



Performance-based design of SolSt; a roof system integrating structural morphology and solar energy transmittance.

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Abstract

In this paper we address the design of large roof structures by integrating interdisciplinary performance evaluations in the early stages of the design process. Specific focus is given to structural and solar energy related performances. Geometry is stressed as a key interface between the different disciplines. Parametric modelling is used to automatically create geometric design alternatives. We propose coupling genetic algorithms with a parametric model and evaluate the result with performance simulation software to explore design alternatives. The large roof SolSt used as a case study to present the method.

Keywords: large roofs, performance-oriented design, parametric modelling, genetic algorithms.

1 Introduction

In this paper we focus on performance-oriented design of large roof structures, integrating performance evaluations in the early stages of the design process.

We define large roof structures here as roofs that cover wide areas, such as urban public spaces, squares, entrance halls, courtyards and galleries. During the design and construction phase, key performance aspects commonly investigated are economics, aesthetics and structure; structural performance of large roofs is well covered in the literature and realized projects of both continuous and discontinuous systems. However the current increased emphasis on energy-related aspects confronts the design with the additional challenge of reducing energy consumption and even the potential for energy production. The integration of photovoltaic cells exemplifies the use of active technology for energy production, which is used in recent projects, such as the roof designed for the Masdar Headquarters [1]. Passive strategies for improving daylight and thermal comfort have the potential to reduce energy consumption and cover the remaining energy need through the passive use of on-site renewable resources; both ancient and recent examples can be mentioned, such as the roof of the Dolce Vita Tejo in Lisbon, whose ETFE cladding system passively reduces the summer overheating.

By referring to this context, emphasis is put on the connections between energy related aspects and structural morphology. In this paper we focus specifically on early performance evaluations related to passive strategies for thermal and daylight comfort



and to the structural behaviour of discontinuous systems, such as plate and reticular structures. The reticulated roof for the new Milan Fair in Italy [2] and the roof of the inner courtyard of the British Museum in London are just two of the many recent examples of discontinuous systems, through which the importance of structural geometry is made evident. When focusing on the interrelations between structural morphology and energy related aspects, geometry becomes a key interdisciplinary interface. The envelopes for the Esplanade Theatres in Singapore exemplify the subject based on the geometrical and constructive relations between the structural double layer space frame and the shading system [3]. The Eden project in Cornwall, in turn exemplifies the subject based on the integrated studies through which the pattern of the space frame was enlarged as much as possible to increase daylight and to minimize the costs related to the length as well as the number of connections of the aluminium frame of the cladding [4]. Both for energy-related performances and structural behaviours, geometry offers a basis for structuring a number of interrelated aspects. Integrating in the early design process interdisciplinary performance evaluations is therefore presented here as a key support in the decision making process regarding different design alternatives. This subject is discussed in the paper by presenting an active design process in which the exploration of performance design aspects is combined with the development of digital tools to support it. Digital supports consist of parametric modelling techniques (Generative Components), on one side integrated with customized applications (in Processing) and on the other side coupled to performance evaluation software (Ecotect 2011 and STAAD pro) by making use of a Genetic algorithm system to guide the search of the design solutions.

2 Interdisciplinary performance oriented design of large roofs.

Passive strategies for thermal comfort are based on various interrelated aspects, such as the thermal mass in which the heat is accumulated, stored and dissipated, making use of thermal inertia to stabilize the temperature; the solar energy transmission, absorption, reflection of the roof; the airflows occurring in the area due to natural wind as well as created by the built environment; the presence of vegetation and water for adiabatic cooling; and other aspects. These not only directly affect the thermal comfort based on the way solar heat gains and losses are controlled; but they also have direct impact on the daylight transmission, reflection and absorption. Since each of the mentioned means is interrelated and encompasses aspects acting at a different scale, the roof behaves as a complex system of interrelated thermal and daylight factors, from the large scale design to the details. More specifically, the solar energy (heat and light) behavior is subjected to large influences coming especially from two key families of factors of the roof and in general of the built system: its geometry and its material properties. This closely relates them also to aspects besides solar energy, such as the structural behaviour of the roof, and makes this large set of factors involving different disciplines. In order to take into account all aspects as well as their cross disciplinary dependencies, the complexity of the resulting design process is high.

