimisation software ESO.

5.1 Case Study I: The Beijing Biennale Project

The research undertaken at for Beijing Biennale project was a simple pilot model to feed-back data from structural analysis to a parametrically flexible organised geometry, thereby helping to generate a structurally optimised shape. The framework for the display of the exhibits consisted out of a bamboo-elements that were organised in a self-supporting grid-structure. The performance aspect of this project lay in the attempt to associate geometry to programmatic constraints and simultaneously structural-integrity of the exhibition-layout. Definition of the parameters had to take place to resolve the conflicts between design implications of these distinct considerations. A way forward in this scenario was clearly to distinguish variables of 'non-design' elements from elements that allow for a certain margin. The first were associated through fixed parameters, the latter were defined within a range of possibilities, therefore allowing the interplay of performance-related forces.

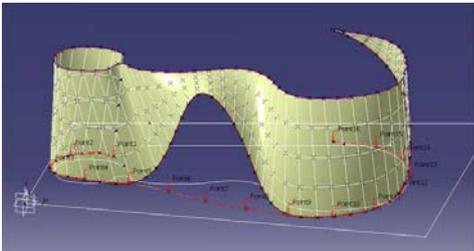


Figure 3 CATIA bamboo-model

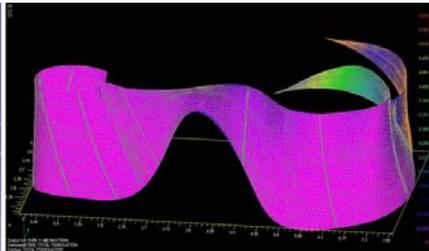


Figure 4 FEA displacement map

An attempt using a solid model to assimilate the bamboo for structural optimisation, was discussed, but rejected by the engineers as the subtractive methodology of the generic optimisation process would have reduced the template-surface to a structurally necessary minimum instead of indicating alterations for its shape. Engineers and architects agreed on a lofted 3D surface as template. On a practical level this was instantiated through a CATIA model that divided the exhibition space through lofted 3D-surfaces between a series of guiding curves in plan (Figure 6). These curves represented the initial layout and were defined by several constraints that responded to exhibition-specific design issues (e.g. viewing distances to exhibits, pathways for escape-routes, etc). The surface itself was informed by the exact divisions for a bamboo-grid, where production-relevant data of each element (position in 3D, dimension) could be extracted. Any slight change in the guiding curve had an immediate effect on all the bamboo elements, thereby updating a spreadsheet that passed on the necessary information to the builders.

Design Using Evolutionary Optimisation and Associative Geometry

The performance-data of structurally relevant parameters was acquired by exporting the surface-template to a finite element analysis tool (NASTRAN) by the engineers. Stress contour and replacement-map analysis was undertaken to pre-process the intrinsic stresses of the structure under different configurations. The idea was to iteratively approach the optimum shape through versioning and examination of the stress analysis in a feedback-loop between architect and engineer instead of limiting their task to reverse engineering.

Data transfer between the different applications worked without any major difficulties, the CATIA surface could be read into NASTRAN and analysed according to engineering constraints. The resulting FEA model (Figure 7) gave a clear indication of elements that needed stronger support and therefore alteration of the guiding curves. The data received from the analysis was nevertheless not directly applicable to the reconfiguration of the CATIA model as the analysis was based on an isotropic surface-based model instead of a non-isotropic grid-structure (like bamboo). Architect and engineer would have had to define the purpose of the analysis in more detail to actually determine which method would lead to optimum performance data. The bamboo-structure had to be built without optimisation, as time-constraints did not allow for further investigation.

5.2 Case study II: The Docklands Tower Project

Unlike the Beijing Biennale project, the a-priori goal for this case study is to research how evolutionary structural optimisation influences the morphological development of design from the early stage on. Instead of predefining a shape (in this case a tower) we have chosen to set up an oversized parametric 3D-model with arbitrary design to analyse the effects of structural optimisation. Variable structural components such as wall-thickness and parametrically alterable position of the core are set up as 'design' elements which have to support the floor-plates (defined as fixed 'non-design' elements). For the next step we are currently investigating how the evolutionary optimisation will process different morphological outcomes of that tower in relation to changing vertical loads, wind-loads and a repositioning of the core. The CAAD model used for this exercise is very simple, but will increase in complexity during future procedures. The aim is to incorporate additional parameters at a later stage that also respond to manufacturing and cost-issues of the façade elements of the tower.

