DIGITAL DESIGN EXPLORATION OF STRUCTURAL MORPHOLOGIES INTEGRATING ADAPTABLE MODULES
A design process based on parametric modeling

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ABSTRACT: We present an example of parametric modeling of a large span roof and discuss a parametric approach to integrating performance oriented design in the conceptual phase of the design process. In the case study shown here, architectural geometry is related to structural morphology; as part of a larger process, its parameterization aims at supporting further performance related investigations, including thermal aspects, by meaning of both the large scale investigation and a more detailed level of design.

KEYWORDS: Parametric modelling, performance-oriented design

RÉSUMÉ: Nous présentons un exemple de modélisation paramétrique d’une toiture à large portée et examinons une approche paramétrique à l’intégration d’un design centré sur la performance dans la phase conceptuelle du processus de design. Dans l’étude de cas présentée ici, la géométrie architecturale est liée à la structure morphologique ; dans le contexte d’un processus plus large, sa paramétrisation vise à supporter plus d’investigations liées à la performance, incluant les aspects thermiques, par le moyen d’étude de grande échelle et par un niveau de design plus détaillé.

MOTS-CLÉS: Modélisation paramétrique, design centré sur la performance
1. INTRODUCTION

In this paper we discuss the use of a model defined by parametric geometry for the conceptual design of a large span roof. The goal of the model is to allow for design explorations which integrate strategies for on-site energy use and structural morphology in the early design phase. The parametric model is presented for its role in design support, in exploring architectural geometry to achieve those goals and integrating aspects from different disciplines (Kilian 2006). The first section briefly introduces the context of the roof and offers an overview of the larger project it is a part of. The role of the roof in relation to the use of on-site energy resources for climate comfort is explained, especially referring to passive strategies for thermal reasons. These strategies enable achieving indoor thermal comfort by using on-site renewable energies, and reducing the need for imported energies. Taking advantage of periodic climatic changes enables one to store the solar thermal energy needed for heating the indoor spaces or to disperse excessive heat to the outside. The architectural geometry of the overall shape and the roof details can support this effect and are investigated here. Including performance criteria in the conceptual design stage increases the dependencies that need to be taken into account at this process stage. In the second section of this paper, parametric modeling is introduced with respect to managing a network of dependency relationships in order to explore variations within their design solution space. This is meant to support a performance oriented design, which integrates multiple disciplines from the very early design stage. Particularly, a parametric model is introduced with respect to three aspects: modeling the overall shape, investigating the structural geometry and, according to the responsiveness required to support passive heating and cooling, integrating openable modules in the structural morphology. The third and fourth sections present the parameterization process as well as the creation of different instances of the model with respect to the overall shape of the roof and its structural geometry. Both the advantages and limits of the model are indicated by following two levels of discussion: first the missing coincidence between the parametric model solution space and the real project solution space; secondly the evaluation process of different design solutions. The fifth section focuses on the parametric modeling of reconfigurable modules. Integrating these in the roof structure aims at controlling its air permeability. Designing these in relation to a modular structural typology requires the design exploration of both the structural morphology and the movement of each module. Parametric modeling is presented on both levels of the design exploration.
2. THE ACTIVE DESIGN PROCESS: CONTEXT AND TASKS

The roof structure is part of a larger project consisting of high-rise and low-rise buildings, and a public square, partially covered by the roof in question. The overall area is illustrated in Figure 1, showing the design concept developed for the site by the architectural office.

