Computational Design in Engineering

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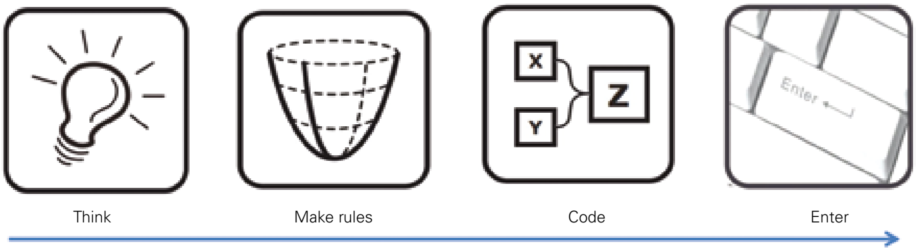


1. Four steps of the algorithmic approach, inspired by Dr.-Ing. Milos Dimcic (www.programmingarchitecture.com).

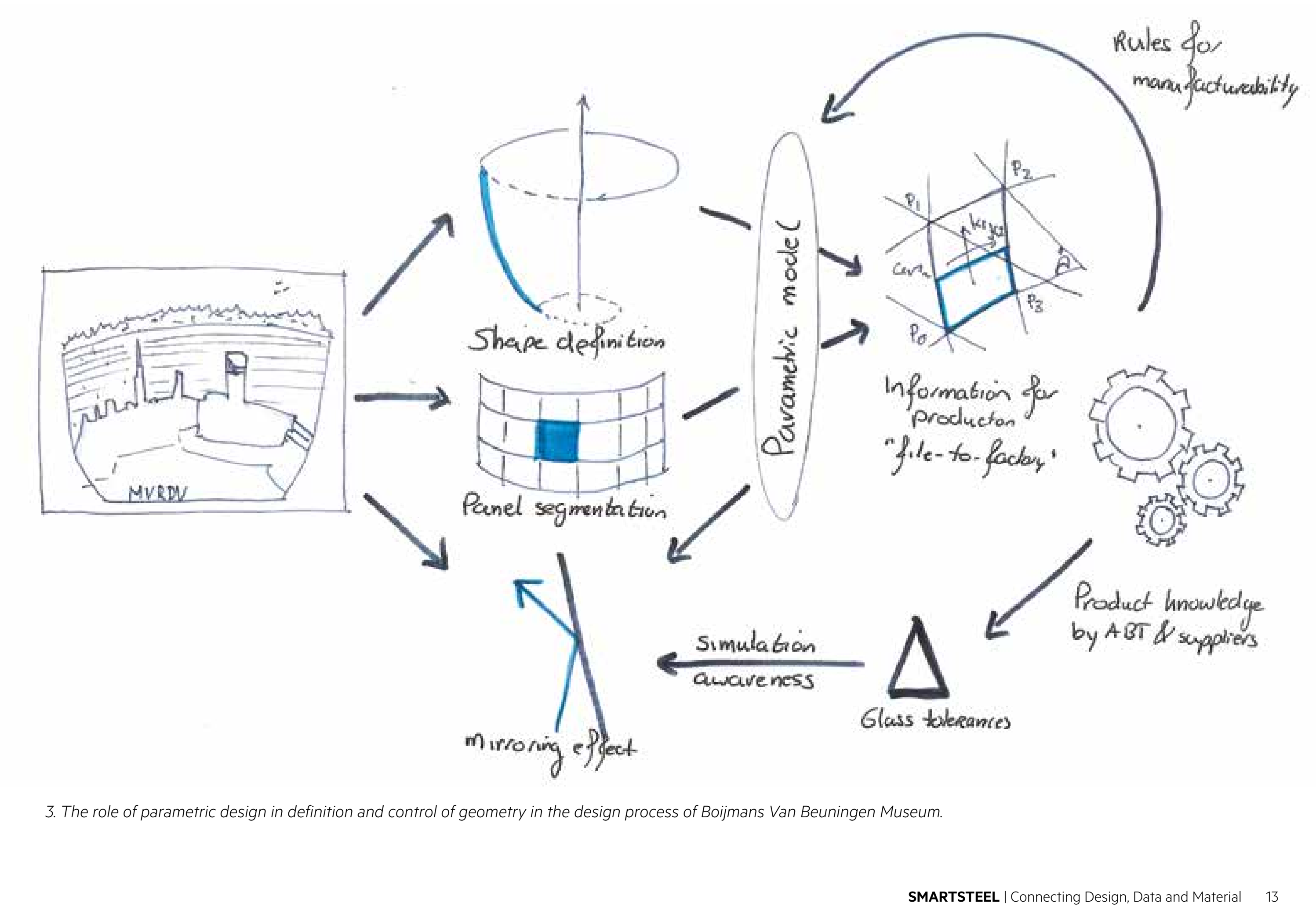
Building Information Modelling, computational design and data determine the long-term viability of design firms and consulting companies in the current performance-driven built environment. The integrated complexity of current-day building designs and design processes require a certain anticipatory power and workflow intelligence, which can only be achieved by using 'smart' techniques, or rather computational solutions.

