Parametric modeling and optimization for adaptive architecture

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Abstract. In this paper we address performance oriented design applied to adaptive architecture in order to satisfy the performance requirements for changing contextual conditions. The domain of adaptive architecture is defined and specific focus is given to form-active architecture, in which geometric changes occur as a means of adaptivity during the use of the building. A parametric design approach and related computational tools which are able to support the very early conceptual phase of the design process are introduced. Three examples are shown concerning different aspects of the design process. These are the identification of meaningful geometric properties as a means of adaptivity, of different configurations within predefined geometric properties and of reconfigurable systems. For each of these, benefits and limitations of parametric design and computational search techniques are discussed.

1 Introduction

The work discussed in this paper addresses architecture as the mediator between the environmental conditions and the human demands of users, owners and society. None of the factors involved is constant over time. Despite this situation, traditional buildings are quite static, and are usually designed based on satisfying the average predictable conditions. In contrast to this, we suggest a building capable of reacting to changing human needs and fluctuating environmental conditions. In this paper we refer to this concept as adaptivity in architecture, and discuss it as a possibility to satisfy changing needs in changing environments. The complexity of this challenge we view as part of performance oriented design. In order to support performance oriented design we embrace the complexity of the task through the use of parametric modelling in combination with computational search techniques. Specific focus is given to optimization techniques, among which the details of evolutionary optimization based on genetic algorithms have been presented in previous papers (Turrin et al. 2010a, Turrin et al. 2010b). In this paper, we specifically tackle a number of design aspects for adaptivity and discuss parametric modelling and optimization processes as support for the design of adaptive architecture.

In the next section, adaptivity in architecture is introduced together with a selection of aspects design complexity depends on. In the third section, an overview of categories of adaptive architecture is provided, one being form-active architecture. The parametric design of form-active architecture is discussed in the fourth section, and is illustrated with three examples respectively in the following sections. Finally conclusions are provided.

2 Adaptivity in architecture

Adaptivity is intended as the capacity of a building to be responsive to a changing context (Negroponte, 1975). The work presented in this paper investigates adaptivity with reference to performance oriented architecture. Architectural performance is the efficiency with which, architecture fulfils its intended purpose. The assessment of the expected architectural performance refers to architectural requirements, which confront needs and demands of human actors (users, investors, society, etc.). Human needs and demands refer to the human perception of complex factors, and the formulation of architectural requirements. This entails a decomposition of human needs and the understanding of their subparts. Behind architectural performance, there is therefore a complex formulation of requirements based on expertise through which phenomena are decomposed, modelled and interrelated. This leads to a first level of complexity of performance oriented design. A second one derives from the fact that the architectural performance does not depend only on the building in relation to the human actors, but is also directly related to its natural and/or built surrounding environment. Environmental conditions have a great impact on the accomplishment of the architectural requirements, and need to be taken into account when assessing architectural performance. Both the human conditions which need to be satisfied and the environmental conditions that may either inhabit or facilitate the fulfilment of human demands are considered as part of the context. The context of a building is therefore represented as a double data set, whose analysis is at the base of performance oriented architecture. Identifying a design solution which satisfies the expected performance, when given a specific data set describing the context in its parts, is well known to be a challenging task. The complexity of this operation increases even more when considering that the data set does not offer a fixed framework. On the one hand, human needs and demands change over time, in the short and long term use of the space. On the other hand, changing environmental factors affect the performance of the building: daily and seasonal climatic conditions impact daylight and thermal performance; changes in the number of occupants affect its functionality, but also its thermal load or acoustics; functionality is affected by changes in the surrounding built environment, which interfere also with solar radiation or daylight reflection; and so on. The result is a situation with several layers of changing needs in changing conditions, which need to be considered during the design process.

