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From Daylight Optimization to Additive Manufacturing

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PULSE:

Integrated Parametric Modeling for a Shading System From Daylight Optimization to Additive Manufacturing

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ABSTRACT

This paper presents a parametric approach to an integrated and performance-oriented design, from the conceptual design phase towards materialization. The novelty occurs in the use of parametric models as a way of integrating multidisciplinary design constraints, from daylight optimization to the additive manufacturing process. The work focuses on the case of a customized sun-shading system that tailors daylighting effects for a fully glazed façade of the alleged PULSE building.

The overall workflow includes preliminary analysis on simplified models and an initial parametric model to run computational optimization loops. The output consists of individually unique sun-shading panels, optimized for varying daylighting requirements based on programmatic distribution and specified viewing areas. The resulting geometric complexity was resolved through subsequent detailed parametric models; implementing the structural design requirements and integrating the constraints dictated by the additive manufacturing process, including the necessity to minimize material and 3D-printing time. This paper focuses on a particular part of the overall workflow, describing the support provided by parametric modelling to control geometric complexity and multi-disciplinary requirements.

Author Keywords

Multi-disciplinary design optimization; daylighting; additive manufacturing; performative facades.

1 INTRODUCTION

A number of precedent projects have investigated both static and kinetic solutions for optimized building skins, specifically with regard to daylighting performance through design tools and computation. Some studies aim for the improved performance of daylight harvesting, tackling issues of human comfort and energy efficiency [3]. Others study the performance-based shading capacity of intelligent and kinetic features in building skins [4, 22] while exploring complex geometry for improving building performance, as a potentially more optimal approach [19]. The built projects include the dome of the Louvre Abu Dhabi museum [24], and the Esplanade Theaters in Singapore [21], among others. Numerous precedents address the urgent needs for a more sustainable built environment based on optimized performances.

Nevertheless, most designs of traditional shading devices highly depend on modularity and the related reduction of customized unique items. This restriction is mainly dictated by the traditional production techniques, which are usually unable to deliver customized elements at affordable costs. Unfortunately, this often prevents the designer from customizing the sun shading according to specifically desired performances.

On the contrary, customized shading devices could potentially be beneficial for the performances of the building. Shading systems have major impacts on solar gain, daylight control and visual connections. For any of these concerns, the indoor requirements are not homogeneous throughout all indoor spaces of a building, as each indoor area may have different requirements. Hence, a uniform sun-shading system across the façade may not satisfy these appropriately, leading to discomfort or excessive energy consumption for climate control.

In recent years, the potentials of digital manufacturing for the building industry are creating opportunities to overcome the need of repetitive modularity and standardized components. Specifically, additive manufacturing is showing remarkable potentials to create tailored products with high complexity in shape and variations. As such, it allows producing customized elements, each of which can be unique at no additional cost.

The combination of parametric models, performance simulations and the additive manufacturing process also offers the opportunity to generate a library of generic scenarios, sharing the same systematic workflow, making them re-applicable to multiple specific design cases. The benefit of these generic parametric geometries is that they can be optimized based on the performance requirements of

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each specific design case and produced by means of additive manufacturing. An example of previous studies on is [8].

The methodology presented in this paper is based on several parametric models. Via the parametric models, the shading system can be applied onto different façades and optimized according to any orientation and conforming to different indoor daylight-requirements. The paper focuses on the workflow for handling the optimized complex geometry of the shading of a large building façade via parametric models, toward 3D-printing of individually unique modules. The handling of all multi-disciplinary constraints is a challenging task. The paper identifies the difficulties encountered through the integration of multi-disciplinary requirements and related results from the performance simulations introduced at various stages of the computational design process; and it demonstrates the entire workflow until 1:1 prototyping.

The paper focuses on a case study, the PULSE project. Within the specificities of the case study, the paper argues that an integrated and highly collaborative process is essential to identify the optimal geometry for making the transition from the digital geometry to the fabrication output possible. The PULSE project allows discussing the digital workflow at length and through demonstrating the influence of the collaboration. In doing so, the paper underlines the importance of defining the priority and timely integration of design criteria that inform the order of geometric operations.

The paper is structured as follows; first an analysis of precedents and relevant references is provided in section 2; then the specific case of the PULSE building is described in section 3; the digital design process of the PULSE shading is presented in section 4; finally, discussion and conclusions are provided in section 5.