Interdisciplinary approaches are important in traditional design processes already but are rarely reflected in an integrated design approach from the early stages. This often



results in distinct design phases. Specifically focusing on energy related aspects, traditional design processes tend to address them in an advanced stage of the design by delegating most of the expectations concerning performance to material properties. In this way, a given geometry is often expected to fulfil energy performance requirements mainly based on technical construction systems. The material properties that are needed in order to fulfil the expected performance requirements are deducted based on an inverse computing that relates a given geometry and its given environmental conditions. In such a process, performance requirements, environmental conditions and geometry of the project are given little prospect for variation, while the entire search for suitable solutions is focused on a large set of alternative materials and constructive systems. Differing from that approach, in this paper we stress the importance of the geometry by treating it as a key variable in the search for energy related design alternatives. The generation of the shape is proposed as a process directly driven by the simulations of the related energy performance, by applying a process of inverse computing also to the geometry. This means that both geometry and material properties are computed in order to fulfil the expected performance requirements of a project in given environmental conditions. Such approach was used by the authors in a previous case study, the Vela roof in Bologna (Italy), where parametric modelling supported the design [5]. A well known example of such energy-related inverse computing based processes is the design of the dome of the Louvre Abu Dhabi museum, in which the structure has been designed based on a perforation ratio derived from the perception and the variation of the light, the variation of the temperature levels and the user's comfort [6]. Specifically focusing on structural design instead, form finding processes are well known and largely applied. What is emphasized here is the interdisciplinary nature that is required for the process to converge toward geometrical solutions that are pretty good overall and at the same time for each individual disciplines. Early performance evaluations during the design process are presented by blurring the boundaries between single mono-disciplinary geometrical inverse computing.

The next section introduces a case study through which the described topic will be addressed in the paper.

3 SolSt, a large roof case study

The topic introduced by the previous section is discussed in this paper based on a project currently used as case study. The project consists of a free-form roof covering an area approximately 50m x 50m, and located in Milan, Italy, called SolSt. It is expected to contribute to the required daylight and thermal comfort in the covered spaces by tempering the local climate by means of passive strategies.

As shown by the EERE statistics data [7], the local climate in Milan is characterized by high annual thermal variation of about a 23°C difference between the coldest month, January, and the warmest, July; limited wind speed and North wind direction, especially from September to January; high air humidity and little precipitations. In such a climate, in order to mitigate uncomfortable conditions, the reduction of both summer overheating and winter overcooling is required. On one hand, this leads to increasing the solar gain, possibly to be stored in thermal mass so as to benefit from it during night

and to avoiding the heating losses in winter time. On the other hand, it is also desirable to reduce the solar gain in summer time and promote cooling effects, such as through evaporation and ventilation, possibly increased at night to cool the thermal mass. The thermal mass as well as the vegetation and water ponds is here intended to be underneath SolSt, with possible integration of water sprayed on the outer surface of this latter. In order to facilitate the air flow for cooling, the overall shape of SolSt is conceived based on roof peaks where heat extraction can occur through top openings due to the stack effect; the airflow needs however to be limited when considering winter conditions. The cladding system is meant to reduce the summer solar heat gain, but is expected to favour the winter solar heat gain; in both cases it should allow the income of indirect light in order to meet the daylight requirements. According to what described, summer and winter conditions lead to evidently conflicting requirements, especially when focusing on the solar energy transmission, absorption, reflection of the cladding system and on the airflow. Concerning this latter, the top openings of SolSt are meant to be adjustable in order to control the air flow; specifically, they are expected to regulate the air flow by switching from an open to close configuration through intermediate positions. While concerning the cladding system, different strategies are being investigated, including two main directions: the use of geometrical configurations negotiating conflicting needs and the use of adjustable geometries switching between configurations optimized for different specific conditions. The use of adjustable material properties needs to be mentioned too, but is not discussed within the focus of this paper. Finally, concerning the structure, two structural typologies are being evaluated: a reticulated steel bar frame with the addition of the cladding layer and a plate based structural skin integrating structure and cladding. In both cases, the load bearing supports of the roof consists of branching columns. These are located in correspondence of the peaks in order also to support the adjustable openings and integrate their activation system. Figure 3 shows the overall concept of the roof SolSt.