3 Adaptive architecture

According to the above introduction of adaptivity in architecture, the concept of adaptive architecture is based on the interdependence between the varying needs/demands and the capacity of a building to satisfy them in a changing environment. Still this definition identifies a large domain including subcategories, about which current literature does not univocally agree, neither for content nor nomenclature. The present work refers to two criteria of classification, identified as the main steps in which the process of adaptation can be subdivided: the way architecture interfaces with the changing context and the way architecture can adjust to achieve the desired changes. The way architecture interfaces with the changing context involves the manners (including automation and level of integration) by which changes in the context are detected, information is processed and consequent changes in architecture are actuated. While the way architecture can adjust to achieve the desired changes refers to the manners in which adaptation is reached. Specifically, these can be changes in geometry, based on geometrical reconfigurations of elements, and/or changes in material properties. The first kind requires a change in shape through the movement of one or more elements or parts of them. This category refers to the so called kinetic or reconfigurable architecture. The second kind occurs without implying geometrical variations at perceivable scale, and adaptation is based on the integration of materials able to vary their properties, such as their transparency, colour, porosity or others, rather than shape. Both categories run transversally to the previous subdivision. With reference to this main domain description, the focus here is given to reconfigurable architecture and specifically to a sub-category called form-active (or shape-active) architecture. The sub-domain of form-active architecture consists of architectural constructions conceived to adjust their shape while in use, during their life in a specific location, with possible high frequency of shape changes according to the short-term or real-time needs. All changes in shape of this sub-domain are responses to performance requirements. The wide range of possible performances implies a high variety of aims for which movement is designed and used. The cases discussed in this paper focus on large roof structures responding to wind changes and to solar energy, as examples of this larger sub-domain.

4 Parametric design of form-active architecture

While much attention has been given to the detailed design of systems that allow for geometric reconfigurability, modest efforts have been invested in supporting the early architectural design toward the integration of reconfigurable systems in buildings. In contrast, the work described in this paper focuses on the early phase of the architectural design process. The primary reason for this lies in the large impact that preliminary design decisions have on the performance of buildings over their life time, in form-active as in static buildings. With focus on static architecture, the potential of parametric modelling in supporting performance oriented design was discussed by the authors in previous publications (Turrin et al. 2010a, Turrin et al. 2010b). These possibilities are summarized here as the systematic generation of a large set of alternative design solutions based on a preset range of independent parameters. Exploring such large design solution spaces based on performance evaluations was also shown as beneficial and possible to support by means of computational search techniques, such as genetic algorithms (GAs). Moreover, properly selecting the independent parameters and structuring the chain of geometric associations were emphasized as key points in order to define solution spaces meaningful for the analyzed performance. When focusing on form-active architecture, the potential and benefits as well as the recommendations discussed concerning the parametric approach still have influence. However, as compared to the design of static architecture, the approach needs to consider an additional perspective, since the alternative design solutions generated based on the parametric models are not necessarily design alternatives anymore, but can be embedded in a form-active design solution as different configurations of the project. Also, when compared to the design of static architecture, the conceptual design of form-active architecture embeds additional tasks necessary to be confronted while using a parametric approach. Among them, attention is given here to three enterprises, for which the support given by parametric modelling and computational search techniques is demonstrated respectively in sections 5, 6 and 7. They consist in identifying respectively the proper geometric means of adaptability; the suitable configurations within predefined geometric properties; and proper systems for form-active architecture. More specifically, the first one deals with the identification of the changes in various geometric properties that positively affect the performance trend of architecture during contextual changes. Particularly, addressing the trend of a certain performance (in order to satisfy changing requirements in a constant environment or constant requirements in a changing environment or the combination of both) implies the analysis of geometrical variations of a different nature, some of which can be beneficial, others less. Especially when the geometry is complex and the considered performance is affected by multiple phenomena, identifying the meaningful set of geometric properties to be changed can be challenging. The second aspect deals with identifying the specific configurations that are suitable to achieve the desired performance trend, already knowing the nature of the required geometric changes. This also allows tracking the expected frequency of needed reconfigurations as well as their patterns during the life span of the building. The major difficulties of this consist in relating the pattern of changes in the context with the needed responses by the building. Finally, the third aspect deals with the identification of technical means to integrate in the building geometric adaptivity, which can include predefined systems or customized and new reconfigurable systems. While designing new reconfigurable systems is an evident challenge, integrating systems based on well-known reconfigurable structures (such as foldable or deployable units) is also a difficult task, particularly due to the geometric constraints limiting the exploration that is proper for the early phase of the design. The approach to these three aspects cannot be univocal, nor is it within each of them, but for each of them benefits are shown in the following sections based on parametric modelling techniques. By considering this perspective, three examples are presented in the following sections, with reference to specific case studies of long span roofs.