The role of an engineer is to realise the ambitions of his or her clients using smart technology. Today's available digital technologies help us meet the increasing demands more efficiently, delivering higher standards.
We have identified the following key drivers for the digital transformation of our design process: the need for time/cost-effective design processes; availability of new technology; and the increasing demands of the performance of the design outcome e.g. sustainability. Consequently, the use of computer-driven methods not only dominates the way we design, engineer and manufacture buildings and its components, it also dictates the way we collaborate, exchange information and organise construction processes.
ABT Consulting Engineers addresses the term Computational Design as one of the three key digital technologies that distinguish their high-end technical advisory service. These digital technologies are referred to as Building Information Modelling (*BIM*), *Computational Design* and *Data*. According to the authors, these three technologies determine the long-term viability of design firms and consulting companies in the current performance-driven built environment. The integrated complexity of current-day building designs and design processes require a certain anticipatory power and workflow intelligence, which can only be achieved by using 'smart' techniques, or rather computational solutions.
In this digital age, technology will keep developing at an increasingly faster pace. The availability of technology itself is not the bottleneck for use in daily design practice anymore, however the ability of engineers, to learn, adapt, adopt and implement these new technologies in their design process is. For this reason, ABT has introduced computational solutions to stimulate staff in their use in design projects and to start a discussion on the future of us engineers, as computation-driven knowledge workers who can provide a complete turn-key advisory service for clients.
In this article, we provide our view on how computational design helps us to create smart solutions, following the three drivers for the digital transformation of our design process: design process efficiency, new digital technologies and the increasing client demands, and what this means for our role as engineers in the construction sector.