*Figure 1. Design Sketch [Image courtesy of Open Project Office].*

While the office tower and the building facing it are in an advanced stage of the design and construction process, the low-rise buildings and the public space including the roof are still at a conceptual level. In designing them, one main criterion is the development of a system that joins the specific architectural, functional and climatic requirements. Following this direction, various strategies are being investigated considering both active solar technologies and passive systems for heating and cooling. Reflecting on an expected critical summer overheating, especially the second kind of systems has been analyzed more deeply. With respect to these issues, the roof is expected to play a key role in contributing to the climate control. The covered space is in fact a semi-indoor space partially surrounded by adjacent indoor spaces. Passively avoiding the coldest and the overheated conditions positively affects not only the direct use of the spaces covered by the roof, but also the indoor thermal behavior of the surrounding buildings. A more detailed description of these active studies is outside the scope of this paper. However, it is important to emphasize the general character of this investigation aiming at defining the architectural geometry of the roof through an integral approach involving climate comfort performance evaluations across the project scales. On one hand, the role of the shape of the roof in directing the airflows is an example of the close relationship between aspects affecting the passive thermal behavior of a build system and its geometrical shape. Preliminary design evaluations have been made based on wind behavior calculations on the project site and, due to extremely low wind speeds on site, special attention is given to using the...
roof to direct the wind in order to provide some cooling effect. Modeling
the geometry and the curvature of the roof for this wind effect affects the
large scale definition of the early design concept. On the other hand, in
order to reduce summer over-heating, additional options such as the use
of rainwater collected from the roof and green roofs on the low buildings
are considered; different ways of regulating the sun coming in through the
roof are being evaluated and the air permeability of the roof is being ana-
lyzed with respect to passive cooling. Specifically, the air flow regulation
requires switching the roof between a closed (barrier like) to an open
(filter like) condition and related kinetic components are studied with
respect to two possible approaches. The first is based on large scale kine-
matism of the overall shape. The second is based on the repetition of
openable modules, integrated in the structural morphology. This latter
approach is the one that will be discussed further in the paper and requires
considering the roof geometry at a more detailed scale.

*FIGURE 2. WIND ANALYSIS [IMAGE COURTESY OF L.AANEN] AND RELATED DESIGN SKETCHES.*

3. PERFORMANCE BASED CONCEPTUAL DESIGN OF THE ROOF AND PARAMETRIC
MODELING. DEFINITION OF THE FOCUS OF THE MODEL

In the decision making process of the context described above, including build-
ing performance criteria early on in the process is a fundamental issue chal-
lenging the design. The convergence of different disciplines into the first
elaboration of the project leads to a more integral design but also increases the
system of relationships on which the conceptual design is based. While aiming
at a performance oriented conceptual design, parametric modeling serves to
model the roof in order to support its design exploration. The choice for using
parametric techniques is based on their capacity for creating design alternatives
while managing the complex system of relationships.

A parametric model can in fact represent the characteristics of its compo-
nents as well as their interrelations. This means that through the digital model
a network of dependencies is described. Some attributes are described by
independent values and others by values that vary in relation to other attributes.
When varying these, the independent values act like inputs to the model and
the dependent attributes are processed by receiving data from their related
attributes. This flow of data keeps the network of dependencies consistent, which itself remains constant, but processes the input values by generating variations of the output. These variations are produced as different solutions of the model and are called instances of the model. In accordance to the role of the geometry mentioned above, the present context focuses on parametric geometry where variations of parameters mainly result in geometrical variations, which embed performance data. Most of the software available for parametric design allows the visualization of the network of dependencies next to the visualization of the geometry, which means that, besides the outputs, both inputs and data flow are also kept explicit. While systems with this potential are well known in the engineering field, they have become only recently commonly used in the architectural field. Examples are Revit, Catia, SolidWorks, ParaCloud and Generative Components (GC). GC was used in this study.

The dependencies network must be related to a pre-established approach for exploring the different design configurations, and this approach must be chosen in the initial phase from possible ways to describe any design state. This choice strongly conditions the overall design process that follows. In this study, the parametric model models the overall shape with respect to both architectural and thermal issues, investigates the structural morphology of the roof and the option of operable modules; three families of geometric instances are therefore expected as outputs generable by the model. Concerning structural morphology, the model assumes as conditions the preliminary studies conducted by the engineers (see acknowledgements). These studies favoured the selection of a double-layered space truss as the typology. Within this structural choice, the engineering office has conducted evaluations on various morphological alternatives. The parametric model presented here combines an external triangular-based layer and an internal triangular and hexagonal-based layer, which has been preferred by them due to its architectural transparency. As a third aspect, the required reconfigurable elements form an integral part of the architectural space and integrating them in the design from the early conceptual stage emerges from the process as an important aim.