5 Parametric searches for geometric properties as means of adaptivity

This first example refers to the identification of geometric properties whose changes should be considered for inclusion in a form-active design solution. As expressed above, especially in case of complex geometries and/or performance interrelations, identifying which changes in geometry would positively affect a certain performance trend of architectural constructions (or specifically of large roofs) during contextual changes, requires a design exploration. By means of parametric approaches, such design exploration can be formulated upon independent parameters and a related chain of geometric dependencies (Turrin et al., 2010b), aiming at distinguishing the variables that allow for improving the performance over the contextual changes from the ones that do not. The solution space of the parametric model can then be explored based on performance evaluations, to group the independent variables. The output of this process consists in a subdivision of the initial variables into two groups: one should be embedded into the final design solution as variables (describing the form-active properties), the others as specified values (describing static properties). This process narrows down the design solution space to a defined set of both variable and constant geometric properties. An example (Figure 1) illustrates on-going case studies subjected to changing environmental conditions (and constant human demand). The case shown is discussed in its planar configuration. In it, the modular density, orientation and inclination of a set of roof cladding elements, are explored by looking at the solar related performances of the spaces underneath the roof. Specifically, a set of panels is explored by looking for configurations allowing the minimum solar exposure in summer and the maximum in winter, over different times of the day.

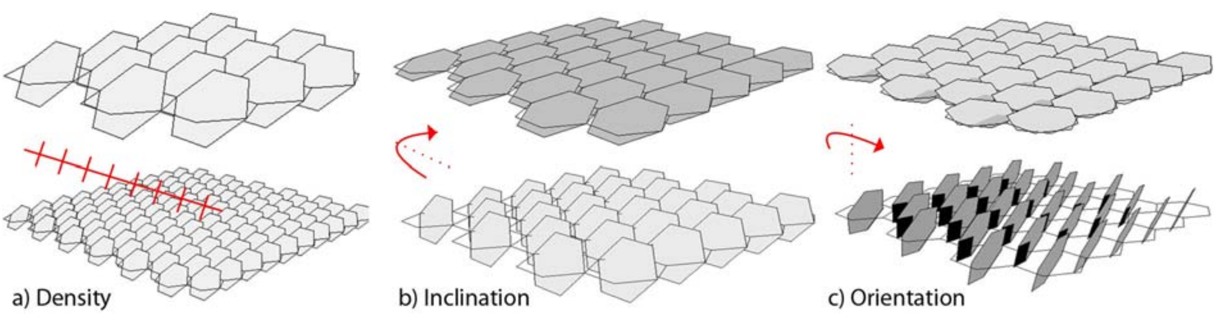

Figure 1: Variables of the parametric model and related examples of instances.

Table 1 shows the variations of the solar exposure levels over the time of a winter and summer day, for different variables. Aiming at comparing the relative influence of density, inclination and orientation singularly, each variable has been first explored separately. For each one, a search has been run looking for minimum (summer) and maximum (winter) values (taken as absolute values or as ratio with daylight). Genetic Algorithms (GAs) have been used for searches which explore large solutions spaces. The final results show how optimal values are found either with or without relevant variations of each variable. Performing the optimization with all variables at the same time allows the relevance of eventual interrelations among them to be assessed. The variables that in both cases do not relevantly vary in the optima can be assumed not to require adaptation in this design context.

Table 1: Solar Exposure levels (W) for variable density (north-south orientation; 45 degrees inclination), inclination (density 16; north-south orientation), orientation (density 16).

	21.Dec h.10.00	21.Dec h.12.00	21.Dec h.14.00	21.Dec h.16.00	21.Jun h.10.00	21.Jun h.12.00	21.Jun h.14.00	21.Jun h.16.00
Density []	110.6[48]	73.9[16]	43.9[24]	5.5[16]	228.8[32]	157.0[48]	113.4[32]	141.9[32]
Inclination []	198.4[89]	112.6[89]	80.4[89]	7.5[89]	77.8/28[0]	62.6/28[0]	47.0/28[0]	39.6/28[0]
Orientation []	207.4[76]	126.3[68]	90.6[-70]	8.4[-68]	77.8/28[0]	62.6/28[0]	47.0/28[0]	39.6/28[0]

Among the few currently available tools coupling GA and parametric modelling, ParaGen (Turrin et al. 2010a, Turrin et al. 2010b) incorporates a cycle that includes a parametric modeller, performance evaluation software, a GA based search engine and a searchable database which includes solutions values and graphic depictions. As compared to other tools, a major peculiarity of ParaGen consists in the interactive design exploration that the designer can experience during or after the generation of solutions by the GA. Currently, this potential is being further implemented in order to facilitate even more the processes such as the multiple explorations described above. This includes the integration of search filters by which the generated design solutions stored in the database can be sorted and investigated, using any combination of variables or performance results.