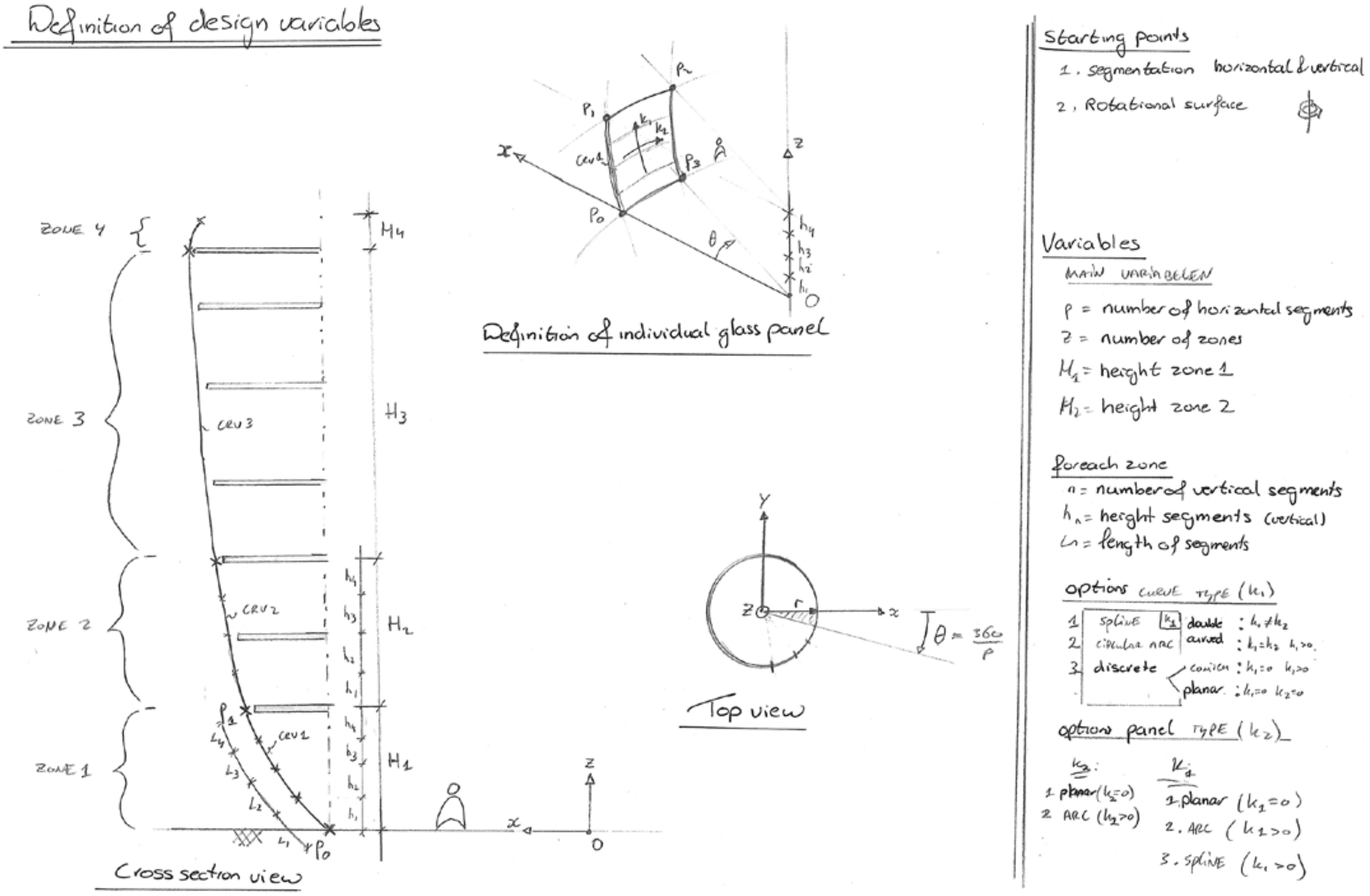
The need for cost-efficient design processes
The use of building information modelling (BIM) in the construction industry has stimulated the cross-disciplinary exchange of design information, as the need for faster evaluation of alternatives and mitigating conflicts between design partners demands this to service the client. Although quite sophisticated, the early use of computer-aided design (CAD), computer-aided engineering (CAE) and computer-aided manufacturing (CAM) technologies typically enhanced, or rather automated, already existing workflows within the traditional overall design and construction value chain. The introduction of BIM and parametric and generative design software around the late 1990's, on the other hand, affected the architectural design process in an integrated way. Based on predefined goals and constraints, nowadays, an optimal design can be found and consequences of design changes can be made apparent avoiding costly errors, or worse: re-work.
For this to be effective, certain design processes or workflows need to be efficient in time and costs. The automation of workflows is consid-

Artist's impression: MVRDV.

2. Artist's impression of the to be built Boijmans Van Beuningen Museum.



3. The role of parametric design in definition and control of geometry in the design process of Boijmans Van Beuningen Museum.



4. Rationalisation of design variables in the design of the double curved facade of the Boijmans Van Beuningen Museum.

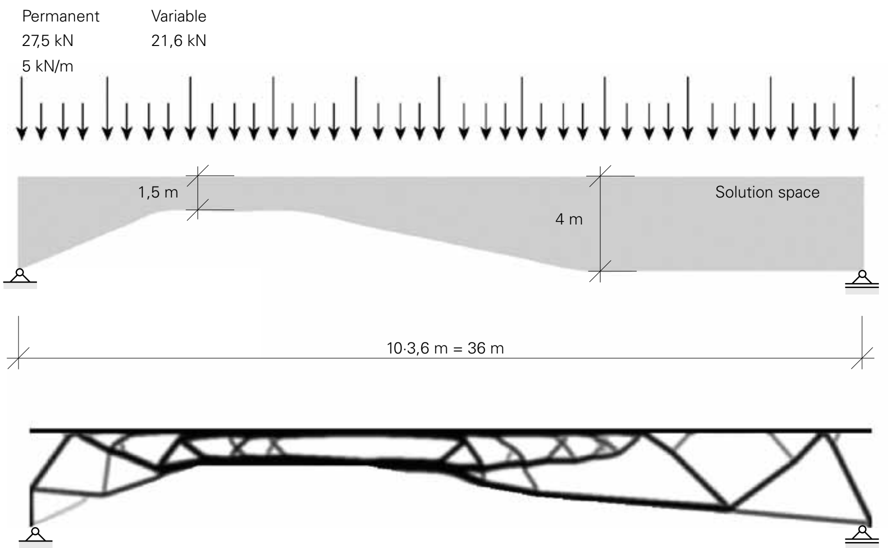
ered quite effective as it minimises the engineers time (and thus costs) and at the same time minimises the risk of (human) errors.
The algorithmic or parametric approach of computational workflows (automation), nonetheless, asks for a new mindset in design, engineering and manufacturing. Typically, when working with algorithms, four sequential steps need to be taken for the approach to be effective (*Figure 1*): think, make rules, code and press enter. First and foremost, one has to think what one wants to achieve and what boundary conditions are in place for the desired outcome. Secondly, one has to create the rules, hence set up the logic workflow by identifying what variables are to be of influence on the project and by rationalisation of the associations between these parameters. Next up, one needs to teach this workflow to the computer by means of programming (code) and lastly, you press enter to commence the workflow.
The use of algorithms within the engineering practice typically enhances the efficiency of the engineering work by automating repetitive tasks, such as the calculation of column reinforcement or pile caps. A smart algorithm may enable a large variety of reinforcement layouts (which might be desirable from the point of view of reducing the use of material), while using the same programmed logic.
This parametric design approach enables a more efficient generation of alternative solutions and provides the opportunity to respond to design variations along the way. As long as the goal or logic doesn't change (and break the rules implemented in code consequently), the created algorithm is able to support the project over time. Uncertainties in the project should be considered to be included as design variables in order to mitigate the risks of modifications and make the algorithm more robust to support the project process.