By focusing on these three aspects, the model is articulated in two stages. In the first stage, two levels of independent parametric investigation have been structured: one for the overall shape of the roof and one for the density of its modular structure. This stage is discussed in the following section. In the second stage of the model, within its modular structure, deployable modules have been modelled by referring to two levels of independent parameters, morphological ones and kinematic ones. This further stage of parameterization is presented in Section 5. For both stages, the parameterization process and the generation of instances are shown.
4. OVERALL SHAPE AND STRUCTURAL GEOMETRY. PARAMETERIZATION PROCESS AND GENERATION OF INSTANCES.

The section above has introduced the potential of parametric techniques in using computation for generating geometrical alternatives within a described structure of relationships by varying the independent parameters of the model. This potential amplifies the geometrical representation by providing a model of the design which is actually a large set of possible configurations. While working with such a system, the effort is moved from the direct definition of design states to two other levels of the design (Aish and Woodbury 2007): one is the parameterization process which is preliminary to the computational generation of alternative solutions; the other one is the selection process among the large set of generated instances.

Once the aspects on which the investigation focuses have been established, the parameterization process defines which components of the model vary and how the variation occurs. In other words, the parameterization process determines the attributes subject to parametric transformations and the rules following which they vary. It consists of the selection and definition of the interrelations during the earlier structuring of the model and is the fundamental step required to exploit the potential and advantages offered by parametric modeling. The conceptual structure defined during the parameterization process is in fact the one that guides and determines the variation of the geometrical output. Usually the result of the parameterization process is a hierarchical structure, which describes the dependency chain used in the model, starting from the independent parameters. This is what makes the earlier choice of the model focus so important. The parameterization is a time consuming process of abstract elaboration which needs to be addressed through relevant criteria. This is especially so when we recognize that the hierarchical nature of the abstract structure has little flexibility in changes once a model has been created (Kilian 2006). In the case presented, independent parameters and the hierarchical structure have been defined based on various criteria discussed below. First general choices have been made to generate robust free-form design oriented instances, as required by the first architectural concept.

The overall shape of the roof is described through a NURBS surface. Independent parameters have been set in order to model the surface. They correspond to the Cartesian Coordinates of the NURBS Control Points. For the early modelling of the roof, sixteen Control Points allow modelling the surface with a reasonable degree of precision with respect to the free-form shape proposed by the architects and engineers. Therefore a set of forty-eight independents parameters has been specified to parameterize the overall shape of the roof.
A starting configuration has been modelled as a square flat surface on which the parameterization of the structural geometry has been applied.

**FIGURE 3. NURBS SURFACE AND ITS INDEPENDENT PARAMETERS (CARTESIAN COORDINATES).**

In order to parameterize the structural geometry, a parametric tessellation of the surface has been determined on the base of a point grid. Different point grids have been defined. Among them, one based on parallel sections and one based on UV coordinates. For the reason of architectural purposes the latter is presented here. In this latter case, the main issue is modelling the structural geometry by describing the position of the points on the surface parametrically as well as reciprocally among them, using UV Coordinates. The problem is reduced to a two dimensional array set on Pythagoras relationships and the number of rows is assumed as an independent parameter, $n$, to regulate the density of the grid (see Figure 4).

**FIGURE 4. PARAMETRIC POINT GRID DESCRIBED THROUGH UV COORDINATES.**

The obtained point grid is used to model the structural elements, by combining hexagonal and triangular configurations for the bottom layer, and using only a triangular configuration for the top one. The second layer
is set to a distance $d$ from the bottom layer. The distance is an independent parameter as well. A set of diagonals is then introduced by following the space frame requirements. Figure 5 shows both the bottom layer and the combination of bottom layer, top layer and diagonal elements.