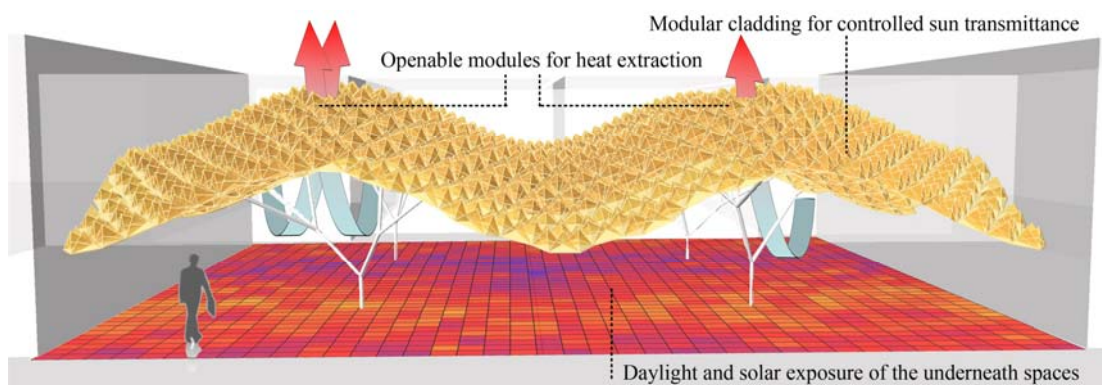


Fig. 1: Concept of SolSt.

4 Performance oriented parametric geometry

In order to explore geometrical alternatives, parametric modelling is used as support. Parametric modelling allows in fact representing both geometrical entities and their



relationships. These are structured in a hierarchical chain of dependencies which is established during the preliminary parameterization process of the geometry. Data represented by independent parameters are processed through the dependencies and produce the geometrical output. Since different values of the independent parameters generate different configurations of the model, a single parametric model can provide large sets of design alternatives. Each alternative is a different instance of the model and together they describe the solution space of the model, which can be then be explored with respect to a given set of design criteria. With respect to this potential, the chain of dependencies formulated during the preliminary parameterization process needs to be formulated according to the performances that are being used as key drivers for the design. This allows obtaining solution spaces of the parametric models that are meaningful with respect to specific performances. The potentials of such a process have been employed for the Vela roof in Bologna; the parametric modelling developed for this project as well as a more detailed discussion of its potentials and limitations can be found in previous publications by the authors [5,8].

4.1 Parametric modelling of SolSt

Similarly, the current project SolSt makes use of parametric modelling to investigate design alternatives. The aspects that are meaningful to the performances driving here the design process are identified in the overall shape of the roof, in its tessellations for structural geometry and in the configuration of its modular cladding system. More specifically, the overall shape is investigated based on different curvatures through which the peaks are achieved; the structural tessellation is investigated based on a variety of different polygonal patterns as well as different densities of each of them; the modular cladding is investigated based on different polygonal patterns each of which with variable densities (matching the structural geometry) and on different geometrical configurations of the cladding modules. Similarly to the approach used for the Vela project [7, 8], a first parametric model parameterized the overall shape of the roof through the Cartesian coordinates of the control points of a NURBS surface; and the structural geometry was parameterized through a set of variables mainly controlling the distribution of a range of points lying on the surface, based on their UV coordinates. Such an approach is powerful and provides a good control of the shape as well as of the point distribution. However a higher mathematical control of the shape was required. This was due to two the integration of the adjustable top openings. Integrating openable modules has in fact a lower degree of complexity when modules are based on planar and regular polygons. This indeed allows the adjustable modules to be designed based on simplified geometrical rules usually resulting in a less complex mechanical behaviour. An example is provided by openable modules based on deployable geometries [9]. The need of obtaining planar regular polygons on the top peaks of the roof shape means that a horizontal plane intersecting the top part of the peaks was expected to generate a closely approximated circular section. Achieving this condition through a NURBS surface with control points would require the subdivision of the NURBS surface into patches. Instead of that, directly describing the shape of the roof through a mathematical function was preferred. Previous examples of such an approach include the roof of the British Museum Great Court where a surface was described by