2 BACKGROUND AND PRECEDENTS

In this paper, geometric complexity and systematized customization controlled through digital models are tackled for the sake of enhancing performance.

Recently, the potentials of additive manufacturing (particularly 3D-printing) to produce complex building components tailored to specific requirements and desired building performances are rapidly emerging. Although the research relating to the application of 3D-printing in the construction industry is still in its infancy [26], relevant precedents have investigated its potentials for a number of building components. Among the examples, structural nodes are optimized and 3D-printed [6, 20]. Here, the geometric complexity resulting from the structural optimization is concentrated in localized components. Further potentials are highlighted in [18]. Focusing on facades, [23] investigate the tool-less production with additive manufacturing that allows for new shapes and less, but higher integrated functional parts, such as fittings, offering a better performance with lower material consumption. Recent studies also investigate to what extent 3D-printing technologies can be successfully applied to the construction of large/scale structures, including full buildings [5, 12, 13, 16, 25].

As [26] indicates, depending on the technologies used in the 3D-printing process, there are five distinct types. These are stereo-lithography, fused deposition modeling (FDM), inkjet power printing, selective laser sintering and contour crafting. For each of these, the implementation in the building industry faces various challenges commonly related to economic feasibility and scale of the printed components. This research aimed at pushing the boundaries of relatively inexpensive technology toward reliable building applications, making it competitive with more traditional shading systems. As such, FDM was selected. In the case of FDM, one of the highest challenges relate to the post-processing in case of support material to be removed and to the uncertainties of the long term behavior of the printed materials, especially in case of plastics. In [5], a new material is discussed, to print at a building scale a glass reinforced plastic, claimed as light, solid, anticorrosion, anti-aging, waterproof and insulating.

As compared to the precedents, the uniqueness of the case study presented in the paper is the completeness of the digital workflow applied to a large-scale design toward additive manufacturing. This included iterative loops across digital sketching and simulations, advanced multi-objective optimization, multi-disciplinary models coping with constraints dictated by the production process and production files.

In precedents, parametric design has been largely utilized as a method for performance optimization, constraint-handling and integrated modeling of complex geometries. Among the relevant examples are [2, 7, 9, 17]. Precedents using optimization in combination with parametric modeling and simulations are numerous. Regarding simulations for shading systems, [10] provides an interesting overview, whereas [11, 14, 15] focus particularly on optimization.

However, precedents rarely focus on the complete workflow, (from optimization to production). The fabrication of shading devices for building is mostly centered on standardization in order to meet the requirements of traditional production techniques. In contrast, the workflow presented in this paper supports the customization of individually unique modules.

3 THE PULSE PROJECT

PULSE (Practice, Unite, Learn, Share & Explore) is a multifunctional building for the Campus of Delft University of Technology (TUDelft) (see Figure 1). It is designed by Ector Hoogstad Architecten (EHA). It is to be located at the central axis and will facilitate an interfaculty educational center. It will cover an area of 4700m2 and its expected realization date is in 2017. It is designed with the ambition to be the first building on the campus to reach the target of becoming energy neutral. Several aspects have been investigated to achieve this target. Besides the optimal orientation of the building and its program, the articulation of the façade plays an important role in reducing energy consumption. For various design intentions, the project includes a prominent west/southwest fully glazed façade, which covers an area of 463m2 on the first floor and 647m2 on the second floor. The indoor spaces behind the façade are large open spaces accommodating multiple functions. The functions are distributed on two floors interconnected by an atrium and the program includes traffic space, study spaces and lounge areas with coffee corners. Based on the different programmatic functions, the daylight requirements are different (300, 400, 600 and 800 lux). Also the architectural preferences for the quality of the light are specified, preferring filtered light close to the façade and allowing desirable, indirect light to enter the core.

This research focused on the need for sun-shading and daylighting control on the facade to minimize the heat load on the facade and increase the lighting conditions in the interior. The team involved in the project for the design of a 3D-printed version of the sun-shading device was a large multi-disciplinary team, including experts from TUDelft regarding computational design, 3D-printing and structural design; and from Yaşar University involving evolutionary optimization; the architects from EHA; and other external parties for 3D-printing facilities.

