APPROXIMATING COMPLEX SHAPES WITH INTELLIGENT STRUCTURES: EMBEDDED DESIGN INTELLIGENCE IN SYSTEMS FOR THE EARLY PHASES OF DESIGN

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SUMMARY

In contemporary architecture and structural engineering a trend towards the increased use of advanced geometry and computation can be observed. This poses new challenges for the structural engineer, the designed structures and structural types, and the technology used to design, describe, model, calculate, engineer, communicate, produce and assemble these structures. System concepts, like parametric associative design, can be used to capture the design intelligence in parameters, associations, rules, objects (features) and programmatic components [1]. Although these technologies have many features for the modelling the geometrical representation of a structure, buildings consist of more than only geometry and generation. For free-form structures, surfaces should be meshed, tessellated or populated to impose a grid-based structure consisting of these parametric elements. However, not all restrictions of the structural design can be expressed in a single surface model of the intended design, since often the structure imposes restrictions in the form of angles, lengths, stresses, etc. Therefore, surface population is often not the appropriate technique for defining a structure. This paper presents a computational method to model a geometrical and structural representation with embedded design intelligence in the form of simple rules, constraints and the generation process. With the presented method a designed shape can be automatically approximated in order to allow the architect and the engineer to quickly apply and test a typical structure (for instance a space frame or a beam-column-structure) on the designed shape in the early phases of the design, while taking into account restrictions from various aspects, such as the load bearing behaviour, production aspects, etc. Proper structural design and fine-tuning of the design still has to take place by the designers, but this tool allows quick tests and indicative exploration during the first conversations of the design. A prototype implementation has been created in a new parametric associative system, GenerativeComponents [1], by programming components in the C# programming language.

Keywords: *parametric associative design, computational design, embedded design intelligence, computation, geometry, modelling*

1. INTRODUCTION

1.1 Context

In contemporary architecture and structural engineering a trend towards the increased use of advanced geometry and computation can be observed. This poses new challenges for the structural engineer, the designed structures and structural types, and the technology used to design, describe, model, calculate, engineer, communicate, produce and assemble these structures.

In earlier publications [3] the author proposed a direction for the inclusion of more computation in the structural design process, called the Structural Design Tools concept, which aims on providing concepts, tools and frameworks for the structural engineer to use in day-to-day practise of structural design of complex and less complex structures.

This paper will present the development of a specific tool in the field of parametric associative design and optimisation, part of this concept, aimed on the early phases of the design process during the first conversations between architect and engineer.

1.2 Structural Design Tools [3]

As stated Structural Design Tools provides concepts, tools and frameworks to persuade the structural engineer to use more computation and more advanced computation in the structural design process. Instead of proposing completely new advanced analysis technology, the structural design tools concept is aimed on enhancing the currently already very advanced tools with a approach to design and making the use of advanced computation easier.

A distinction between design and analysis has to be noted here. Analysis tools aim on providing accurate answers on for instance the behaviour of the structure. Design tools aim on providing indicative answers, fast and with as much ease as possible. During the early design steps not much time is available for elaborate modelling of the input and for high analysis times, but fast answers are required to be reached easy.

Secondly, another strange phenomenon needs to be noted. Recently, documentation software mainly aimed on the construction stages of the design has arisen, often referred to as 3D, 4D, 5D, xD or nD modelling, or Virtual Construction [4]. These technologies require a great amount of detailed and explicit data, but strangely enough do not include any method of coming to this level of detail by supporting a design process.

The Structural Design Tools concept can be seen as a solution direction towards a technology that will fill this gap. The approach is mainly aimed on the early phases of the design and extends roughly to the detailed design.

Useful technologies that can be used to aid the structural engineer in the design of the structures are amongst others parametric associative design and optimisation algorithms. System concepts, like parametric associative design, can be used to capture the design intelligence in parameters, associations, rules, objects (features) and programmatic components [1].

2. PARAMETRIC ASSOCIATIVE MODELLING FOR STRUCTURAL DESIGN

Parametric and associative definition of structural elements is extremely suitable for the use for geometrical advanced designs, where in the structure every element differs as well as every position. Although parametric associative modelling systems have many features for the modelling the geometrical representation of a structure, buildings consist of more than only geometry and generation. In essence this is supported, however in practice hardly.