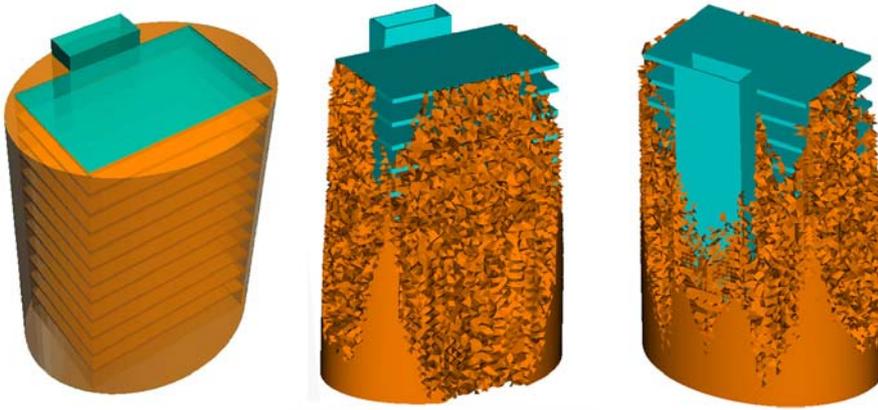


Figure 5-7 ESO tower model - Optimisation for gravity only

After 70 optimisation-iterations of the first load-scenario (only gravity forces), the evolutionary process is showing a clear structural tendency reflecting the characteristics of the momentum-stresses in the building (Figures 8-10). A far more differentiated outcome can be achieved if lateral forces are combined with gravity. Depending on the direction of impact, the generic algorithm generates unexpected structural patterns and starts to shift the building-mass in manifold directions (Figures 11-14). Following observation can be made: Increasing the percentage of ‘design’ (variable) elements in the parametric model will automatically lead to a decreased resolution of structural solutions, but also a stronger morphogenetic impact on the initial volume. This effect gets diminished if multiple-load considerations get applied simultaneously in the optimising process. In a next step, more target orientated results can be achieved by re-defining the distribution of specific ‘non-design’ (fixed) elements of the parametric 3D model, resulting from analysis of the previously optimised shape.

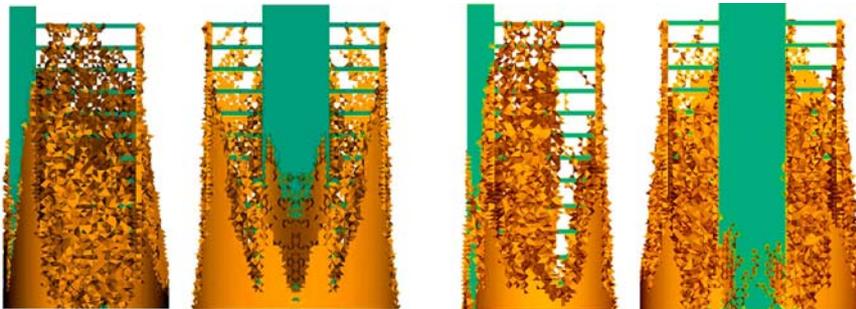


Figure 8-11 Optimisation for gravity and lateral wind-forces in N-S direction / Optimisation for gravity and lateral wind-forces in E-W direction

6 CONCLUSIONS

The paper has shown that an unprecedented variety of formal solutions can be found through the convergence of architectural and structural thinking at the early stages of design, mediated by a 3D CAAD model which is both parametrically reconfigurable while at the same time remains dynamically responsive to optimising input. A synergetic work methodology can be experienced on different levels of resolution in the creative design process, ranging from primary morphological form-finding to detailed optimisation and versioning. In order to achieve efficient results, it is a crucial pre-condition that the precise design-intent gets formulated and communicated amongst both partners in this collaboration. A mutual investigation of tools and methodologies that drive the design of both engineers and architects intensifies the work-flow, averts misconceptions and enables co-authorship. Generic algorithms for structural optimisation introduce a level of automation in the design process that is capable of handling multiple, even conflicting performance aspects. The definition of design priorities in particular regarding geometries of fixed and those of variable values can be facilitated through parametric design and offer a basis for the evolutionary optimisation process, which in return is capable of resolving complex structural issues. The final outcome will always depend on feeding back results of the versioning process to enable appropriate decisions-making by both members of this trans-disciplinary process.

As part of our ongoing research in the innovative structures group, we will gradually increase the level of complexity of both geometrical as well as performance-oriented constraints of our CAAD model. Apart from these considerations, we will strive for interfaces that diminish still existing barriers for reading bi-directionally between high-end parametric design software and optimising software.

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