6 Parametric searches for geometric configurations with given properties

The second example refers to the identification of suitable configurations with predefined geometric properties of the design. In contrast to the previous case, the parameterization is limited within a structure including variables and dependencies that have been already identified as meaningful for adaptivity, and that are embedded into the design of the form-active system. The design exploration is therefore structured by searching for the specific configurations required for the system under certain contextual conditions. An example (Figure 2) illustrates the identification of suitable configurations, also in this case under changing environmental conditions (and constant human demand). The process was carried out by a master student (see acknowledgements) co-mentored by one of the authors. In this case, the combined use of parametric geometry and optimization of performance is used for the design process of form-active roofs reacting to varying wind load conditions. Specifically, a design tool was developed by the student, which enables determining the geometric configuration of a discrete structure to minimize its bending moments under variable load conditions. The process can be seen as an iterative form-finding that outputs a compression-only structure when possible for any change in loading. The inputs expected from the user are a two-dimensional grid of points (representing the structural nodes projected on a plane) and the wind loads. Here a combination of several methods is applied, in order to identify bending moment-free, three-dimensional configurations of the structure for variable loads. The thrust network analysis (Block, 2009) is used for identifying the reciprocal force grid (planar), which provides multiple solutions in case of systems having more than three bars converging at one node. Next, the complementary energy method is used to identify the suitable (lowest energy) solution among the multiple ones provided. And finally, the force density method is used for determining the third dimension of the structure (Z coordinates of the nodes in structural equilibrium). The details of these methods and their implementations are beyond the scope of this paper, but will be described in forthcoming publications by the graduated student (Liem, Y., Borgart, A., forthcoming).

The focus here is on the design tool developed based on the parametric modelling software, Grasshopper (a plug-in for Rhinoceros, McNeel). The tool is based on a set of scripts which embeds the whole process within the parametric modeller coupled with Excel. Specifically, inputs are given in Grasshopper as a planar grid of points (which have variable positions, except for the perimetral supports), and directions and intensities of the wind loads (variable as well and expressed as independent parameters). Lines connecting the points are then generated, and their lengths and reciprocal angles measured and automatically recorded in the Excel spreadsheet. With this information, and by varying the magnitude of a number of support reactions, the reciprocal force grid can be defined and tested with different load distributions, and optimized for minimum complementary energy. The optimization is automatically re-run upon any change of input points in Grasshopper or wind loads in Excel. The reciprocal diagram is also automatically drawn in the parametric modelling software to visualize the results and facilitate both the understanding of proper solutions (grid with closed polygons) and the detection of eventual unwanted tensile forces (grid with open elements). Finally, the Z coordinates of the nodes are automatically calculated in Excel and outputted to Grasshopper, where the geometry of the provided structural solution is visualized (Figure 2a).

The method has limitations and will need further development to enlarge the current range of applications, but it exemplifies the search for well performing configurations of a given family of adaptive structures, as form-active discrete systems. Within the boundaries of form-active discrete systems, a number of possible structures can be included. In order to support the choice of a proper structural typology, the design tool is meant to be used to identify extreme configurations, by determining the range of required geometric variability (examples are shown in Figure 2b). In the specific case, the student has chosen to work with Variable Geometry Trusses (Miura, 1988) by developing a set of studies for modular aggregations that would satisfy the needed range of variations (Figure 2c). Knowing seasonal or daily patterns of the dominant wind directions or the wind behaviour in the area, estimation can also be made concerning the expected predominant configurations of the structure.

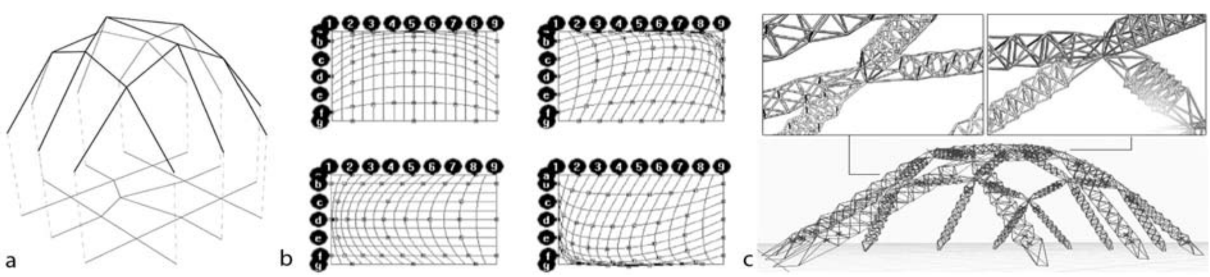

Figure 2: a) example of generation of 3D structural grid; b) four configurations for extreme variations; c) example with Variable Geometry Trusses

