Inaugurational lecture by Prof. Dr. J.C. Paul MBA

Digital (r)evolution in the structural / architectural design and execution of buildings with complex geometry

TU Delft

Delft, 14 November 2007
1 Introduction

Dear Mr Rector Magnificus, Members of the Executive Board, Colleagues, Family Members, Friends, Ladies and Gentlemen

Buildings with complex geometry have become much more popular in recent years. Their complexity lies in the fact that they cannot simply be reduced to basic geometric shapes such as lines, circles, cubes, cylinders, cones and spheres. Anyone looking at international design curricula and design competitions will be aware that this trend is set to continue for some time to come.

The language of complex geometry consists on the one hand of irregular double-curved shapes, and on the other, of collections of surfaces at random angles. There are of course also many intermediate shapes, each with a character of their own.

In the last ten years I have been involved with different types of this kind of buildings, and I have become more and more fascinated as time has passed.

The digitisation of the architectural and structural design process has removed barriers that used to hinder complex building designs. The two most prominent barriers which are gradually disappearing are verifiability and designability.

![Fig. 1: verifiability finite element method, Swiss Re – Foster + Partners](image)

Digitisation means that the design stage can be speeded up and that costs can be reduced, thanks to the automation of repetitive design tasks and the lowering of the costs of information transfer.
As complex design is not common property, barriers remain. The two most prominent barriers still in existence are affordability and contract/project structure.

I would like to discuss these barriers with you and also look at how they can be removed. Barriers can be removed through the vertical integration of design and execution, optimisation of the design and automation of the execution.

Implications for education and research for the Chair of Structural Design will be illustrated and my role explained.
2 Barriers that are slowly being removed

2.1 Verifiability

Finite element method

The origin of digital evolution was undoubtedly the replacement of the slide rule by the digital pocket calculator and later by the PC.

As well as this hardware aspect, the development of software for designing, drawing and verification has been important in the realization of buildings with complex geometry.

For the design of structures, the development of the ‘finite element methods’ was the most important. By discretising a construction into a finite number of elements, the stresses and deflections of the structure can be calculated for any shape or load for a wide range of material combinations.
Digital empiricism

On the one hand, the breakthrough can be found in the complexity of the structures that can be calculated, and on the other, in the fact that we can move beyond situations for which analytical solutions are available.

Because analytical solutions only partly tackle more complex problems, an estimation based on experience is always needed in order to arrive at a solution to a problem. We can move beyond this empirical character, thanks to the finite element method.

We have in fact now arrived in the era of ‘digital empiricism’, in which thanks to the use of the finite element method we are able to predict how most building shapes will behave in response to the most wide-ranging types of loads, such as wind, temperature or seismic movement. We can verify performance levels and automatically check to see if they comply with regulations and guidelines.

Fig. 2: verifiability – digital empiricism, OVT Terminal NSP Arnhem – UN Studio

Not only structural

Initially, the process was limited to structural calculations, but has now been extended to geotechnical calculations for modelling foundations and soil. The interior climate can also be fully modelled and performance levels for parameters as temperature, humidity, airflow, lighting and noise can be calculated.
Simulations

By considering the time variable, we move from a static to a dynamic situation, and behaviour influenced by dynamic environmental factors can be analysed. The dynamic effects of earthquakes, wind and people walking, running or jumping are of great importance in today's building design.
2.2 Designability

Interaction of designers

The traditional design process is a linear one, in which the focus of the architect lies on the design, while that of the structural engineer lies on the verification of the structure.

For a simple building, architects are able to use their experience to develop concepts and appropriate dimensions for a structure that is then developed further and verified by the structural engineer.

For buildings where no previous experience is available – such as those with a geometrically complex design – the process is cyclical, and the architect and design engineer fulfil a different role.

The architect starts with an initial plan for the architectural form, for which a structural form is designed. This structural form is then verified and the important parameters (including the dimensions) are calculated. The evaluation of the parameters is then the basis for making a proposal for modifying the architectural form, of course if needed.

The method whereby the creation of the architectural and structural form takes place solely with the help of automatic digital technology from the same base is the most recent development. Architectural and structural verification are carried out at the same time and joint decisions are made as to how the architectural/structural form is to be modified.

The evolution that has taken place is that the cyclical process is now accepted by all parties. The modification of the architectural form based on an evaluation of technical parameters, design parameters and cost parameters has also become accepted practice.