An algorithmic approach proves effective for the design of the New Collection Centre for Museum Boijmans Van Beuningen

In the design of the double-curved façade of the Boijmans Van Beuningen Museum in Rotterdam The Netherlands (*Figure 2*), a parametric strategy has successfully been applied. A project designed by MVRDV and soon to be realised as a public art depot featuring exhibition halls. One of the key design features of this spherically-shaped building is its mirrored façade. The experience of the aesthetic quality of this facade is determined by the perfection of the mirroring behaviour and is therefore sensitive to any misalignment in shape or placement. To define the complex

6. *The exterior of the National Military Museum illustrating a large black-painted slab, seemingly floating above the former military site.*

7. *The interior of the National Military Museum illustrating the large steel space frame roof structure with suspended airplanes.*

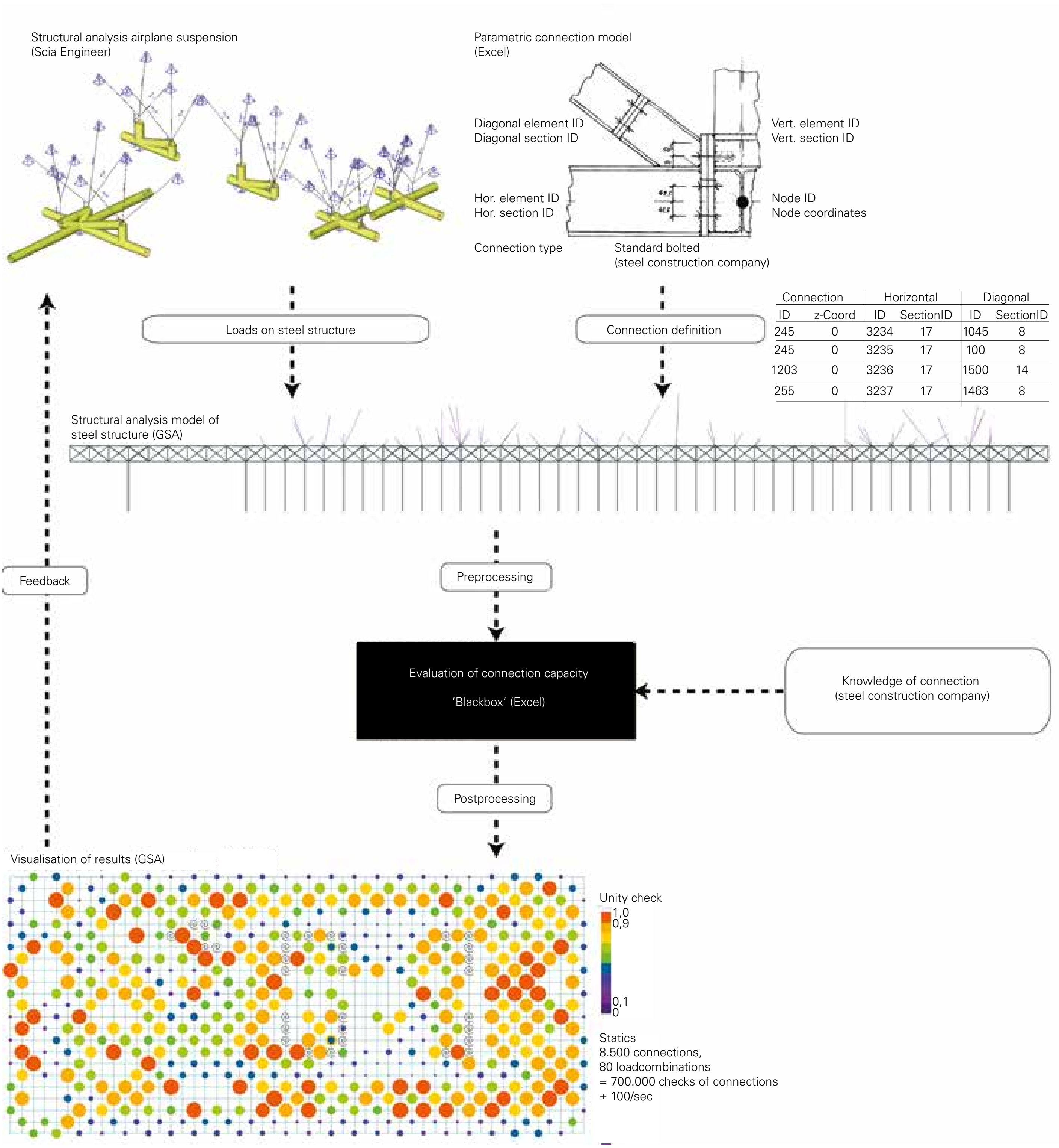


5. *Generation of evolutionary optimised structural layout in constrained design space and the layout of the final (traditional) truss design for the renovation design of TU Delft faculty of Civil Engineering.*

glass geometry with high accuracy, a computational design approach using parametric design tools was introduced.
Complex shapes are not difficult once you understand their rules of creation. With a parametric design approach, the complex glass panel geometries were generated as a product from easily understandable rules, such as the revolving of a curve along a central axis and the definition of a subdivision pattern (*Figure 3* and 4). Insight to the underlying mathematical equations to derive the form has provided more understanding for all parties involved in the design process, and thus reduced the perception of the level of complexity and related risks.
Deliberately handling aspects subjected to change as specific design parameters (e.g. the curve defining the outside shape of the bowl) provided flexibility for modifications without large consequences, which extended design freedom within the overall design process. Up to a few weeks before submitting the final design documentation, the outside shape of the bowl has been modified (i.e. improved). Agreement on the workflow of data exchange made side-by-side work of both design variants and the setup of the documentation process possible, without requiring prior agreement on the final shape.

Availability of new technology

New technology allows us to overcome former limitations and hence improves the manageability of design. Furthermore, new technology inspires engineers to come up with previously unforeseen solutions. As such, the introduction of new technology (or material, for that matter) may lead to a new era of architectural design altogether.
History has taught us that new technology often is required from an engineering point of view to solve a specific technical problem, after which designers make grateful use of the gained knowledge and experience to come up with new applications for this specific technology. For example, the mathematical descriptions (algorithms) that enabled the engineers of Renault and Citroën to define the curved shapes of their new car designs, has eventually led to the widespread use of such parametric functions in computer-aided design (CAD) tools, which has inspired architects such as Frank O'Gehry, Zaha Hadid, and many more, to design their free-form buildings.
For today's architects, geometrically complex designs, which required architects of the past



8. Verification of connection design after updated airplane loading for the National Military Museum Soesterberg by linking engineering workflows using parametric design thinking and data visualisation.

to devote large parts of their lives to, are now considered within reach by means of a few clicks. Advanced computational design tools such as Rhinoceros and Autodesk 3Dmax allow for designing complex-shaped three-dimensional structures that were considered too difficult or time-consuming to communicate or modify with traditional two-dimensional drawings or small-scale models. The availability of sufficient (cloud) computational calculation power and advanced analysis software, such as Finite Element Analysis (FEA), allows us to use digital simulation to obtain insight in structural behaviour of any structure. Digital fabrication, including techniques such as 3D-printing, computer numerical controlled (CNC) tooling and robot-aided manufacturing, opens up the door to fabrication and production of uniquely shaped items without the need for mass-production to make it cost effective. In other words, mass-customisation. The use of computational methods for producing and processing manufacturing data enables mass-customisation in the design of building components. Simply put, where uniformity was typically considered a boundary condition in the design of building components, such as façade panels, floor slabs, beams and columns, digital design and fabrication techniques no longer require constrained variables. The digital fabrication of these unique items requires a fabrication partner who can deal with digital instructions that are automatically generated and are directly used by the production machines (file-to-factory).