For the unique definition of free-form structures, required to accurately design, engineer and construct these structure, often surfaces should be meshed, tessellated or populated to impose a grid-based structure consisting of these parametric elements on the designed surfaces. The early design often consists of a single surface model of the intended design to further develop with the other partners in the design process. However, not all restrictions of the structural design can be expressed in a single surface model of the intended design, since often the structure imposes restrictions in the form of angles, lengths, stresses, etc.

Therefore, surface population is often not immediately the appropriate technique for defining a structure, and it is required to develop new methods that are able to model the complex relationships that are part of a real structural design. There is a need for technology that aids the structural engineer and the architect during the first stages and conversations of the design process to quickly impose the first structural concepts on an advanced geometrical design without extensive input and modelling in the computer. The computer is required, because of its ability to deal with the advanced geometry and the fact that an increasing number of models are created directly in the computer as three-dimensional models.

3. CONCEPT

As a solution direction the author proposes a method based on predefined and pre-developed parametric associative computational components that need to be adapted to the intended design by a computational method.

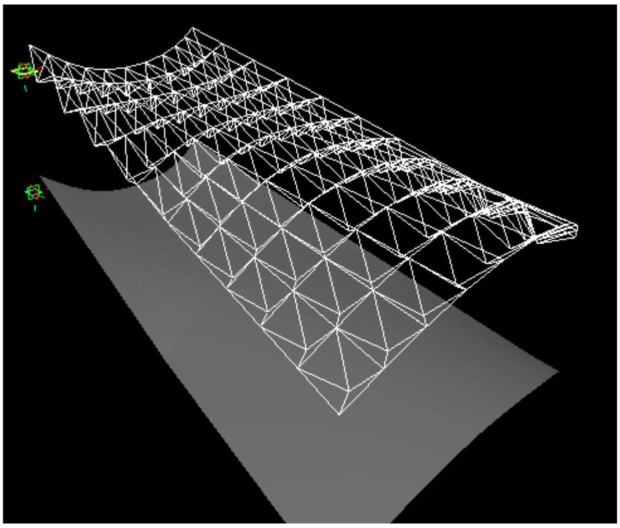

Figure 1. *Mock-up of the tool: The space-frame definition needs to approach the surface below*

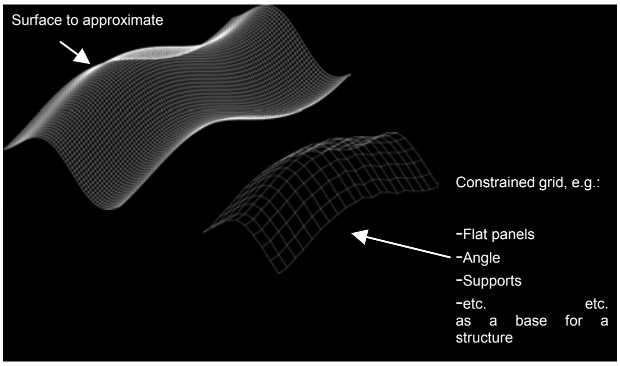

Figure 2. *Earlier results for a grid definition that approximates a double-cosine surface*

The author proposes a computational method to model a geometrical and structural representation with embedded design intelligence in the form of simple rules, constraints and the generation process. Intelligence should here not be interpreted as in that the computer or the software possesses real intelligence and can act independently from a programmatic behaviour. The intelligence is captured in the form of pre-programmed (pre-developed) design knowledge which is defined by the structural engineer and which is taken into account by the software when solving an approximation of the design.

Figures 1 and 2 show a three-dimensional mock-up model of the intended capabilities of the method (Figure 1) and a demonstration of earlier obtained results with a similar method of a grid structure to be approximated to a double cosine surface (Figure 2). With the presented method a designed shape needs to be automatically approximated in order to