**FIGURE 5. PARAMETRIC DOUBLE LAYER SPACE FRAME, $N = 40$.**

Different instances of the resulting parametric space frame can be generated both varying its density and modeling the overall shape, as shown in Figure 6. The ability to generate instances leads to the second level where the effort of the designer is moved to the search for meaningful instances among the ones embedded in the parametric model. A parametric model can in fact be seen as a family of models as big as the possible combinations of independent values, therefore sometime even infinite, like in the case described. Being able to generate an infinite number of alternative design solutions is quite a potential, but becomes senseless if it is not associated to a meaningful selection process. This aspect is tackled in the next section.

**FIGURE 6. EXAMPLES OF INSTANCES GENERATED BY MODELING THE OVERALL SHAPE THROUGH THE INDEPENDENT PARAMETERS REGULATING THE POSITIONS OF THE CONTROL POINTS (CP).**
5. SOLUTION SPACE, SEARCH FOR MEANINGFUL INSTANCES AND POTENTIAL INTEGRATION WITH OTHER COMPUTATIONAL SYSTEMS

Focusing on the generated instances, this section points out two levels of discussion: the missing coincidence between solution spaces and the evaluation process of different design solutions.

5.1. Solution space

Regarding the first aspect, it evidently appears that there is an intersection but no coincidence between the project solution space and the set of instances that can be generated from the model, because this set is much larger. This is a common situation due to the need to limit the focus of the parametric model first while choosing the exploration focus and second while choosing the factors to parameterize and define their hierarchy. In other words, on one hand the hierarchical structure of the model cannot be exhaustive because it cannot include all the design aspects nor all the factors affecting the chosen aspects. On the other hand it cannot allow explorations other than the ones following the stated dependency chain. This latter limit directly relates to the mentioned lack of flexibility, which requires a new parametric description when the exploration focus is changed and therefore requires an evaluation of the time-investment when setting a parametric model. From a time and effort investment point of view, the limitations of parameterized aspects and factors can be approached from two directions: either reducing the chosen aspects and factors toward a simplification of the model or choosing them with respect to possible generalizations, avoiding a specificity that is too highly contextual. This second direction is especially feasible when dealing with aspects that can refer to general rules, like the ones concerning space frame constraints in the case described.

Even when limiting the focus to the early structural design, not all the instances belonging to the solution space of the parametric model also belong to the solution space of the real project due to factors that are not included in the parameterization process. These factors are numerous. Among them, the angle of convergence between adjacent bars of the structure, which is a very well known constraint coming from the construction domain. Others are related to the cladding system which, in the most traditional case of triangulated glazed surface, also requires attention to the minimum angle. Further, a limitation of the variability among the elements can be required. Especially in the case of non-standard architecture, taking these and other factors into account simultaneously is already a difficult issue while working on a chosen design configuration. Including all of them in the parameterization process while exploring different design solutions at the conceptual design stage, involves an even higher level of complexity. This becomes affordable only as long as it is comparable to the achievable benefits.
From a general parametric point of view, there are two possible ways to pursue a more exact intersection between the mentioned solution spaces. First, a constraint solving approach, however, this will not allow the creation of specific instances from the described constraint. Second, a propagation-based approach through which relationships can be assessed in order to rightly address the properties of the created instances. This second approach is the one considered here by introducing a further set of rules in the distribution of the achieved point grid. In order to do that, first the solution space needs to be enlarged even more. Besides the density and the height of the space frame, the solution space is also affected by the pattern of the tessellation. Within the general choice of a triangle based top layer and a hexagon-triangle bottom layer, the range of possible variations is large. The above described model has been set to create instances starting from a regular tessellation on a flat surface. While changing the surface curvature, adjustments of the tessellation can be required, for example due to the way they affect the angle between convergent bars. In order to introduce them in the model, a further parametric factor $a$ has been set. Including it in the description of the two dimensional array, the factor acts on the position of the points by distorting the regular tessellation (stretching or squeezing the regular figures). Furthermore, a parametric factor $b$ has been introduced in order to move the tessellation grid on the surface, allowing operations like the search for alignments. Examples are shown in Figure 7.