The overall digital workflow for the sun-shading of the façade can be summarized in the following interrelated phases: a) the initial concept and the preliminary simulations; b) the parameterization of the model; c) the multi-objective optimization; d) the selection of optimized design options and the structural analysis; e) the tests for 3D-printing; f) the integral parametric models; g) the final configuration and production of 1:1 scale prototype. Section 4 of this paper presents phase f) and partially g). The following sections 3.1, 3.2 and 3.3 provide a brief presentation of the phases a) to e).

Figure 1. Render of PULSE Building on TUDelft campus. Image Courtesy of Ector Hoogstad Architecten

3.1 Preliminary Analysis and Optimization

Based on local weather data and preliminary building simulations for solar radiation, the initial shading concept was defined. It consisted of a cloud of sun-shading elements in front of the façade. The shape evolved from a traditional horizontal shutter into a concave element because it increases its reflective capacity. Later tests indicated that pulling the maximum points along its concave surface to the side proved more beneficial as well. These studies resulted into an asymmetric panel that could accommodate different widths along its axis.

In order to identify the meaningful design variables for parameterization, a second set of preliminary simulations were run, this time on parametric models. Daylight studies were done using Rhino and Grasshopper for geometric modelling; Diva and Ladybug (plug-in for Rhino and for Grasshopper) to simulate daylight. A series of systematic analyses were conducted by running daylight simulations for interval values of each design variable, in selected times of the year (different hours and different seasons). This way, the solution space was sampled to better understand the trends between geometric features and daylight performances of each different functional zone. Additionally, a large number of geometric configurations were saved and inspected with the architects upon criteria that were not included in the simulations (such as visual connections with the outdoor and aesthetic appearance of the façade). Based on this process, appropriate design variables (and their numeric ranges) were identified prior to optimization.

Based on the identified significant variables and on the studied daylight requirements, a final parametric model for optimization was built in Grasshopper by a team at Yaşar University; and connected to a genetic algorithm optimization solver developed at Yaşar University. The optimization objectives included the minimization of the areas of the shading modules (in order to save material and time when 3D-printing) and the target lux values for each different functional zone (in order to maximize the amount of time in which the targets are reached, based on daylight only). Divided by the total hours of operation, the obtained percentage demonstrates the efficiency of the solution.

To obtain a higher resolution, the functional zones were further subdivided into squares to which these target illumination values were assigned. The illumination at each of the tiles is simulated for all hours of operation throughout the day. With minimal-tolerance (testing only for approximate target values of 300, 400, 600 and 800 lux), the best performing solution reaches 17% (see Figure 2).When the tolerance is adjusted to instead include a range of target values, this percentage increases significantly.

Several optimization runs were performed by using a large computer server physically located at EHA while being controlled from distance from Yaşar University; and at TUDelft. Each new run included improvements of the models and algorithms. Using the output of the optimization runs, several design options located on the identified Pareto fronts were inspected (an example is in Figure 2). The related 3D models were visualized by the architects and assessed also based on criteria not included in the fitness functions of the optimization. As a result, a design solution was chosen for further development, as it was identified as the most promising one.

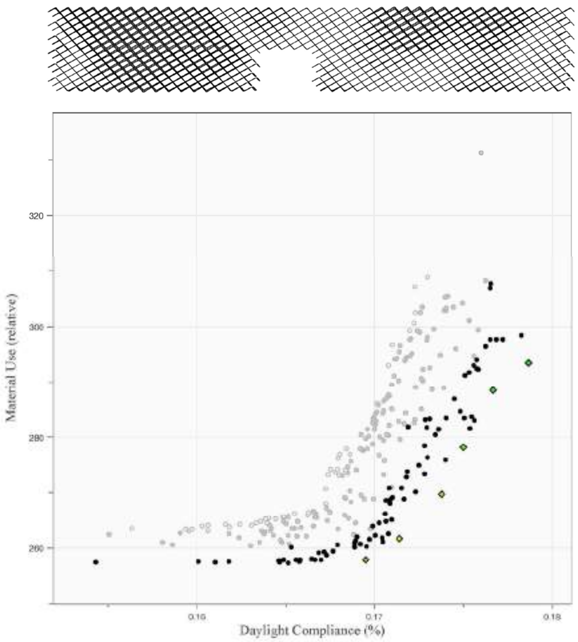

Figure 2. Results of the optimization and a related 3D model.