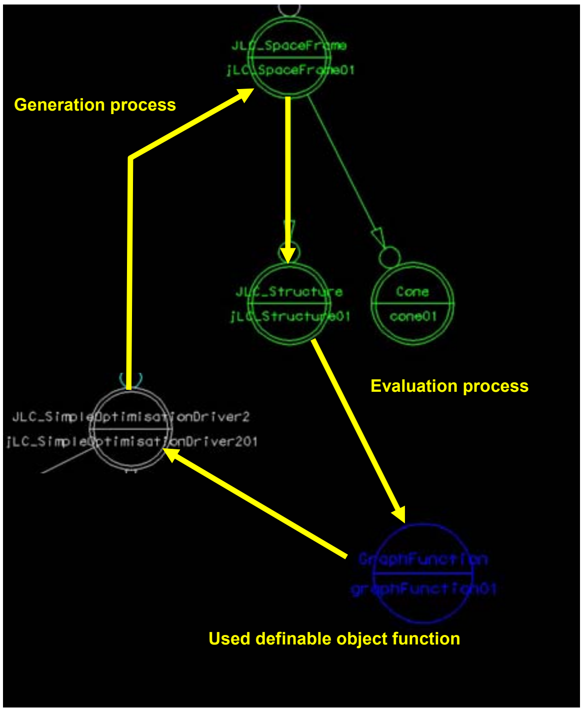

Figure 3. *Sample Conceptual workflow of the proposed method in a modified GenerativeComponents symbolic model*

allow the architect and the engineer to quickly apply and test typical pre-developed structures (for instance a space frame or a typical beam-column-structure) on the designed shape in the early phases of the design, while taking into account restrictions from various aspects, such as the load bearing behaviour, production aspects, etc. Proper structural design and fine-tuning of the design still has to take place by the designers, but this tool allows quick tests and indicative exploration during the first conversations and explorations of the design. This method uses parametric associative technology, constraint solving and optimisation techniques.

Figure 3 shows the conceptual workflow of the proposed method.

4. ADVANTAGES OF EMBEDDED DESIGN INTELLIGENCE IN COMPUTER MODELS

The advantage of the developed method is that in the early phases of the design, when only the first ideas about the shape of the structure exist (perhaps only in a single designed surface) quick tests can be made of several typical structural types. One could think here of structural types, like a space frame, a typical shell, one of the basic membrane types, a typical beam-column structure, including all kinds of options such as (space) trusses, Vierendeel beams, etc.

The architect and engineer can obtain advanced results from this structural model and information of these structural types, such as the shape (for architectural purposes), estimated weight, estimated cost, etc.

Pure parametric associative design could provide this information as well, but this method has two advantages:

The method is able to take into account restrictions or constraints, from aspects such as structural behaviour, production, etc. This could also be modelled in a regular parametric associative model, but often requires very advanced knowledge over geometry, etc. and a clear set-up of the models on beforehand, which often is not the case in a design process. Secondly in the case of structural aspects such as maximum stresses, deflections, etc. it often is not possible to take these aspects into account in parametric associative systems as these systems do not allow for such input.

The method is able to approximate a predefined shape or surface that defines the intended design of the architect. Most probably the intended design cannot directly and accurately be build with the structural type, because of the restrictions described above. Therefore, methods like meshing and population, which do not take into account these restrictions, will lead to invalid structures from other point of views. This method will find the position and configuration of the structure that respects all constraints (or, when instructed, can even disobey sometimes) but is as close to the intended design as possible.

5. IMPLEMENTATION

A prototype implementation has been created in a new parametric associative system, called Bentley GenerativeComponents [1], by programming components in the C# programming language. In this parametric associative system it is possible to build custom "features", objects or components by modelling, scripting (in the GCScript scripting language) or programming in the .NET environment. The implementation uses the last method, which allows the most control over the behaviour of the end result. GenerativeComponents, or short GC, was chosen as a prototype implementation system, based it provides an open API (Application Programming Interface) that is open to the users and developers to extend the system. However, the technology presented here could be implemented in any available parametric associative system with such capabilities.

The techniques are based on the earlier developments by the author at Delft University of Technology on the "openStrategy Form Finding" framework [2]. This software framework is a generalised optimisation-driving framework for computational form finding, (structural and non-structural) optimisation, iterative, and generative calculation techniques.

Advantage of the use of this framework is its ability to let the user choose the most appropriate optimisation method for the problem at hand. Currently in a programmatic manner the openStrategy Form Finding framework allows very thorough customisation of the process, the problem and the translation between the problem and the algorithms. The setup of the framework allows attachment of interfaces to these customisation possibilities to allow more easy-to-use choice of the used method of solution.