The dogged loyalty to the exact design in the early days of complex geometry has moved on to closer interaction between the architectural and structural form, and between architects and structural engineers.
Generating the architectural and structural form

In the early days of complex geometry, the architectural form was determined primarily through sketches or physical models. In recent years, digitally creating the architectural form has really taken off and there are now many software packages available that can make a considerable contribution to the freedom to generate any shape that is wanted.

The generating process can vary markedly. On the one hand it may involve complex geometry resulting from a random and manual process, but on the other, it may be a computerised process based on certain parameters and the juxtaposition of parameters by establishing associations between them, such as parametric design and methods based on swarm theory.

For generating a structural form there are various methods. On the one hand, methods may be based on a different structural and architectural form, while on the other, they may be founded on the fact that the structural form coincides with the architectural form, or at least resembles it.

The technology that is used depends to a large extent on the characteristic shape of the building and the composition of the design team. Because the shape of every building is unique, there are no solutions that can be applied universally.
However, the following examples show a trend.

This is a shift from methods with a manual non-digital character based on different forms to methods with an automatic digital character with the same basis for creating the architectural and structural form.

<table>
<thead>
<tr>
<th></th>
<th>architectural form</th>
<th>structural form</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>hand-made non-digital</strong></td>
<td>physical model</td>
<td>physical model</td>
</tr>
<tr>
<td></td>
<td>sketch</td>
<td>systematic reduction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>simple rules</td>
</tr>
<tr>
<td><strong>hand-made digital</strong></td>
<td>hand-made digital</td>
<td>systematic reduction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>simple rules</td>
</tr>
<tr>
<td></td>
<td></td>
<td>minimal energy</td>
</tr>
<tr>
<td><strong>automatic digital</strong></td>
<td>parametrisch</td>
<td>parametrical</td>
</tr>
</tbody>
</table>

Fig. 5: designability – generating form

Fig. 6: 1975: Multihalle Mannheim Frei Otto

physical model

physical model
Fig. 7: 1995: Media Centre Lords, London
Future Systems

Fig. 8: 2000: OVT terminal NSP Arnhem UN Studio

Fig. 9: 2005: Guangzhou TV tower
information based architecture
Spatial coordination

The spatial coordination of various disciplines with 3D software is slowly catching on, particularly during the design stage. To see whether the dimensioning of the different disciplines is properly harmonised in cases where the geometry is complex, software packages featuring structures, building installations, façade and architectural elements are essential. Clash detection can be a fantastic tool as a means of really seeing whether or not everything fits, and tolerances and deflections / movements can be included in this.

3 Barriers that are still present

3.1 Affordability

The construction costs of buildings with complex geometry are currently the greatest barrier. In my experience, most clients are prepared to pay 5 to 15% more for a building with charisma that can be achieved through complex geometry. Nevertheless the extra costs associated with a complex geometric design are sometimes much higher.

Comparing market structures

Although complex geometric designs can be found in the car, aircraft and shipbuilding industries, the structure of these sectors is significantly different to that of the building industry. In the car and aircraft building industries, large production runs make it possible to invest large sums in design and automation of production. A more legitimate comparison can be made with the shipbuilding industry which also often involves the construction of a unique product. But here, too, design is to a degree merely functional and the level of costs is much higher than is the case with buildings.

Automation of the construction phase – component production

Although the digital supply of design information is one of the preconditions for the automation of the actual construction, complex geometric design is not really running in tandem with developments in the construction and related supply industries. In the construction phase a far-reaching automation of the production of standard elements and products is present. Buildings are unique as a rule, and can be regarded as a collection of standard products. At present, there are insufficient standard elements to facilitate complex geometry, which means that
new solutions often have to be devised that require a great deal of manual labour.

![image]

**Fig. 10: unique product of standard elements (Chesa Futura – Foster + Partners)**

**Automation of the construction phase – vertical integration**

Construction work is still largely a manual activity and is still often carried out using a significant number of drawings. The automation of combining building elements and products on the building site – during the work preparations and control phase - is only partly developed. The fact that spatial detail coordination – and the related visualisations - is so often not automated that increases the costs and risks of executing complex geometry. Considerable investments in automation and knowledge development in building companies and their supply industries are required in order to facilitate building with complex geometry, investments which cannot usually be written off against one single project.
3.2 Contract and project structure

The traditional design process is divided in a linear fashion into phases with a different focus and a greater degree of refinement in each phase.

