Performance Based Pavilion Design

A dialogue between environmental and structural performance

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Abstract. *This paper investigates the design process of a performance based pavilion from concept towards construction phases, by challenging conventional form and fabrication techniques. The proposed project is considered as a temporary structure, located in Antalya, Turkey. A free-form structure and a parametrically defined cladding are designed to serve as an installation unit, a shading element and urban furniture. The pavilion geometry, performance assessments and proposed fabrication schemes are clearly described in the paper. The method integrates form, performance, material and fabrication constraints and exposes how environmental and structural performances, including Solar Access Analysis and Static Structural Analysis, may inform the design project.*
Keywords. *Parametric design; performance; architectural geometry; material; fabrication.*

INTRODUCTION

Design process consists of various phases from conceptualization to construction, including structuring of the problem, preliminary design, refinement and detailing (Goel 1992). Towards manufacturing of architectural form, different parties are involved in the design process, including the design and consultant teams. Architectural geometry needs to incorporate many requirements of aesthetic, programmatic, functional, technical and environmental aspects (Holzer and Downing, 2008). However, performance simulation of buildings is mostly undertaken in a later stage and cannot be integrated into design-decision making (Schlueter and Thesseling, 2009). This issue reduces the efficiency in the design process radically.

There are methods and tools developed for architectural design process, which investigate form, performance and material aspects of design. The rationalization process of free-form surfaces towards fabrication is widely investigated along with panelization tools, in which architectural geometry is subdivided into smaller components. The number of unsolved tasks is enlarged by the number of different materials being used, because their performance and manufacturing technology have to enter the panel layout computation (Pottman et. al. 2008). The statics-aware initialization procedure for the layout of planar quadrilateral meshes is approximated a given free-form surface, by obtaining the mechanical properties of the initial mesh (Schiftner and Balzer, 2010). A recent study aims to explore fundamental principles of a system, in which a performance based architectural geometry is generated. Parametric modeling, panelization tools and series of analysis tools are used with the intent of assigning different materials to the geometry within the same boundary conditions and comparing their structural performance results (Yazici and Tanacan, 2012). An integral computational model promotes an understanding of material, form and performance not as separate elements, but rather as complex interrelations (Hensel and Menges, 2008). As a similar approach, a research project investigated the possibilities and limitations of informing a robotically manufactured system with principles derived from biological structures (Krieg et al., 2011). In parallel to the projects fabricated, a recent research offered a software model, in which material, form, structural performance and manufacturing constraints are integrated into one system (Yazici, 2013).

Although the methods and tools mentioned are important in terms of incorporating various design issues, a holistic approach is necessary in order to integrate multi-performance requirements to the early stage of the design process. Different performance types, such as structural or environmental performance, require different issues to be considered in the design process.

In this paper, a performance based pavilion design is investigated as a case study. The intent is to create an integrated approach of which form, performance, material and fabrication constraints inform each other. By assessing structural and environmental performances of the pavilion, a free-form surface structure, along with a parametrically defined cladding is designed.

METHODOLOGY

The applied methods and constraints which influence the design process are identified. First of all, the pavilion geometry is clearly described in terms of its Non-Uniform Rational Basis Spline (NURBS) properties. Following this, performance assessments, including Solar Access Analysis and Static Structural Analysis, are explored by observing their influence to the overall geometry. Finally, possible fabrication schemes are investigated specified as steel and wooden structural systems.

The Description of the Pavilion Geometry

The pavilion is created by a combination of constraints related to the geometry, performance, material and fabrication techniques. A free-form NURBS surface is generated, which defines a 3D space specified by two major construction curves.

One of the construction curves is the *cross section rail* of the geometry. This curve is generated as a free-form profile. The idea is to generate both urban furniture as a sitting element and a semi-enclosed space, which may be organized as an installation unit and shading element. In order to accommodate these requirements, the profile defines two major curvatures, which define the section of the sitting element with h=0.58 m and section of the semi-enclosed space with h=3.32 m. The profile is designed to solve both of these requirements in a seamless and continuous way.