6. CONNECTION TO STRUCTURAL ANALYSIS SOFTWARE

In order to make quick structural analysis of the generated and optimised models possible, and in the future to include structural optimisation, a connection has been designed and implemented to connect parametric associative models in GenerativeComponents to GSA, a structural analysis application by Oasys. This connection allows the 'upgrading' of the geometrical features within the model to their structural counterparts (points to nodes, lines to beams, etc.), assembling them in a structure and sending them off to GSA for further structural analysis.

Figure 8 shows the concept of this extension as a modified GenerativeComponents symbolic model.

7. RESULTS AND TESTING

7.1 Testing the results of the optimization

For the tests presented in Figs. 4 through 6 Genetic Algorithms [5] have been implemented and used as an optimisation algorithm. The openStrategy Form Finding framework allows more optimisation methods and solvers, artificial intelligence methods, such as Particle Spring Systems and Simulated Annealing, but also more "classical" methods such as steepest decent methods.

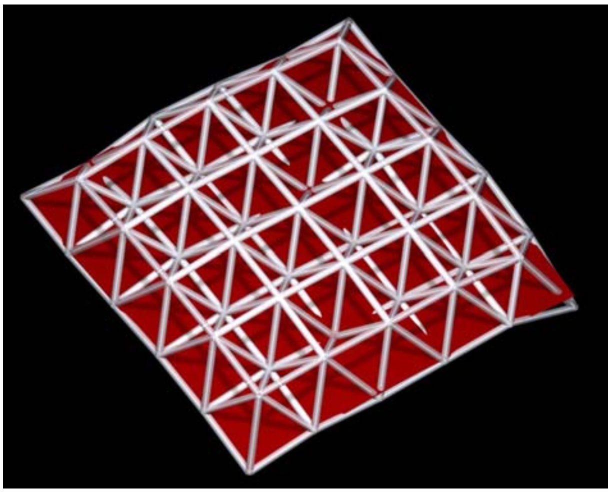

Figure 4. *Rendered image of the result of the prototype implementation: as a final result the space-frame finds the target-surface (in red)*

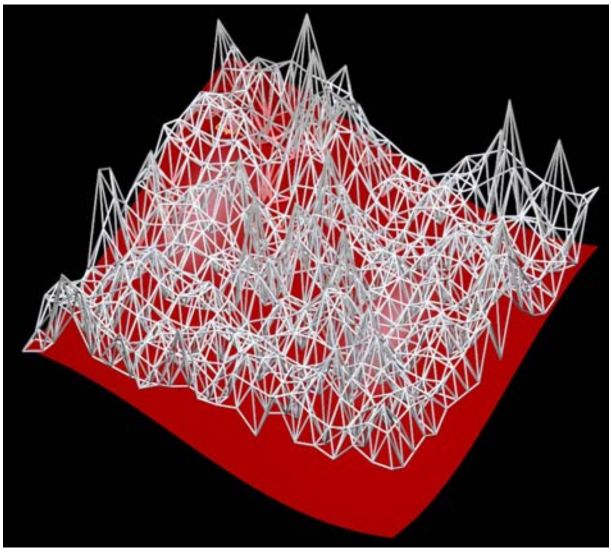

Figure 5. *Rendered image of an intermediate result from the optimisation process, showing the random behaviour of Genetic Algorithms while not converged to a final solution*

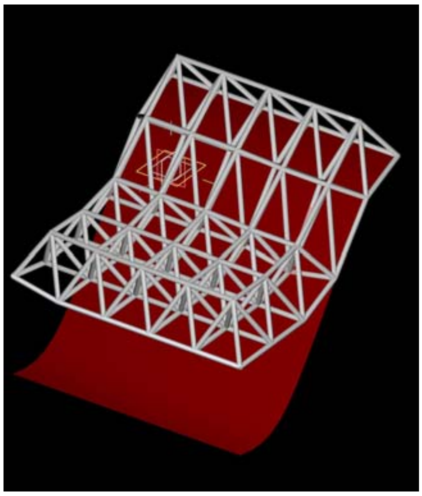

Figure 6. *Results of the prototype implementation: the space-frame is restricted above a certain height, while the target-surface is going below, resulting in the nearest possible position as a trade-off between the constraints*

However, for all results in this paper Genetic Algorithms have been chosen because of their general applicability for problems.