Chris Williams, with height z function of x in the easterly direction and y in the northerly direction to meet different conditions in the curvature as well as in the centre and along the edges; and the nodes of the structural grids were then defined as points lying on the surface [10, 11]. A similar approach is here proposed for SolSt, but in this case, a mathematical function directly describes the positions of the points, based on Cartesian coordinates. The x and y values define the density of the grid as well as its overall dimensions; the z value is described based on a sin function whose amplitude defines the height of the peaks. The sin function is doubled by following both the x and y directions in order to achieve the desired curvatures in both. Further, the edges of the roof are expected to be on a planar square; in order to meet this condition, the z values are smoothly driven towards 0 when close to the edges by multiplying the sin function with an additional function. This is achieved by subdividing the overall grid in nine zones, each of which corresponds to the part close to each of the four corners, of the four middle parts of the edges, and to the middle area of the grid. The whole function is composed by the single couples of multiplied functions describing each zone. Such mathematical description allows meeting the desired conditions both at the edges and in correspondence to the peaks. Further more, independent parameters have been introduced in the functions in order to generate parametric variations of the output points. Since different height of the peaks and different densities of the structural geometry were to be investigated, the independent parameters target these geometrical properties. Specifically, the amplitude of the sine function is an independent parameter a , regulating the height of the peaks; and the x and y values are defined through an independent parameter n , which varies the density of the grid. Finally, based on an independent parameter p , the variations of the density can occur homogeneously along the x and y directions or based on different proportions by differentiating the density in each of the two directions. Figure 2 illustrates the parametric point grid.

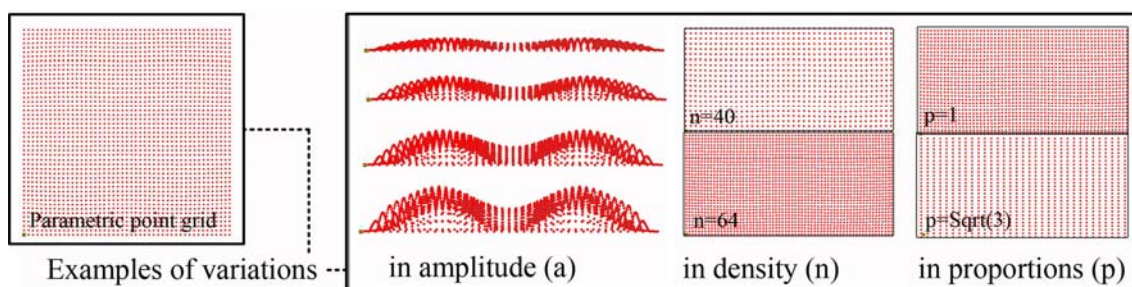


Fig. 2: The parametric point grid

Based on the distribution of points so obtained, the roof can be tessellated using quadrangular, triangular, hexagonal polygons or combinations thereof. Such tessellations are defined by lines or by polygons modeled by using all or a selection of the points as vertex nodes. The tessellation follows the variable amplitude of the roof shape as well as changes when varying the density or the proportions of the point grid. This allows generating different polygonal patterns each of which is variable in density and can be squeezed or stretched along each one of the roof shapes. Figure 3 illustrates the examples of tessellations.

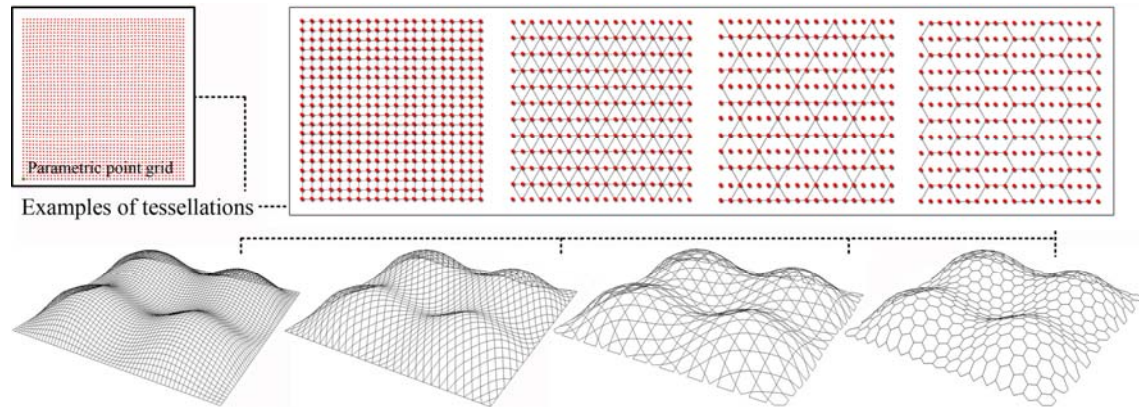


Fig. 3: Examples of tessellations based on the point grid.