In general merely one part of the design process is automated as an efficiency improvement, the true potential of computational methods will be reached when all (digital) workflows can be aligned consistently from design, fabrication, transportation, and assembly. Having said this, when the potential of digital fabrication is taken into account in the design, the fabrication process may even require other design input than would be the case in a more traditional, non-aligned workflow.

The link between both, the conversion from a concept of design towards the final realisation including the structural engineering, detailing and specification for production, is concerned with a certain increase in complexity.

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> *Increasing demands of the performance of buildings and built environments require integrated processes*

Structurally-optimised truss layout for the extension of the faculty of Civil Engineering using new digital technologies

As part of the renovation design of the Delft University of Technology (TU Delft) faculty of Civil Engineering, a new truss structure, spanning between the existing cantilevered lecture rooms, has been designed making use of evolutionary structural optimisation algorithms (*Figure 5*). These algorithms distribute material only to the places where it is most effective. The end result represents a design that requires a minimum amount of material to realise, but, however, is not by definition cost-effective to realise.

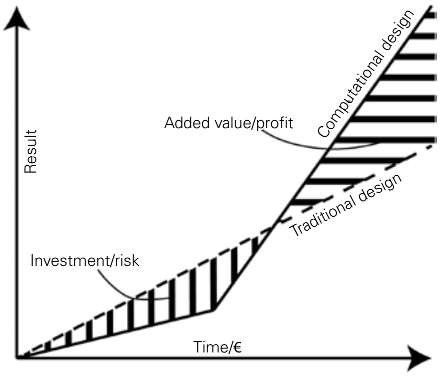
Nowadays, trusses are typically constructed as an assembly of standard rolled steel sections and have connections with identical geometry to limit the required labour in both design and fabrication. The fine details and varying geometry in evolutionary optimised structural layouts, are more difficult to realise using these traditional techniques. On a smaller scale, new 3D-printing techniques overcome these limitations as demonstrated in the design of the 3D-printed connections by Arup. Also at full scale, the realisation of unique layouts composed out of standard sections will be cost-effective with the ongoing automation of the production lines at steel construction companies. In conjunction with automated structural verification of connections, structurally-optimised truss layouts will come within reach allowing for the realisation of material efficient structures as well as geometrically-complex, yet aesthetically-pleasing designs. Technological advances in both design, engineering and fabrication go hand in hand.

The increasing demands of the performances of buildings

The increasing demands of the performance of buildings and built environments, e.g. sustainability ambitions, require integrated processes to achieve these. As a result, the complexity of designs and design workflows increases significantly. This enhanced complexity creates the need for advanced simulations to gain insight into the interdependency of the numerous input variables and thus the consequences of design alterations on the overall result. In comparison to traditional, more consecutive design processes, an integrated design process demands matching one another's objectives and boundary conditions at the early design stage. Simply put, for obtaining a more sustainable built environment, we need better designs, smarter design processes and earlier cross-disciplinary collaborations.

From an engineering point of view, by default, engineers try to determine design solutions that minimise the amount of material required given the design conditions using their knowledge, experience and skills to the resources they are given. From the perspective of efficiency, simplified engineering methods are preferred over more advanced calculations methods such as Finite Element Method (FEM) analyses to limit analysis time. On the other hand, the number of evaluated alternatives is preferably limited to reduce the amount of work. The resulting intermediate solution space has to be estimated at best based on experience, knowledge (e.g. linear correlation) or common sense. All compromising the optimal use of the material.

For relatively simple situations, engineers are very capable of predicting the quality of an alternative by knowing and understanding the underlying relations or equations. Although for more complicated situations, engineering sense and available knowledge should still be sufficient to provide full insight into the structural system's behaviour, the quantitative interdependencies of the various design variables (or parameters) are likely to be difficult

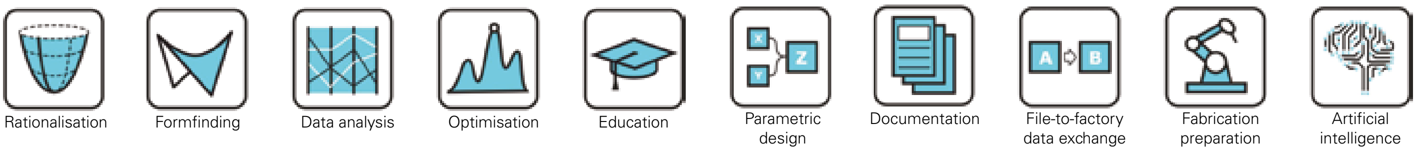


9. A comparison between a computational design approach and a traditional design approach in terms of progress and results related to time or costs.