The concept is developed in the Concept Design phase, where the space requirements are set down, while spatial coordination is executed in the Scheme Design phase. In the Tender Phase, the working details and coordination of details takes place. Information from previous phases is used in subsequent phases.

However, for complex geometry this linear refinement is a myth. The concept and details are often so closely interwoven that the concept cannot be developed without considering – and sorting out - the details. Therefore a shift is underway of the detailing (of specific parts) from the Tender to the Concept Design phase. The traditional classification often functions as a hindrance in such cases because there is neither any money nor time for this necessary detailing, or indeed sufficient understanding.

Another obstacle is that the building contractor is only involved when the design is ready. It is precisely where complex geometry is involved that there are great benefits if the contractor is familiar with and able to handle such specific
geometry and uses building methods suitable for that, and if the design is made on the basis of the contractor’s specific qualities in this area.

Fig. 12: contract and project structure

4 Removal of barriers

4.1 Height of the barriers depends on the situation

The fact that buildings have always been designed and built with complex geometry implies that the barriers are sometimes lower and therefore less relevant.

Projects that have been carried out show that on the one hand there is a lower level of cost sensitivity, and on the other an environment that allows a complex design with a great deal of manual work for relatively low extra costs.

In one case, the complex geometry and design determine the image of the owner or user.

In the other case the execution is taking place in countries with low wage costs but which are technologically well developed such as India, the Gulf Region, China and eastern Europe.
4.2 Integration of design and execution

Vertical integration of design and execution can bring about complex designs that are more reliable and at more acceptable costs.

Fig. 13: combination of low cost sensitivity and low labour costs
Olympic Stadium Beijing – Herzog de Meuron

Design strategy

In order to allow vertical integration to work as effectively as possible, three approaches can be used that all include execution and costs among their starting points, and which are successful when combined.

• The architectural / structural form should be obtained through transformations and summation of basic shapes that are structurally reliable.
• A relatively simple construction method should be sought.
• It should be possible to produce recurring parts – in an (almost) similar fashion, though allowing certain variations - that play a key role in determining the shape: ‘near mass customisation’.
Fig. 14: integration of design and execution (Stadsbalkon Groningen – KCAP, Guangzhou TV Tower – information based architecture)

**Change to contract and project structure**

There are organisational structures that promote vertical integration. Design and execution are then combined and brought under the auspices of one firm or collaboration agreement.

- **Within one firm:** real-life examples include steel construction and fabric structure firms.
- **Required by clients:** Public-Private Partnership contracts.
- **Started by commissionees:** temporary partnership agreement between designers and executing parties who combine a certain style with a certain method of building.

**4.3 Optimisation of the design**

In addition to the careful selection of starting points, today’s digital tools offer sufficient possibilities for far-reaching optimisations.

On the one hand they may be related to quantities, and on the other to the execution costs.
Slight modifications to the design, design criteria and the execution may result in significant cost savings.

Fig. 15: optimisation of the design (Olympic Aquatic center Beijing – PTW)

Methods for the optimisation of buildings, and parts of buildings, are getting more and more mature. The process for generating alternatives, establishing criteria, evaluating these criteria and taking decisions is becoming increasingly automated. In particular, the generation of alternatives and one-dimensional optimisation (while other parameters are looked at to see whether or not they are ‘good enough’) are being used more and more often.

One group of optimisations generates a finite number of alternatives which are ranked according to their suitability.

Another group of optimisations generates a new alternative based on the evaluation of an existing alternative – such as evolutionary structural optimisation.

4.4 Automation of execution

Investments in automation and digitisation of the execution process are profitable, especially for contractors and related supply industries specialising in buildings with complex geometry.
Production of parts

Mass customisation provided through automated technologies is only available on a very limited scale at costs that are acceptable. But it is precisely in this area that a process of evolution is required in order to facilitate complex geometry.

Horizontal integration

The application of Building Information Models (BIM) for buildings with more complex geometry is an important means for bringing down costs.

This can be an excellent instrument especially for complicated details and costs incurred in cases of failure can be cut considerably, as no modifications have to be made during the execution phase.