The cladding of the roof is designed as a modular system propagated over the tessellations. Various cladding options are explored based on the different tessellations, on different topologies of modules for each tessellation and on different geometrical variations of each topology. Each option is modelled by using a polygonal frame acting as an interface between the cladding system and the structure. Based on it, the cladding geometry can be modelled for different base polygons to match various tessellations or as single options specifically built for a given polygon. The two options presented here belong to the second group, being examples for hexagonal tessellations. The first option combines south-oriented opaque panels and north-oriented transparent panels; independent parameters regulate the inclination of the panels. The second option combines south-oriented transparent panels and north-oriented opaque panels with a shading elongation; independent parameters regulate the inclination of the panels and the length of the elongation. Both aim at reducing the summer direct solar gain while allowing the income of indirect solar light; increasing winter solar gain is expected as potential mainly of the second option. In both cases, once the geometry is modelled based on the established dependencies, the procedure is saved as separated feature that can propagate on this roof, as well as on other hexagonal based geometries.

The structural geometry is included in the model for both the options described in section 3. On one hand, reticular systems of bars correspond directly to the polygonal tessellations. Thanks to the curvatures of the roof needed for increasing the ventilation through stack effect, the structural frame is intended as single layer system. However the parametric geometry can be implemented for double layer space frames based on a second layer of points [7]. When using reticular bar systems, the cladding acts as covering layer and can provide lateral stiffening for the system. In this example the cladding is explored as a system of glazed transparent and serigraphed panels, with metal frame. Additionally, combinations of timber (opaque) and glazed (transparent) panels were also evaluated. Furthermore, ongoing explorations aim at utilizing the structural properties of a folded plate timber skin to eliminate the need for the supporting grid of bars. The hope is to find geometries which can function structurally while meeting the environmental performance criteria. Finally, for some of the densities of the grid, branching columns have been included for support with parametrically variable proportions among the lengths of their members.



4.2 Performance oriented exploration of the solution space

Once the parametric model is set, a large set of design alternatives can be automatically generated and explored based on their performances. Due to the breadth of the solution space, an exhaustive, systematic exploration is not possible by the designer alone. In this case the exploration can be based on the performance simulations of a limited number of selected design alternatives, where interdisciplinary collaborations are an essential need in addressing the selection of solutions. Limiting the exploration is however a drawback of the potentials of parametric techniques, especially when dealing with complex geometrical variations affecting a large set of performances. Coupling parametric modelling, performance evaluation software and genetic algorithms (GAs) is presented in the next section as a possible solution to this problem.

5 Combining parametric modelling with genetic algorithms

In order to support the exploration of the solution space of the parametric model, a method called ParaGen is proposed by looping the parametric generation of design alternatives with performance evaluation tools, and by orienting such generation toward suitable solutions by using GAs. ParaGen is under development at the University of Michigan, Taubman College, where it has been used for structural form optimization [12,13,14]. In current collaborations with Delft University of Technology it is being extended toward interdisciplinary optimization [14]. In the current version, a series of both custom written and commercial software packages are looped in a cycle having three main steps. GA provides the values of the independent parameters based on selection, recombination and mutation; parametric modellers generate the geometry based on the variables provided by the GA; performance simulation software evaluates the geometries provided by the parametric modelling software. Currently Generative Components is used as parametric modeller, STAAD-Pro as FEA software for structural evaluations, and Ecotect as simulation software for thermal and daylight performance. The system is however open to different software, such as Grasshopper or Digital Project for parametric modelling and Radiance for daylight simulations. Besides objectives expressed by numerical quantities (such as structural and the solar energy behaviour), the system can also potentially integrate soft evaluations (such as for aesthetics and functions) left to the designer, either through intuition or by means of other computational support. This is based on a high level of interaction allowed to the designer, who can freely explore the generated solutions by sorting them according to different criteria and whose subjective selections can contribute to addressing the generation of the design solutions.

Various sets of analyses are being run on SolSt by using ParaGen. These are aimed both at the explorations of design alternatives, and at the implementation of the tool in a parallel processing environment. Both for understanding how single factors affect the roof and for a proper testing of the tool, some simplification is made at this stage.

5.1 SolSt in ParaGen

A preliminary analysis of SolSt was done concerning its structural behaviour only. The version of the parametric point grid based on UV coordinates (see section 4) was used.

Parametric variations of the overall shape of the roof and of the branching columns were explored for a fixed density of the structural tessellation. Standard ASTM steel pipe sections were used for member sections. A single uniform load of approximately 1.5 kN/m^2 was used to simulate the load of cladding and moderate snow or roof live loads, while the dead load of the steel structure was added in as a separate load. Several iterations were run to get convergence of the design solutions by minimizing the weight of the steel [14]. Figure 4 shows examples of analyzed instances.

