Parametric engineering: twisted logic or common sense?

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Abstract

Architectural designs are getting geometrical more complex as a result of the increasingly advanced digital design tools. On the other hand, current trends of more integrated design decisions extend design freedom at the costs of the increase in complexity due to more restraints to be obeyed and objectives to be considered. This has a negative impact on the feasibility, structural safety and efficiency of these structures, since the ability of the engineer to understand its behavior and oversee consequences of design changes is limited. Apart from traditional common sense engineering, logic-based (or parametric) geometrical design and analysis approaches are therefore required. Intentional parameter variations may help to gain insight into the influences of each parameter on the whole performance, i.e. learning from simulation.

This strategy has been applied in the design and realization of a landmark communication tower. The tower structure consists of a fabric-cladded spatial steel truss that is twisted along its height. The geometric logic of the structure is based on three triangles with different sizes that vary their orientation along the height of the tower. Simulation results convinced the architects that loosening of their geometry restraints would improve their objective of slender appearance. Due to the lightweight character of the structure and large surfaces prone to the wind, wind-induced fatigue effects turned out to be normative for the connection design. Traditionally, calculations required to check the fatigue design lifetime of a single joint are extensive and rather complex. With the use of an automated structural evaluation procedure based on a parametric joint model, numerous alternatives for every connection have been evaluated. In collaboration with the manufacturer, final decisions were made to ensure constructability, where at the costs of steel efficiency a more feasible structure has been realized.

Parametric engineering is considered not just ‘twisted logic’, but common sense in contemporary structural design.

Keywords: Learning from simulation, parametric design, tower structure, optimization, structural design
1. Introduction
The complexity in the structural engineering profession is increasing. For today’s architects, geometrically complex shaped designs, which required architects of the past to devote large parts of their lives to, are now considered within reach by means of a few mouse clicks. Advanced digital computational design tools such as Rhino and Autodesk 3Dsmax allow for designing complex-shaped three-dimensional structures that were considered hard and time-consuming to communicate or modify with traditional means as 2D drawings or small scale models. The nowadays available production techniques such as computer controlled manufacturing or the upcoming 3D printing method contribute to the realization of these designs. The link between both - the conversion from a concept of design towards the final realization including amongst others things the structural engineering, detailing, and specification for production - has to deal with the same increase of geometric complexity.

Another current trend in building design is the so-called “integrated design”, where designers work in integrated design teams rather than consecutive or parallel engineering of individual disciplines. This allows all team members to strive for an optimal overall efficient design instead of keeping an eye on the individual discipline specific goals and responsibilities. The advent of building information modeling (BIM) in the building industry has stimulated the multidisciplinary exchange of design information and brought the need for faster evaluation of alternatives to mitigate on conflicts between the design professions. The common objective of the design team opens the possibility to explore explicitly the effects of variation of design variables originally connected to only one of the parties on the overall performance. Thereby extending the overall design freedom and allowing evaluation of design alternative, which may increase the overall performance. On the other hand, more restraints have to be obeyed and the more objectives performances have to be considered in the early stages of the design.

Insight into consequences of design variations is often restrained, by available means or time, to the evaluation of a limited number of situations and combined with estimates of the intermediate space. This gap can be filled based on experience, knowledge (such as linear correlation) or common sense (like does not satisfy strength requirements, select stronger section). For simple situations, the engineer can predict the quality of an alternative by knowledge of the underlying relations or formulas. Although for more complicated situations, engineering sense and available knowledge should still be sufficient to provide full insight into the systems behavior, the quantitative interdependencies of the various design variables (parameters) might be difficult to fully comprehend. This lack of insight may lead to less efficient design choices or more severe, not understanding the full consequences of engineering choices and their sensitivity may have a negative impact on for example structural safety. On the other hand, better alternative solutions that can improve the overall performance of the project may remain undiscovered and unknown. This objective to realize a (cost) effective structure is still of mayor importance for feasibility, not to speak of our common responsibility to make more sustainable design decisions.
One way to compensate for this lack of insight is by increasing the number of evaluated alternatives. Apart from traditional common sense engineering, logic-based (or parametric) geometrical design and analysis approaches are therefore required to allow computational evaluation of alternatives without requiring significant engineering effort 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 as i.e. geometry, structural behavior, costs, constructability and many more. In other words: "learning from simulation".