A time dimension can also be included in these BIM packages and objects can be linked to a timetable. As a result, the progress of the work can be simulated and an accurate assessment be made of how closely the execution is keeping to schedule.

5 Significance for education

Learning digital skills is an essential part of the Master’s variant of the architecture and building technology study programme. These skills should be firmly integrated in the curriculum and there should be a wide choice of optional subjects available in order for students to be able to acquire and practise digital skills at the highest level.
Attention should also be given to the inclusion in the curriculum of a new generation of digital architectural professions. It is my belief that activities in the design process will evolve into professions in their own right. Examples could include digital toolmaker, digital model builder and BIM administrator.

The faculty will have to ensure that when the time comes it will be able to cope with the movements in this direction.

In my educational role, I will be supervising students approaching graduation, where complex geometry and digital design technologies make up part of the overall assignment.

I will also be supervising workshops of a digital and interdisciplinary character. I will be working on two workshops that seek to replicate modern-day practice as closely as possible. I have a great deal of affinity with both subjects as a result of my own professional experience.

The High Rise Building Workshop and XXL Workshop are interdisciplinary workshops for students on various study programmes, where they join forces to come up with a design for a building. For High Rise they will be looking at a
building of between 200 and 300 metres high in Rotterdam, still the only really high-rise city in the Netherlands.

XXL is a large building with a complex design – last year this was the design of the Olympic Stadium in London, and this year a football stadium in Rotterdam is to be the focus.

Fig. 18: announcement workshop XXL

6 Significance for research

It will be clear from the above that the focus of research should be aimed at removing the barriers.

There are three directions that require attention:
- Vertical integration of design and execution
- Automatic optimisation of the design
- Automation of the execution

The research structure in the department of Building Technology has five clusters, in two of which - Blobs/Complex Geometry Buildings and Informatics - most of this research will take place.

The aim is to carry out leading research of an international standard, and to combine forces with Civil Engineering within TU Delft, and with the three Universities of Technology in the Netherlands, as well as with leading universities such as MIT and ETH - Zürich. The most important relationships on the design side are with leading architectural firms and with my colleagues in Arup. In addition to sustainability, digitisation is an important area of focus in Arup. The relationships with the developers and building companies will be further expanded as they have an important role to play in this research.

6.1 Vertical integration of design and execution

Research into the vertical integration of design and execution will consist primarily of studying design strategies and reach conclusions about which strategy is successful in which situations.

The contract/project structure will be an important precondition for this.
6.2 **Automatic optimisation of the design**

Automating optimisations will be the next evolutionary stage in the design process. What I have in mind is automatic generation, evaluation and optimisation as a continuous process that can take place without any intervention.

Design will then be more and more a matter of drawing up the correct starting points, selecting the appropriate evaluation tools and giving an indication of how the design results are to be evaluated. The automation of more dimensional evaluations – an ultimate form of horizontal integration – represents a big challenge here.

6.3 **Automation/digitisation of execution**

Research into execution will deal with the following points:

- Possibilities of mass customisation or near mass customisation of parts;
- Better administration of the building process on the actual site, with the help of digital tools.

An inventory will be made of the available manufacturing methods for complex geometry during the production of parts.

The new production methods that make the principle of mass customisation possible will also have to be looked at. An initial step in this direction has already been made within the faculty with the recastable mould – a great success. We would like to broaden this success by carrying out research into new possibilities.

Research into better administering the building process on the actual site and into supplies will have to concentrate primarily on the application of digital tools for managing information at the building site. The application of the Building Information Model (BIM) at the building site and in the supply chain is being considered in this connection. For complex geometry what is particularly important is an improvement in the management of the shape through better coordination of working details, setting out, and control technologies.
Fig. 19: automatic optimisation design

**Conclusion**

It has been a great pleasure for me to be able to share this holistic approach with you. I consider it a privilege to be in the position I find myself in, and I am very thankful for that. It is a privilege that I will use to inspire the current generation of students and researchers and to support them in their quests. Quests towards the shaping of a better and sustainable world.

Thank you.
Images:

Cover (left to right):
Top: Zvi Hecker, Future Systems, Future Systems
Middle: PTW, UN Studio, EEA
Bottom: Foster + Partners, information based architecture, ONL, Mecanoo, Herzog de Meuron, UN Studio

fig. 1 to 16: Arup
fig. 17+18: TU Delft
fig. 19: ONL (right half)