to fully comprehend. This lack of insight may lead to less efficient design choices, by taking the easy way out or be on the safe side of time versus cost. Moreover, potentially more cost-effective or more sustainable alternatives may remain undiscovered.
One way to compensate for this lack of insight is to increase the number of evaluated alternatives through the use of computational methods, without requiring significant engineering effort or time for each evaluated alternative. Intentional parameter variations may then help to gain insight into the influences of each parameter on the overall performance on aspects such as geometry, structural behaviour, costs, constructability and much more. In other words: 'learning from simulation'.

Balancing between structural efficiency, architectural functionality and constructability with the design of the roof of the National Military Museum in Soesterberg
The design of the National Military Museum of the Netherlands is a fine example of an ambition-driven design process in which computational methods are effectively applied to reduce the amount of CO_2 emission related to the amount of structural steel that makes up the roof of the building. The building resembles an extensive black slab that seemingly floats above the site of the former military airbase Soesterberg (*Figure 6*). Beneath its impressive 250 m long and 110 m wide roof, military equipment such as field guns and tanks are arranged, whereas most of the airplanes are suspended from the ceiling in what seems a 'dog fight' pursuit (*Figure 7*).
The load-bearing characteristics of the roof are decisively influenced by the fact that all structural members combined produce a steel space frame. In order to minimise the dead load of the structure and reduce steel consumption, basic parameters such as grid dimensions, beam depth and truss spans were subject to a computer-based optimisation process already during the design phase. In a later stage, sizing optimisation of all approximately 8000 structural steel members in terms of strength capacity has led to a reduction of steel consumption by 40% in comparison to comparable structures. The optimisation algorithm determines the lightest profile from the corresponding list for every structural component and recalculates internal forces. Elements dimensioned insufficiently in terms of strength capacity are replaced by the following profile in the list until the structural requirements of every component are met. The boundary conditions included the architects' design specification calling for visible profiles that are as slender and uniform as possible. Practical considerations such as onsite bolted connections of members furthermore determine the minimum depth for profile sections. These somewhat contradictory criteria were translated into various section lists that permitted allocating suitable profiles to the different building component groups (top chord in direction x, diagonal in direction y, vertical bar, etc.). For uniformity in appearance, section types applied for the top and bottom chords were chosen to have identical outer dimensions as the HE200 series. Nowadays available visualisation methods such as Virtual Reality can be applied to fine tune criteria related the structure's aesthetical appearance and potentially extend design freedom, yet arriving at one smart, high-quality solution: efficient from a cost and environmental point of view, yet aesthetical pleasing.
During design, the exact placement of the airplanes suspended from the roof needed to be kept flexible, so the structural calculations were based on 72 different load combinations and a resulting irregular pattern of surface loads. After completing the roof and determining the exact positions of the airplanes, a new analysis of all structural members was undertaken, taking into account the exact point loads at the suspension connections (*Figure 8*). This re-evaluation also included assessment of the impact on the design of the connections. These connections were initially designed by a steel construction company and were not part of the structural optimisation. For the re-evaluation of the 8500 in 80 load combinations, i.e. 700.000 connection checks, the knowledge of connection design was integrated and linked in the digital workflow. The inclusion of connection design in original optimisation would have led to a total 'smart' structure with potentially an optimisation on overall costs-effectiveness.
The deliberate alteration of the solution space, by loosening the various boundary conditions, provided insight into the consequences of certain design choices.