In the next sections, the necessity of application of parametric engineering and intentional variation of parameters in contemporary structural design practice are being illustrated with the design case of a communication tower with complex geometry. The follow topics are being discussed: definition of the parametrical model, the use of simulation strategies to discover the design domain, obtaining insight into parameter correlations by simulation and automation of repetitive calculations for structural optimization.

Figure 1: The twisted communication tower at day (BroekBakema) and night (LivingProjects)
2. Parametric engineering in the structural design of a communication tower.

Parametric simulation has been key in the design and realization of a communication tower with a complex twisted shape. This spectacular tower structure has been realized at the Chemelot campus, a community of chemical industry-related companies next to the Highway A2 in the South of the Netherlands. The 30 meter high landmark has been designed by the architects BroekBakema to express the region’s innovation. The main purpose of this tower is branding of the region and communication of events using two large LED screens positioned at the top. The main load-bearing structure, designed by ABT Consulting Engineers, consists of a twisted three-dimensional steel truss structure build up of circular hollow sections. Fabric covers the exterior of the structure. The integrated lighting provides a spectacular appearance at night. The construction by Bouwbedrijf Hendriks Gemert and VDL Technics has finished in August 2014.

2.1. Parametric definition of geometry

To be able to evaluate the consequences of shape variations, a parametrical model of the structure has been created. For complex geometries such as the design of this tower, the definition of the rules for generation of the layout may be more straightforward or less laborious than user-creation of specific geometries. The main variables of these design rules are the so-called design parameters. Parametric design is a design approach making use of these parameter driven rules. Parametric design requires a clear definition of the concept to be able to define the rules.

Figure 2: The basic concept of the architectural shape (left) (BroekBakema) and the single curved, in-plane, columns (right)
Figure 3: Overview of the parametric design model and design parameters (left) [1] and a 3D View of the final BIM model. (EVR Anssems & VDL Technics, part of the VDL Group)
2.1.1. Concept of shape

The tower consists of a spatial steel truss that is twisted along its height. At the first impression, the shape looks complex in appearance, although the basic concept provides a straightforward and clear geometrical concept that can be well implemented in design rules. The geometric logic is based on a triangular cross-section that varies in width and orientation along the height of the tower. The base concept consists of three triangles (refer to Figure 2). These were initially strictly related to each other in the proportions: 2:1:4 for respectively the base (A-B-C), middle (A1-B1-C1) and the largest one as the top section (A2-B2-C2). A smooth curved column is then drawn through the corners of these three triangles (the dotted line in Figure 2). This results, by definition, in a single curved element and is relatively easier to produce compared to a double curved element.

2.1.2. Anticipation on variation in design

The success of parametric evaluation in a design process depends on clear communication of its (in)possibilities and expectations with all participants and requires anticipation on possible modifications. A change of concept or rules of the parametric model as a result of renewed insight or external influences may require significant modifications to the parametrical model or even a start over. Application of flexible approach and anticipation on (foreseeable) changes can provide substantial benefits during the design process although this extends the effort required for the creation of a parametrical model. Therefore, all possible parameters of the design concept (such as width, rotation and location of each triangle, refer to Figure 3) have been deliberately chosen as individual parameters. This approach increases the level of design freedom and anticipates on possible design changes or variants of concept. For example, a reduction in height of the tower (from 36 to 30 meter) for cost reduction could easily be incorporated without mayor impact on the design process.

2.1.3. Accessibility of design information

The parametrical model has been developed based on an in-company developed framework for computational structural optimization[1]. This optimization framework provides an object-oriented definition of commonly used (structural) elements, boundary conditions and objectives in structural design, together with functionality for exchange of information towards structural analysis software, BIM software and algorithms for extensive evaluation and optimization. Implementation of new evaluation functionality requires access to relevant design information. In-house control of the underlying data definitions provides easy accessibility of design data and facilitates the implementation of new evaluation functionality.