3.2 3D-printing

After the preliminary simulations and concept development, the relevance of selecting a production technique that could accommodate the variances in each of the modules became evident. 3D-printing was selected as the most advantageous to produce these gradual geometric differences resulting from the optimization process. Moreover, it was considered a relevant research agenda for the construction industry, as the team experimented on the limits and potentials of the technique to be applied in a large-scale outdoor project. Eventually, it also opened related topics, for example regarding recyclability of the materials, among others.

The 3D-printing process was approached with specific demands, as the production was bound to fit the timeline of the construction site; the modules were meant to be translucent; the total budget was limited. In addition, the suspended panels demanded a lightweight material, forcing the team to further minimize material usage. When coping with such demands at a large-scale, several complications add to the geometric definition of the panel, some of which were unforeseen in the early stages.

To proof the concept of using FDM for the manufacturing of the large amount of panels, a big 3D-printer was custom designed and built by Leapfrog 3D-printers. The goal was to be able to manufacture a single panel within the limited timeframe of 8 hours, thereby enabling the production of two panels per day. With hundreds of panels to be produced, the effective, expedient and low cost manufacturing of the panels was key to the viability of the project. As such, multiple 3D-printers would be necessary, also making the custom design of affordable 3D-printers essential.

The first constraint entailed the maximum printable volume of the printer (2100x560x560mm), which is not to be exceeded by the dimensions of the panel. This was taken into consideration in the early stages of the optimization constraints, guaranteeing that each panel would fit in the printer.

Secondly, the thickness of the panel was limited to the size of the custom build 2.2mm-nozzle of the large 3D-printer. As the nozzle completes each section, the final maximum thickness of each panel will be no more than 6mm. Since it is still time-consuming and relatively costly to 3D-print, it was crucial to meet the design criteria within these absolute minimal volumetric dimensions.

In order to save more time and material, an additional goal was to minimize the necessity for support-material, thus constraining the angle between each print-layer no larger than 45 degrees, positioning the panel in such a way that nearly horizontal surfaces are avoided. Upon finding the optimum orientation for the 3D-print, the panels needed to be separated and cut, while adhering to the all of the constraints mentioned above.

Several material experiments were carried out to test for printability, durability, structural strength, UV resistance and cost. PVDF proved promising results at small-scale tests, but still requires modifications for full-scale prints. The possibility of enhancing it with fiberglass to reduce the problematic shrinkage of the material is one of the explored options. As of current, successful 1:1 scale prototype 3D-prints have been completed with PET.

In summary, the primary target of the additive manufacturing process is to make the production of hundreds of panels possible within the allocated budget and time. As of recent tests, the approximate time required to produce each of the full-scale prints is estimated at 8 hours.

3.3 Structural System

In the initial stages of the project, several options were discussed regarding the structural approach as well. Although preferred, a self-supporting structure was not feasible with the selected lightweight materials for the additive manufacturing process. Therefore, the first structural proposal was to suspend the panels with a vertical cable system locking each panel into the correct position.

However, in this scenario panels could potentially break, endangering the people below. Rather than using expensive safety cables as a solution, the option of weaving the steel cable structure through the panels was explored, not only increasing safety but also making them less visible, esthetically enhancing the design. The panels needed to be divided differently, significantly affecting the joint. Instead of producing a single panel, the redesigned panel combined two segments and their cross connection, with the added benefit of strengthening the structural capacity of the panel.

The cable system alternates between a single cable in one direction and two parabola double-cables in the other direction, which cross one another twice per string; once above and once below. The double-cable holds the panels in place and prevents them from rotating. Since the parabola cables are being held apart by the panels, this system requires that they can structurally withstand the inward tension from the two crossing cables.

4 DIGITAL WORKFLOW AND PARAMETRIC MODELS

After the optimization runs, the parametric model contained simplified geometry, although the geometric complexity of the final geometry was anticipated. The primary objective of the post-optimization digital workflow was to reduce the size of each file as much as possible before resuming the further development of the geometry. The output generated by each parametric model is reduced to only necessary information before proceeding to the next model, keeping the size of the operable data manageable. Identifying the segmentation of the parametric models occurred systematically, as each required a different data structure. The following section provides a summary (also illustrated in Figure 3) of each model in order to explain how each panel is geometrically defined according to the design constraints.