The impact of computational design on the role of engineers
In this digital age, technology will keep developing at an increasingly faster pace. The availability of technology itself is not the bottleneck for use in daily design practice anymore. However, it's the ability of us, engineers, to learn, adapt, adjust, adopt and implement these new technologies in the design process. In daily practice, we see that the choice to apply computational design strategies in the design process is often not made at the start of a project or in early stages of the design. Digital methodologies are often introduced by the engineers to improve the efficiency of their work. This limits its full potential. On the one hand, this may come from unfamiliarity with the possibilities of new digital technologies. Enhanced by the fact that most project leaders and senior designers in charge are typically not the generation that has the most affinity with new digital means. On the other hand, in comparison to a traditional somewhat 'linear' approach, a digital or parametric design approach typically does not provide the same expected result in the earlier stages of the process. This may be perceived as a risk both in terms of investment and (lost) design time. In the same time in which a calculation



10. Computational design solutions: a set of digital methods and technologies that may help us to realise better, more sustainable or more efficient designs or design processes.

or detail drawing can be made by traditional means, only a limited set of digital instructions can be created, which does not reproduce the same results at the expected level of quality. At the expense of immediately visible progress, the ability for variation is added. This flexibility allows for simple handling of design modifications, allows for automated evaluation of comparable situations and makes variations for simulation purposes possible. In return, efficiency increases when more alternatives or similar situations are assessed, which may lead to an increase in added value for the project (*Figure 9*).

To stimulate the use of digital technology within our design projects, ABT introduces computational solutions (*Figure 10*): a set of digital methods and technologies that help us to quicker realise better, more sustainable or more efficient designs or design processes. Within our company, we have differentiated a variety of services for which we require various computational methods. These services comprise aspects like rationalisation, parametric design, data-mining, optimisation, software development, pre-processing for digital fabrication. We are able to provide each service either independently or collectively as part of our consulting work. Next to that, the clear separation of solutions provides a starting point for explaining and evaluating the potential of the use of computational design methods at the start of new building projects.

Within ABT, a taskforce of computational design specialists stimulates the use of advanced BIM, data solutions and computational design in the design process. These computational design specialists join design teams on a project basis to support and implement digital solutions. This taskforce is part of a larger group of digital design enthusiasts that share new innovations and technologies on a daily basis.

A separation in profession: engineer vs. programmer

Within the actual work field, the above mentioned requires a slight alteration in people's competencies. You require specialist knowledge with respect to the task at hand, yet also programming skills to comprehend and

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master the workflow in a digital environment. Where programming skills were often seen as a separate skill in the past, in the current practice these are now part of the engineer's skill set. This is encouraged by the availability of visual programming tools such as Dynamo and Grasshopper. We see the transition going on from a few specialists several years ago, to the general workforce nowadays that makes use of programs on a daily basis. In practice these tasks are performed by the same person, as this is considered highly efficient for engineering tasks. Nonetheless, a separation in the profession is taking place more and more as dedicated developers are hired. The combination of two individual persons with different backgrounds working together side by side has turned out to be quite effective as both persons bring their specific expertise to the table.

We see our role as engineers shifting: from doing manual work ourselves to programming software to assist us in the execution of our job, which may shift to verification of solutions solely generated by computational functionality. With the advance of artificial intelligence, we finally might end up in a role where we are teaching computers to recognise errors on their own.

The new and upcoming generation of engineers and designers will have more affinity with these digital-oriented design methodologies. Their computational design skills will allow them to compensate for their lack of knowledge or experience, to a certain extent, by simply learning from simulation results. In this light of this digital transformation, it might even be advisable to assign a junior coach to every senior designer to keep them up to date with the latest state of technology.

What is it all about?

The development of computational technologies can be considered the next logical step in the so-called digital revolution of architectural design. The way that information is exchanged between parties has transformed from exchanging two-dimensional drawings to exchanging information (e.g. through digital three-dimensional models) and to exchanging logic (e.g. through digital algorithms). The next step in the digital revolution would be the exchange of intelligence.

We need to consider that all technology that surrounds us is getting increasingly 'smarter'. For instance, Amazon's refrigerator is able to detect what products are missing and is able to automatically order the groceries through an online connection with the grocery store. Similarly, Google cars are able to navigate autonomously through traffic from one location to another. The aim is to increase safety by minimising human interference (and thus human error). What if computers are getting increasingly smarter and as such start designing complete buildings? What will this mean for the future of architects, engineers, contractors and so forth? Who is accountable for the design?

Often, the motivation for applying computational technologies in the building process is directly derived from a time/money-driven perspective. Shouldn't the question be: what are we going to do with the money we saved? Should we use it to make our investors happy? Should we use it as an investment in educating and training those who struggle to keep up with technical advances, or those who are not (yet) familiar with this changed mind-set (as we stated previously)? Or should we use it to make better designs altogether, or to make the world a better place?

We see computational design as an opportunity and change for the better. A chance to spend time on what engineering is really about: realising the ambitions of our clients in a cost-effective and sustainable way using smart technology, while developing our skills and having fun along the way. •