7 Parametric explorations of predefined reconfigurable systems

The last example dealt with the identification of technical means, to define reconfigurable systems. Reconfigurable systems can also be defined based on the capacity of their geometric configuration to vary. In addition to the variable geometry trusses mentioned in the previous section, well known examples of reconfigurable systems are deployable structures, which "can be transformed from a closed compact configuration to a predetermined, expanded form, in which they are stable and can carry loads" (Gantes, 2001). The example of deployable structures is used to illustrate the process; and focus is given to the investigation of well-known reconfigurable (and specifically deployable) systems, toward innovative solutions for form-active architectural design. Exploring predefined systems tends to facilitate the integration of engineering knowledge into the architectural design process. In fact, while little investigation has been done in architectural design, in the engineering field consolidated knowledge and current research efforts focus on a range of reconfigurable structures. To benefit from this knowledge during the decision making process in the conceptual phase of architectural design, parametric explorations of reconfigurable structural systems are proposed as beneficial; and a taxonomy of deployable structures has been developed (and can be further implemented, also including other reconfigurable systems). The structure of the taxonomy allows the extraction of meaningful parameters concerning the morphological aspects of the deployable structures, as well as the geometric representation of their possible movements. Modular structures, such as the expandable space structures, so called scissors like element structures (Escrig, 1985; De Temmerman, 2007), have been preferred. Also, parametric properties have been considered both for modules and for their aggregations (including different polygons and curvatures). The combined use of taxonomy and parametric modelling is proposed for design explorations, such as the one illustrated in Figure 3. In this example, modules with operable parts are investigated for integration on space frames, aimed at controlling the airflow for cooling (Turrin et al., 2010b). The ones shown in Figure 3 are a hexagonal-based single layer system and a double layer system based on hexagonal and triangular modules. Moreover, once a suitable morphology has been identified, parameters describing the properties of the structure (such as the height of the modules) and its movement can be used for GA-based optimization of the structural behaviour, by taking into account the different configurations. Currently, ParaGen is being used for this.

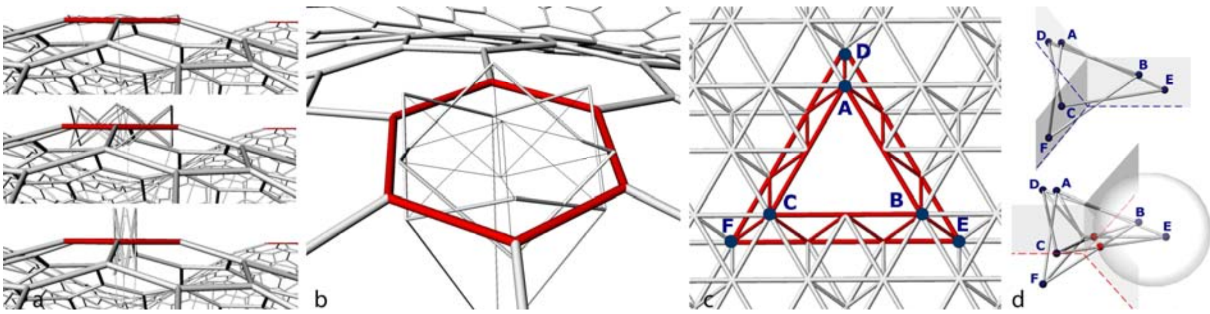

Figure 3: Examples of investigations for openable modules on space frames; a), b) hexagonal (radial or perimetral); c), d) triangular (radial or perimetral)

8 Conclusions

In this paper, the design of adaptive architecture, and specifically form-active architecture, is addressed by means of parametric modelling and optimization techniques. Three examples are used to illustrate different aspects of the process. In the first example, influences of various geometric design properties on a chosen performance are investigated under different contextual conditions. The benefit consists in supporting the identification of useful means of adaptability. The major challenges consist in properly setting the structure of the parameterization (upon decomposition of the problem into single factors). In addition, if searches occur directly for more than one variable at the same time, it can be difficult to explore the results of GA optimization. In this case the identification of groups by the integration of computational clustering techniques would provide additional support. In the second example, suitable configurations are searched, which respond to contextual changes, within the boundaries of pre-identified geometric properties. The benefit consists in identifying the margins of required movements as well as their expected frequency. The current major limits of the form-finding approach used in the second example restrict the applications to parallel loads on structures that are four-valent or less. Finally, in the third example the exploration of various reconfigurable systems (and especially deployable structures with scissor like elements) is discussed. This example beneficially favours the integration of the explorations of such systems into architectural design. Currently, the major limitations involve modular combinations in curved structures. Further effort is planned to develop structural optimization across different configurations. As a final summary of the presented case studies, parametric modelling emerges as a promising support for the design of performance oriented adaptive architecture, with high potential for supporting research across different aspects of design.

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