This illustrates the importance of keeping the structure open to involve further parameters. Once this enlarged solution space has been obtained, relationships that guide the variations of independent parameters can be introduced to address the generation of instances, restricting their possible number. Describing proportional relations between $a$ and the curvature along one section of the roof is one possible way. However, even when restricting the solution space of the model, the graph still embodies decisions about chosen relationships and defers computation of precise values (Aish and Woodbury 2007). This leads to the second issue, the evaluation of the generated instances belonging to the design solution space.

*FIGURE 7. BOTTOM LAYER: AN EXAMPLE OF INSTANCE GENERATED BY VARYING $A$ TO STRETCH THE TESSELLATION PATTERN; $B$ EXAMPLE OF INSTANCE GENERATED BY VARYING $B$ TO SLIDE THE TESSELLATION ON THE SURFACE; $C$ VARIATION OF THE OVERALL SHAPE.*
5.2. Searching for meaningful instances

Due to the relevant dimensions of the set of instances, searching for meaningful instances leads to the integration of other computational techniques, such as ones related to the analysis and evaluation processes. Such techniques have huge potential but they are mainly single-discipline oriented and require a balance between their specific focus and a larger view on the overall design issues. Beside this aspect, due to the high number of possible combinations of independent parameters, the set can be too large to allow a systematic analysis of all solutions. Guiding the generation of instances seems to be a more reasonable process. This moves the core of the problem to the need of appropriate criteria in selecting the combinations of independent parameters. Other possible solutions include integrating search methods that are related to the generation of large sets of alternatives. Optimization processes based on Genetic Algorithms belong to this domain. The analogy between the parametric generation of instances and the genetic creation of populations allows to combine parametric models with a genetic algorithm optimization that is able to address the creation of instances toward the one most fitting a given fitness function. The potential of this is being explored in a current collaboration (see acknowledgements) and will be integrated in the process.

6. INTEGRATION OF RECONFIGURABLE MODULES

The second stage of the model tackles the integration of openable parts in the modular structure of the roof by focusing on the possibility of adding complexity to the model while collapsing sets of repeated relationships into new objects that can be propagated in the model.

Some introductory information on the active studies on passive strategies has been provided in Section 1. In the context of these studies, various systems are investigated that allow the opening of some parts of the roof in order to make it permeable to airflows. While a large-scale kinematism would contribute to an adaptive control of various factors including an eventual wing effect, the introduction of local openable parts is expected to affect the extraction of overheated drafts due to air convection the most. This also allows investigating them at a different hierarchical level than the general morphology to which they are related.

The parametric model described above is based on a number of independent parameters through which the overall shape can be modeled, including the parameter $n$ determining the density of the structural grid and the distance $d$ between the top and the bottom layer of the space frame. Within the solution space of this model, only a relevant subset of instances generable by combinations of these parameters is being considered here. The solution space that can be explored within the given constraints is quite large, as discussed, and its
instances can be grouped in subsets defined on the basis of particular properties. Some of them emerge as relevant in respect to deployability constraints. One such subset is defined by the following two conditions: first the hypothesis of symmetry is introduced at the level of the overall shape constraining the 16 control points to assume positions symmetrical to a central axis; second only the values generating symmetrical tessellation patterns are assigned to $n$. Because of symmetrical relationships, conditions for some deployable modules are matched by the generated set of instances which is a relevant but not exhaustive family of solutions. The same principle can be repeated for other relevant sets of instances; the one presented here is considered only as an example.