2.2. Exploration of the design domain: Evaluation of alternative bracing configurations

The design is the result of the intensive collaboration between the architect and the structural engineer, in which digital collaboration and parametric design have played a prominent role. The ability to provide direct visualization of alternatives has proven to be of great benefit during design meetings to provide insight into the consequences of geometry variations and to allow for qualitative evaluation. A large range of alternatives has been created with variation in geometrical dimensions of the structure and application of alternative bracing configurations. The type of bracing was deliberately implemented as a variable due to the uncertainty in bracing configuration at the time of the creation of
the parametrical model. These alternative bracing systems have been evaluated for aesthetics, structural performance and constructability. The use of moment resisting frames introduced large bending moments in the chords and consequently required larger sections. The manufacturer could not bend columns of these large dimensions in the desired shape. Using diagonals in only one direction required also significant section dimensions to prevent undesired dynamical responses. However, the strength of the twisted design is that it allows diagonals of both directions to pass along each other without intermediate intersection. This beneficial effect is a direct result of the twisting shape where no single facet of the tower is a strict straight plane due to the rotation of the triangular cross-section over the height. The concentration of rotation can be controlled by the vertical location of the smallest intermediate section and the amount of applied rotation. Both have been optimized to minimize the amount of collisions of diagonals by visual evaluation of three-dimensional models. In the lower part, clashes are prevented by a relative large rotation of the twisted shape of 60 degrees over the height of 12 meters. In the upper part, no rotation difference exists between the middle and top section, but due to the continuous curvature of the column, the rotation of the cross-section slightly overshoots in this part. Although the amount of rotation of the top part is relative low, due the larger width of the structure and the smaller required diameter of the diagonals, clashing of the diagonals is still prevented in most locations.

2.3. Insight into correlation of design parameters
In daily engineering practice, often specific design programs are used with graphical user interfaces for input and output. Though reducing the required time of a single calculation, these tools are also diminishing the insight into the underlying parameter correlations, making feasible and efficient solutions harder to find. Tracking the impact of user-applied variations on the solutions performance is often out of the scope of the software but may facilitate learning from these variations. Still these tools can be seen as (black box) parametric models and similar as custom developed parametric design models be used for large simulations if the input and the output can be controlled automatically.

2.3.1. Shape optimization for internal space
The geometry of the tower has been optimized for the conflicting objective of creating the most slender appearance while sufficient internal space has to remain available for the internal maintenance stairs. This available internal space depends on multiple parameters, including the rotation and the width of triangular sections, diagonal configuration, the vertical location of the smallest section and the number of levels.

A wide range of about 8000 alternative solutions, the objective value of available internal width has been calculated. This high dimensional parametric problem is impossible to visualize in standard two or three-dimensional diagrams. To gain insight into the required parameter values, a parallel coordinates plot has been used to visualize all solutions. A parallel coordinates plot can provide insight into a multi-dimensional problem by representing each solution as a single line, connecting its used parameter values. By interactively applying boundaries for each value parameter, parameter correlations can be discovered by the designer. This specific design illustrates that for a required internal free diameter larger than 1.2 meter, a base diameter smaller or equal to 6 meter, the smallest middle section located between 10 or 12 meter and 8 to 12 vertical layers of diagonals, the smallest diameter of the middle section equals at least 3 meters.
Figure 4: A parallel coordinates plot of filtered design alternatives to determine the minimum width of the middle section of 3 meters. [1]

2.3.2. Restraints as “as close as possible” design objectives
Within the perspective of integrated design decisions, one participants’ restraints should rather be seen as wish or objective than a constraint to the common available design freedom. In many cases, design restraints are introduced to prevent re-evaluations of already finished designs or additional engineering works. Definition of design criteria in a parametrical way expressed in some commonly agreed design parameters may provide a more flexible way to deal with design modifications. In integrated design, designers may not insist on holding on to their design restraints if a modification may lead to a more efficient overall goal. In this way, a restraint converts to an “as close as possible” design objective. Parametric evaluation may help to quantify these consequences of alterations.

In this case, a solution to obtain sufficient internal space while striving for maximum slenderness was found in the increase of the diameter of the middle section only. This disobeyed the initial concept of strict related proportions of the triangles. The improvement of slenderness, made made the architect softening this initial architectural shape restraint.
2.4. Structural design optimization

Due to the lightweight character of the structure and large surfaces prone to the wind, wind effects turned out to be normative for the structural design. In the structure’s top part, buckling effects and aesthetical constraints on dimensions are governing for section dimensions. In the lower part, wind-induced fatigue damage at the connections are dominating. Complex shapes often result in complex definitions of (wind) loads, which are often easier to generate based on prescribed rules than by explicit user definition (refer to Figure 5).