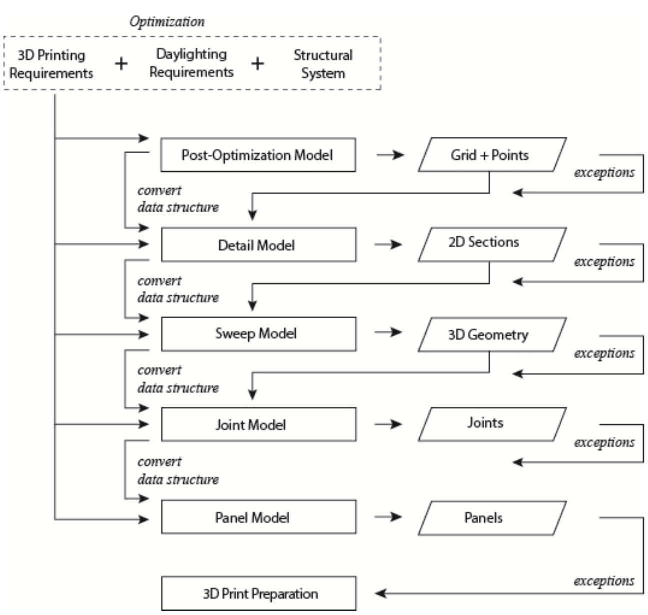

Figure 3. Digital Workflow Flowchart.

4.1 Post-Optimization Model

As a design principle, the diagonal base-grid was generated according to the results of the preliminary daylight studies and the decision to internalize the structural system. The grid controls the orientation and the number of panels in addition to the way the elements are positioned in relation to one another. The optimization was performed on a simplified lofted surface, defined by the dimensions of the grid, resulting in s-shape segments, shaped like the hood of a cobra.

The optimization already incorporated the constraints defined by the integrated structural cable system. For every s-segment, two of the planes intersect the single cable and two planes intersection the double cables of the structural system. In the case the optimization result returned a smaller width than the necessary width between the cables of the double cable system, the optimization result it is overridden to accommodate the cables inside the panel.

The post-optimization model converted the numeric data retrieved from the optimization into a spatial representation, defining the points of intersection and rotation (both in plan and in section) at each of the 4 planes along the s-segments (see Figure 4, top). This point-cloud generated in the post-optimization model was then further used as input for the subsequent parametric models.

4.2 Detail Model

As illustrated, the relationship between the design criteria was first explored at two singular instances in section and only two-dimensionally. Then, the detail model uses the data generated by the optimization results and generates each section on a flat horizontal plane before projecting the two-dimensional geometry onto planes oriented to the directions derived from the post-optimization model. It generates two-dimensional sections located at each plane and defines the width of each section and the appropriate rotation.

The further geometric definition of the sections is entirely informed by structural and additive manufacturing constraints. First, due to the structural system, there are 2 different types of sections, a double cable and a single cable. Secondly, as mentioned, the thickness of the section is derived from the nozzle size (2.2mm) of the 3D-printer, depositing either a single line (3mm) or a double line (6mm). Therefore, the wings are 6mm thick at the tips and are 3mm thick where the inside becomes hollow (see Figure 4, middle).

Due to the anticipated growing complexity of the three-dimensional geometry, the aim was to resolve most of the intricacies emerging from the integration of the design criteria with these planar constructions. The more precise and identical these sections were constructed, the easier it would be the transition from the two-dimensional projection to a volumetric three-dimensional geometry.

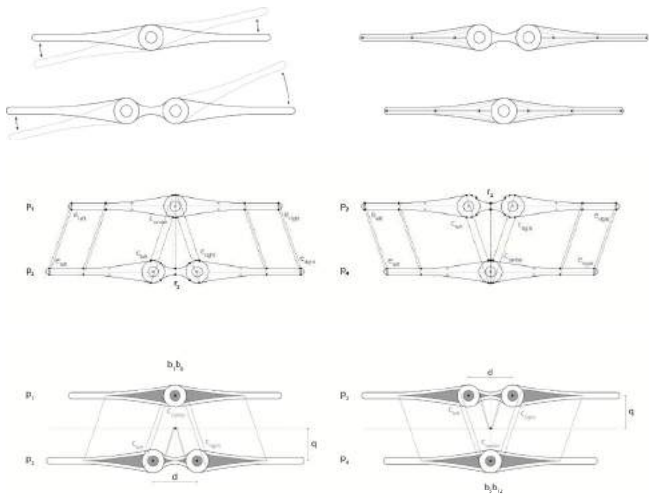

Figure 4. Output from Detail Model.