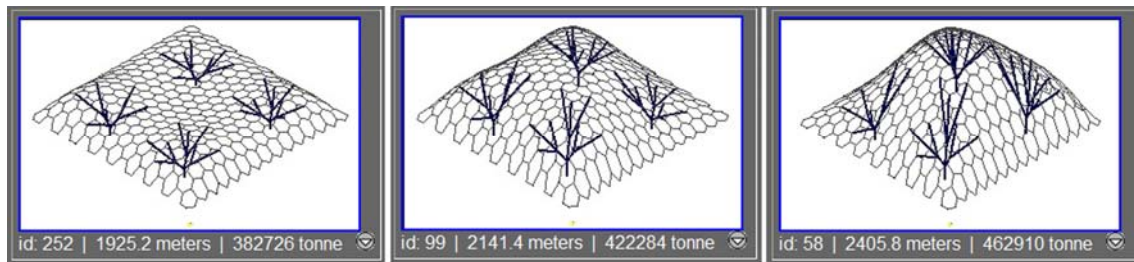


Fig 4: examples of instances from the first testing analysis (structural behaviour)

A second set of analyses focused on the solar energy behaviour only. The version of the parametric point grid generated through mathematical functions (see section 4) was used in combination with the two cladding systems (also described in section 4). Parametric alternatives were explored by varying the overall shape of the roof, the density of the tessellation, the local inclinations of the cladding panels and, for the south-oriented transparent panels cladding system, also the length of the shading extensions. The roof was evaluated based on the daylight factor and the incident solar radiation of the spaces underneath, following the concept of transparent glazed panels and glazed panels with 90% light colour serigraphy. Several iterations were run for summer conditions to get convergence of the design solutions by minimizing the solar incident radiation and by maximizing the daylight factor underneath the roof (Fig 5).

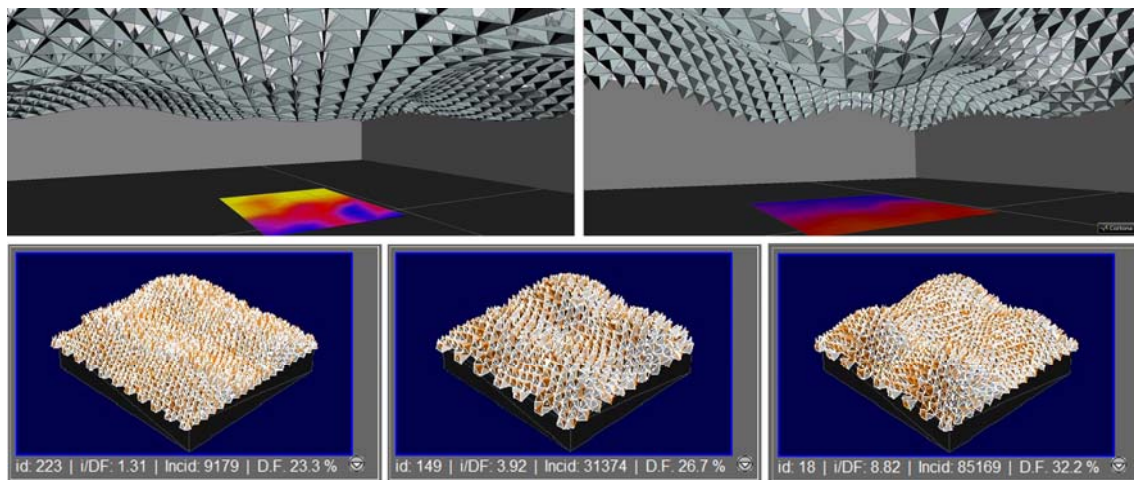


Fig 5: second testing analysis (solar energy). Top Left: example with north facing opaque panels. Top Right, Bottom: examples with south facing opaque panels.

A third set of analysis was made for exploring the design by contemporarily combining structural performances and solar energy behavior. The version of the parametric point grid generated through mathematical functions was used in combination with north-oriented transparent panels cladding systems, for a fixed density of the structural tessellation. Parametric alternatives were explored by varying the overall shape of the roof, the local inclinations of the cladding panels and the proportions of the branching columns. The roof was evaluated based on the weight of the structure using steel pipes, the daylight factor, and the incident solar radiation of the covered spaces. Again the concept of transparent glazed panels and glazed panels with 90% light colour serigraphy was used. Several iterations were run for summer conditions to get convergence of the design solutions by minimizing the weight, by minimizing the solar incident radiation and by maximizing the daylight factor underneath the roof. (Fig. 6, left). Further on, the use of timber plates is investigated, in collaboration with Andreas Falk (Fig. 6, right).