2.4.1. Wind induced fatigue effects in steel connections

To prevent fatigue effects, high concentrations of fluctuating stresses should be prevented. This can be done by preferring column sections with limited diameter and large wall thickness, while for the diagonals a maximum diameter and a small wall thickness is desired. This conflicts with the requirement of to have no overlap of the diagonals at the connections to reduce the complexity of connections and to allow for visual fatigue damage inspection of welds.
Traditionally, the calculations required to check the fatigue design lifetime of a joint are regarded as extensive and rather complex, depending on the specific joint configuration and element dimensions. The governing connection is less clear to predict in advance and the consequences of design changes are difficult to comprehend. Based on engineering sense, only a direction of improvement can be given, but the most efficient solution for the conflicting objectives cannot be given without numerous evaluations. For optimisation of the element dimensions with respect to the amount of material required alternative cross sections needed to be evaluated, each for multiple load cases in order to apply wind direction statistics for a more precise prediction of fatigue effects.

2.4.2. Automation of design evaluations

In order to automate these evaluations, a parametrical joint model has been introduced to calculate the fatigue design lifetime based the joint geometry from the geometry model, given cross section dimensions and corresponding internal forces from the structural model. Formulas are used to predict stress concentration factors are used.

The evaluation results provide insight into the area where optimal solutions can be found (refer to Figure 6). On the vertical axis, the joint definitions along one column are given together with the column section dimension. On the horizontal axis, several alternative diagonal sections are given. For each combination, the design fatigue lifetime has been determined expressed in a part of 50 years. The color classification of results provides a quick overview of feasibility. Definitive section choices (the rectangular box in Figure 6) were made in collaboration with the architect to maintain uniformity in appearance; and the manufacturer to include constructability aspects as segmentation for construction and standardization of element sizes. These design decision had a negative impact in terms of the amount of steel used, but positive effect on the appearance, overall costs and realisability.

![Figure 6: The results of the design life calculation provide insight where the optimal cross section dimensions can be found.][2]
2.5. Fabrication of design

The final structural geometry has been exported to an Autodesk Revit BIM model for documentation and communication of the geometry. This model has been handed over to the steel contractor, who has engineered the detailing up to the last bolts for fabrication using Tekla. This final Tekla model has been used directly in fabrication by sending data files to the machines that create the complex cutting patterns for the hollow core section joints. Application of connections all different in connecting angles and cutting shapes is no problem with this file-to-factory approach.

The structure has been prefabricated in three vertical segments in the factory (refer to Figure 7). The diagonal-column connections have all been welded in the factory. The diagonal itself contains two bolted flange joints to allow disassembly before transport. Eventually, the outer parts of the flange joints will be hidden behind the partly transparent fabric cladding. After re-assembly of the diagonals at the final location, the tree segments have been mounted on top of each other. Afterward the LED screens, outside fabric and internal lighting systems have been installed.

Figure 7: A segment of the twisted tower under construction at VDL Technics, Boxtel.

(VDL Technics, part of the VDL group)
3. Discussion and conclusion

The success of the design of the twisted communication tower was largely dependent on parametric simulation techniques. Simulation results provided insight into the complex geometry relations and allowed to improve the overall design performance.

Where traditionally designers often predict the implications of design variations using their available knowledge and experience, learning from simulation results may extend their insight into the consequences of these parameter variations. Future designs are expected to increase in complexity in terms of geometry and increased integral collaboration of design disciplines. The parametric engineering approach may help designers to explore new domains of design alternatives, to strive for more efficient designs and provide insight in complex problems for which intuition and available knowledge may not sufficient to fully predict the consequences of variation.

Not all design problems are considered to be suitable for a parametric design approach. Definition of the underlying parametrical model requires the availability of explicit design rules and available means that may be limited by (financial) reward or available design time. Likewise, there is no added value of a parametric simulation in terms of obtained insight when the design domain and parameter relations are already fully comprehended by the designer. The ability to recognize parameters for variations in available (conceptual) design models, such as BIM models, together with easy extension of existing parametrical models with new parameters based on new findings are considered as promising for future investigation. Open-source sharing of evaluation functionality may further reduce the required effort for the definition of design models.

The twisted logic or paradox in parametric engineering is that it appears as if all (predefined) parameters are in the end quantified to result in an ‘optimal’ outcome (given the boundary conditions at hand). Although this might be just the case, the added value of parametric engineering is that we can now learn from simulation by deliberately varying parameters. In light of increasing knowledge and obtaining insight, this evaluation of simulation results is preferred over optimisation strategies that focus on finding the single best solution, to maintain designers feeling of correctness and sensitivity, and expand their knowledge to be used in future projects. Parametric engineering is considered not just ‘twisted logic’, yet common sense to deal with the challenges in contemporary structural design.

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References