4.3 Sweep Model

The sweep model uses the sections generated by the detail model to create the three-dimensional continuous surface geometry. The sweep fits a surface through a series of profile curves (sections) that define the surface shape and a series of rail curves that define the surface edges.

The sweep model requires an entirely different data structure. In order to produce the three-dimensional continuous surface geometry, it is necessary to convert the structure from individual s-segments to uninterrupted horizontal branches. The sweep model also generates the hollow inner surfaces by using the offset sections from the detail model. This geometry is subtracted from the solid boundary representation in order to reduce the material and weight of the panel (see Figure 4, bottom).

Upon completion of the sweep model a control-simulation was performed in order to compare the illumination results of the initial optimization with the post-optimization volumetric three-dimensional geometry.

4.4 Joint Model

The joint model produces the joint that occurs at every intersection of the underlying grid between the v-segments and n-segments of each panel (see Figure 5, left-top). The joint internalizes the cable structure to hold the structural system in place and offers structural stability. It needs to withstand both tension forces from the cable system and wind load. To achieve the most equal distribution of these forces, the joint requires a fluid vertical transition between v-segments to n-segments.

According to the additive manufacturing criteria constraining the 3D-print direction, the joint is problematic where it connects the v-segment and n-segment, as it contains horizontal surfaces. Since the two legs of the x-shape panel are printed first, the joint has to bridge a horizontal gap. In order to prevent the need for support material (which is problematic because it adds printing time and material), the bridge between the legs needs to be minimized, resulting in a sharper blend between the v-segment and n-segment (which is undesirable due to structural concerns).

As the goal was aim to minimize material, the joint cannot be solid, so all excess material should be removed. Adhering to the previously established print thickness of 3mm, the inner offset of the joint is created by redrawing the curves according to the previous paragraph. These curves are drawn from a 3mm offset of the original network surface.

4.5 Panel Model

The panel model defines the last parametric relations before exporting the geometry to a format that finalizes 3D-print preparations. It places cutting planes and splits the continuous surfaces from the sweep. Each panel is cut-off according to the size limitations of the 3D-printer, resulting in v-segments and n-segments. Combined with a joint, they form an x-shape panel.

Ideally, this cut-off occurred at the midpoint of each grid element, resulting in a regular x-shaped panel. Unfortunately, this panel exceeds the additive manufacturing criteria restraining the printable angle no larger than 45 degrees. To meet this constraint, the panel is reoriented in such a way that is the legs are not the same length.

In addition, the model resolves the connection between the panels with a tube, ensuring their location and preventing the panel's rotation. The tube is a standardized, straight PVDF cylinder with a diameter of 1.5cm and a length of 10cm. These dimensions are defined parametrically to accommodate various options to be determined later after structural testing and availability of standardized materials.

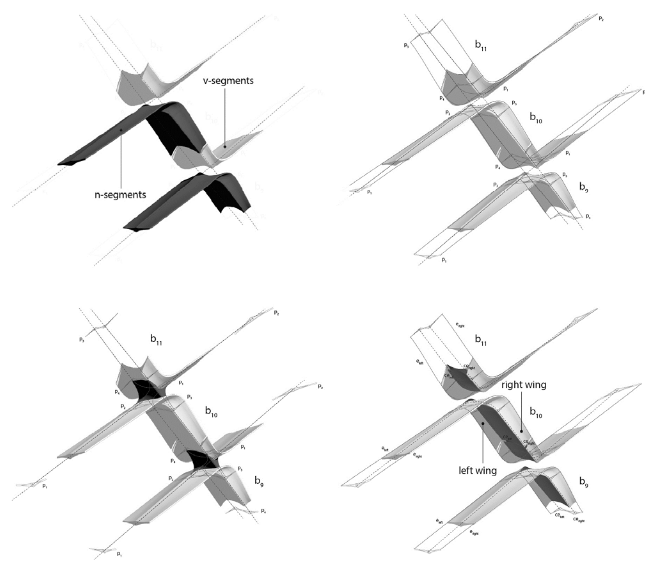

Figure 5. Output from the Sweep, Joint and Panel Models.

Figure 6. Full-scale 3D-printed prototype: one module.