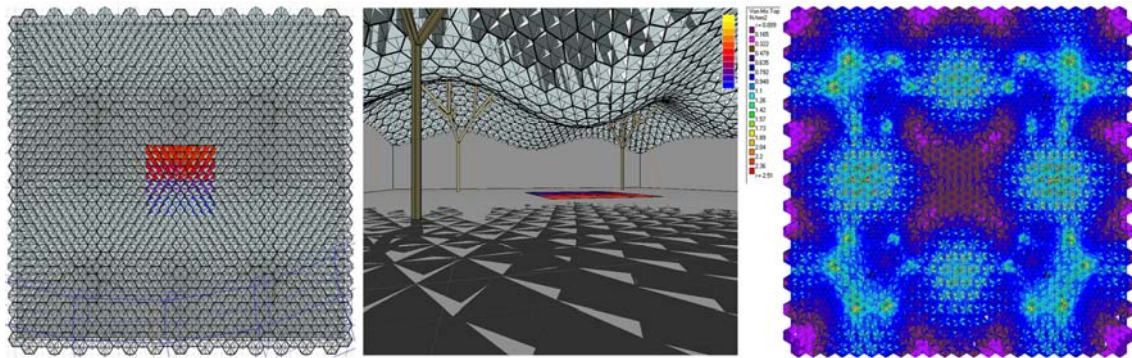


Fig 6: examples from current analysis: left: solar energy; right: structural behaviour

6 Top openings and additional tools

As mentioned earlier, adjustable openings are to be integrated on the top points of the roof and this can be done with a lower degree of complexity when modules are based on planar and regular polygons. Constraining the hexagons on the top of the four peaks in order to centre them on the peaks, makes possible four regular and flat top polygons. This issue was initially approached in GC, by sliding the tessellation according to pre-calculated values in order to stretch and squeeze the polygons in the lower parts of the roof. However, the method has shown some relevant limitations, such as the effort to predefine the deformed tessellations. A separate tool was developed for exploring the tessellation when constraining the hexagons. Specifically, an application was developed in processing, based on the use of particle springs. While guaranteeing the top hexagons to be regular and flat, the application simulates the hexagon distribution with a particle spring system with the particle nodes sliding on a mathematically defined surface function.

7 Conclusions

The importance of the geometry has been stressed with respect to interdisciplinary performance oriented design of large roof structures, with focus on structural and



energy related performances. Parametric modelling has been presented as a support for the early phases of the design, by means of its potential in automatically creating geometrical design alternatives. ParaGen has been introduced as a support to explore the solution space of parametric models, by means of guiding the generation of design alternatives based on GA methods. Further, additional tools have been shown. A successful example of the potential of such a process was shown based on a current case study. Various aspects are to be mentioned concerning the presented work; especially the importance of using interdisciplinary collaborations to parameterize the geometry, in order to obtain meaningful solution spaces of the models; the advantages offered by guided explorations of the solution spaces, utilizing the potential of GAs; and the supports in understanding the design alternatives given by freely sorting them according to different criteria. However we would like to draw attention to two main aspects: the potential of generalizing the parametric models and of combining design activities with customization of digital tools. The first aspect recalls the development of methods, the applicability and relevance of which overcomes the single design occasion. While this is evident for tools such as ParaGen, it is less evident but equally important for the developed parametric geometry. Referring to the described models, examples are given not only by integrating different possible tessellations as well as different cladding modules to easily enlarge the solution space being explored, but also by allowing interchangeability of operations and parts of the procedure beyond the single project. Emphasis is therefore given to the possibility of further implementing, combining, and customizing the described procedures based on parametric modelling. In line with this first aspect, the second aspect recalls the potential offered by supporting the design process through the parallel development of customized digital tools. Specifically, both the implementation of ParaGen and the development of the spring particle tool allowed getting over the limits of standard tools by offering advantages undoubtedly larger than the effort spent in the development. Also in this case, the generalization and possible implementation of the tools beyond the single project play a key role in evaluating the time investment.

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