With reference to a specific group of deployable structures, the pantographic ones, the authors have studied earlier the deployability constraint and the use of symmetry to describe a relevant sub-family of deployable pantographic modules (Turrin et al. 2008b). This sub-family is considered here with specific reference to the semi-symmetry principles.

The deployable module is parametrically built as an entity separate from the general model, based on a set of relationships to this general model. The structure of the dependencies guarantees that its morphology fits the selected structural modules of the roof and, as a consequence of their properties of symmetry, respects the deployability constraint. Additionally, an independent parameter $k$ is introduced to visualize the kinematic behavior of the module (Figure 8). Possible parametric descriptions of morphological and kinematic constraints have been presented previously (Turrin et al. 2008a), also in this case with reference to pantographic structures.

**FIGURE 8. DEPLOYABLE MODULE: DEPLOYED CONFIGURATION (A) AND THREE STEPS (B,C,D).**

The parametric entity defined in this way can be propagated along the roof structure by selecting its bars as input to properly configure and allocate the feature. In the graph structure the deployable module therefore becomes a new node which includes the whole set of dependencies involved. In other words,
it is treated as a sub-graph of the roof structure and is automatically updated when generating new instances of the roof. Particularly, Figure 9 shows the generation of instances which required changes of the morphology of the deployable modules. These changes are automatically obtained while still guaranteeing the deployable behavior.

![Figure 9. Propagation of the deployable modules on the model; different instances.](image)

7. CONCLUSIONS

A first general conclusion on the presented process is that working parametrically requires a different way of thinking. While following a parametric approach in fact, the design aspects involved on the project need to be analyzed early and described using an orderliness, which is uncommon in the conceptual design phase. This aspect embeds the advantage of an early systematic evaluation but also the resistance due to both the difficulties of a different thinking process and the feeling of a loss of creative freedom and intuition. Recognizing this general aspect, specific conclusions of potentials of parametric geometry in bridging different disciplines toward a more integral design approach in the conceptual stage can be discussed. The parametric model described in this paper is part of an active project and general conclusions must therefore be postponed to the end of the process. Partial conclusions are discussed while proposing a critical overview of the process and properly addressing further work. Both with respect to potentials and limitations, these conclusions focus on the possible effectiveness of such a support in current architectural practice.

On one hand, the network of established dependencies connects and relates the entities of the model by allowing large sets of design instances. This ability to quickly create many alternatives by allowing the visualization of a large set of different options has proven useful. However, as explained, this moves the effort from creating instances to defining relational graphs in order to defer the decision on precise values. With respect to this issue, the ability of properly selecting and structuring the factors involved in the parameterization is fundamental but still does not guarantee a return on time-investment. The time-
pressure which is common in practice does not allow such uncertainty and relies on the experience of the designers more than on a systematic exploration of alternatives to produce in time a sensible solution. This limitation is partially solved when generalization can be used in the process. Aiming at this exemplification, the case of the space frame has been shown and is expected to provide a good support within a reasonable spectrum of shape variability in the conceptual stage.

The second point of focus is the search for meaningful instances. We discussed the issue while proposing the support of computational tools in helping to assign values to independent parameters rather than to analyze the overall solution space of the model. This is expected to be a very promising direction and will be further improved in the process. However, the importance of the designer’s and consultant’s expertise needs to be pointed out here; that expertise cannot yet be replaced when dealing with topics such as wind analysis through digital simulation, which requires both too much human interaction and computational power to be applied to large ranges of design alternatives.

At last, parametrically working on deployable modules highlighted the relevance of having an abstract model to refer to during the parameterization process. Particularly, previous systematic representations of rules and extrapolation of parameters to support the exploration of deployable structures have been used to support the process. On the other hand, also the difficulty of having theoretical models general enough to embed the complexity of design cases has to be highlighted. Both in relation to morphological variability and deployable behavior, the theoretical structure used here is based on symmetry. This allows supporting relevant subsets, among which an example has been provided, but does not allow for an exhaustive exploration. Further investigations concerning non-symmetrical modules are a potential area for future work.

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