The geometry of the joint model is imported into the panel model and together with the v-segments and n-segments, generates the x-shape. Since the data structures of these three separate pieces do not align, and do not match the desired organization of the panels, the data structure requires revision once more. Once the data matches, the pieces are seamlessly joined as one and exported accordingly. The inner sweeps are also cut, organized and subtracted; resulting into a hollow, bare minimum volume to print. In this case, the organization of the data resembles the order of assembly during construction. The labels are recessed into the planar surface at the cut of each panel and 3d-printed along with the panels. The final model is visible in Figure 7.

4.6 3D-print Preparation

The last step of the digital workflow requires the exporting, organizing and preparing for 3D-printing. From the panel model, each individual panel is repositioned and exported as a separate file to be printed. The polysurfaces are welded into a closed mesh and converted into a .stl file. Evidently, the exported geometry requires thorough inspection and manual fixes before sending it to the 3D-printer.

As such, several samples have been produced across multiple scales, including 1:5 architectural models, an 2 strings of 7 panels as 1:3 assembly models to test the structural systems and finally a successful 1:1 prototype module (see Figure 6).

5 CONCLUSION

The research presented in this paper investigated the digital workflow of the performative-design-to-production process of an optimized sun-shading system. The proposed process exemplified the challenge of integrating multiple design criteria in terms of performance optimization, internalized structure, and manufacturing concerns that resulted into a high geometric complexity. The final geometry (Figure 7) became the calibrated product of a complex, continuously redefined set of mathematically described rules, rather than a preconceived aesthetic image.

As discussed, the design criteria developed over time as part of the natural challenges throughout any collaborative design process. In doing so, the paper argues that this process of identifying the parameters and constraints that informed the design decisions is not a linear, sequential process. The paper argued for the necessary integration of multi-disciplinary constraints through multiple parametric models. In doing so, the juxtaposition of multiple design criteria facilitated the encounter of several conflicts, which could have never been detected if modeled manually through a panel-by-panel approach.

In addition, this research demonstrates the potential use of additive manufacturing at large-scale and its contribution to the design of performative building envelopes. In future research it would be advantageous to streamline the collaboration even further in advance to ensure that each of the identified design criteria is considered simultaneously, rather than sequentially. Particular additive manufacturing constraints became a decisive constraint too late in the process, where it should have been incorporated from the beginning. As of today, more tests are necessary with regard to the selected material (PVDF) and also to decrease the printing time. Upon evaluation and towards possible future phases of the case study the primary concern is to reduce the complexity of the geometry to ensure 3D-printability.

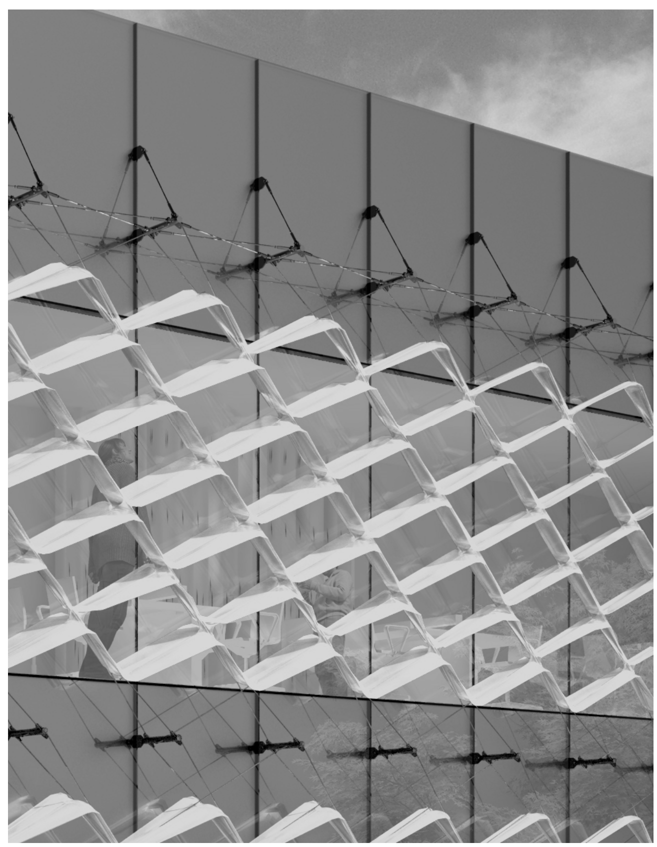

Figure 7. Detail of the PULSE Sun-shading System. Image Courtesy of Ector Hoogstad Architecten

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