7.2 Testing the results of the connection to GSA

In Figure 7 can be seen that the connection to GSA has successfully been implemented in a feature library for GenerativeComponents to upgrade geometrical models to structural models for quick analysis. The structure that was a result of one the tests has been analyzed in GSA and the some of the analysis results have been shown in this figure.

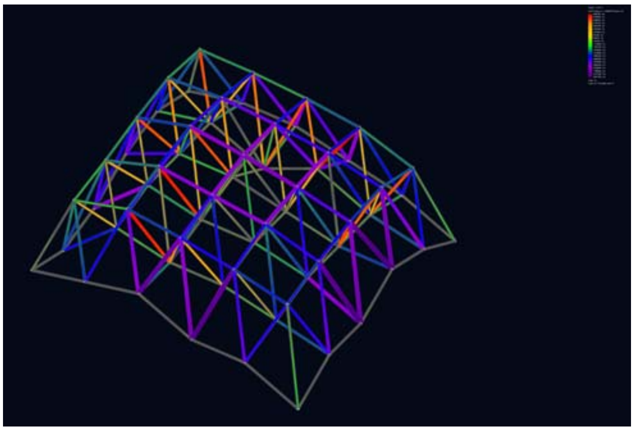

Figure 7. *Structural analysis by making use of the embedded connection to GSA*

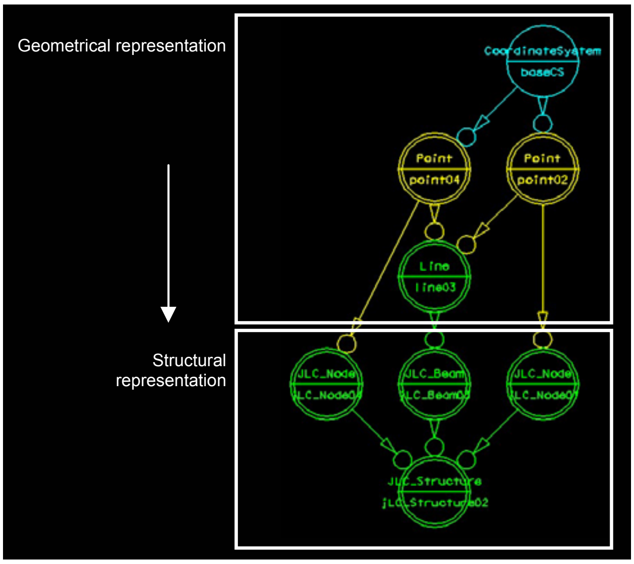

Figure 8. *Symbolic model of the extension of the geometry to a structural model*

8. DISCUSSION

The presented method shows promising results, but the author would like to discuss several issues which will need to be developed further in the future.

The first issue which would increase general applicability is the use of a more general method of description of the intended design, such as a NURBS surface, and implementing the appropriate measuring strategy for the approximation. Currently the method uses a projection strategy for geometrical defined surfaces to prove concept, but this method of description of the intended design is not often used.

The second issue is the testing of more optimisation methods, or surface approximation techniques in the openStrategy Form Finding framework. This would allow the user to select the fastest and best performing method for the approximation.

The third issue and improvement is the enhancement of the connection to GSA to allow for structural optimisation and inclusion of structural constraints in the approximation.

Finally, the author would like to stress two general remarks about the proposed method and implementation. First, it needs to be noted that this method will never be able to replace the structural engineer, because the method always obeys the rules of the game, predefined by the engineer. Only the architect and engineer are able to change the rules of the game and by smart designs allow results even closer to the intended design than the method will be able to come up with.

Second, the results presented in this paper are the first steps of implementing some of the concepts behind the Structural Design Tools concepts [5] by making use of parametric associative modelling techniques. It needs to be noted that GenerativeComponents is still under heavy development and in pre-beta phase at the time of the implementation. This research therefore plays a role in the discussion about the development of constraint solving abilities in this software. It should also be seen that the research at this moment is restricted by the capabilities in this platform and need further investigation.

9. CONCLUSIONS

In this paper a method has been proposed, implemented and tested as a prototype for embedded design intelligence in parametric associative systems, which can be applied to the very early phases of the design to quickly test typical structural types on the first ideas of the intended design. Although the method already shows very promising results, more research is required on enhancing this method for general problems in parametric associative design of these typical structures and the inclusion of more design aspects, leading to new constraints.

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