The other construction curve is a piece of a circle which works as a *rail*. The rail and cross section rail are used to generate the NURBS surface by using Sweep 1 tool in Rhinoceros software. The rail can be selected as a portion of a global circle with r=14.70 m, based on the needs and space available in the environment to construct the pavilion. Pavilion space can be increased or decreased by using same principles of the design and construction. This way of construction is particularly preferred compared to an already completed geometrical composition, in order to maintain flexibility in use of this temporary structure. Various scenarios can be implemented for the pavilion, which may enrich spatial experiences of the users.

The pavilion is considered as a small to mid-scale installation unit and the suitable portion of the global circle used for the pavilion is 50 deg. The geometry is generated free-form style by using 20 control points. The approximate dimensions of the unit are 9.00 m*8.20 m*4.02 m, which is considered sufficient enough to be used for an art installation (Figure 1).

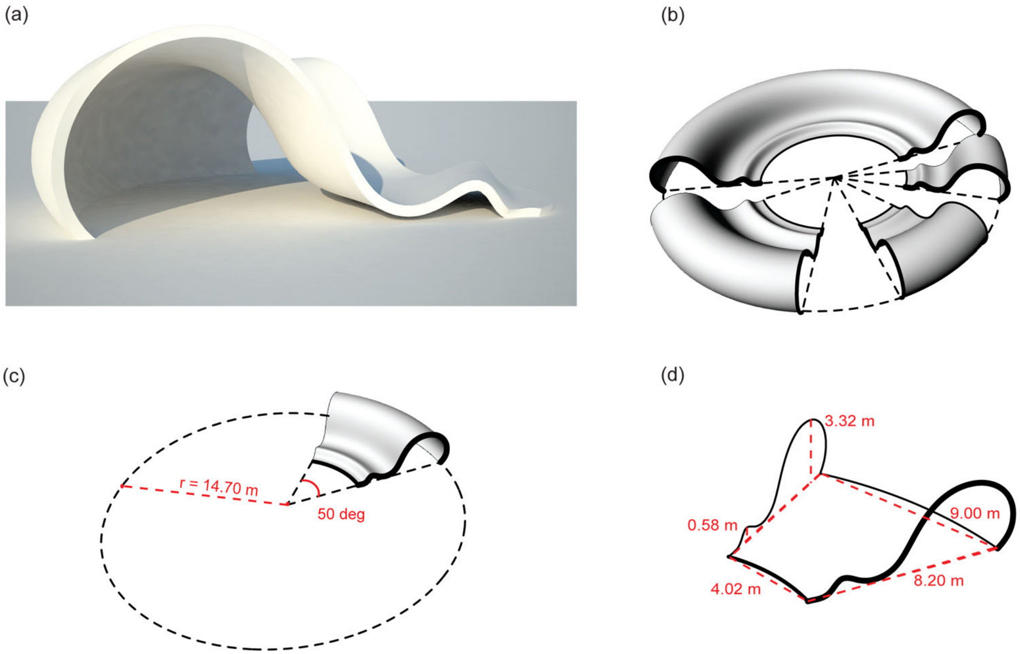


Figure 1
(a) Free-form geometry of the pavilion. (b) The overall geometry is a piece of a global circle which can be increased or decreased based on spatial requirements. (c) The selected piece which is considered sufficient enough for an art installation. (d) Geometrical description of the pavilion.

Performance Assessments through Static Structural Analysis and Solar Access Analysis

The proposed pavilion is located in Antalya Turkey. Antalya has a typical Mediterranean climate, which is characterized by warm to hot dry summers and mild to cold wet winters. Because of this reason, the pavilion has the task of being used as a shading element. Although the pavilion does not obtain a specific site in the city, it is considered be to be installed in north-south or northwest-southeast axes to eliminate the undesirable effect of the sun radiation, through the design of its cladding.

Following generation of the initial form, Solar Access Analysis is operated by Autodesk Ecotect, in order to evaluate the total radiation values affecting the geometry. Solar access analysis indicates incident solar radiation on the surface. The radiation calculations use direct or diffuse radiation data from the *weather file* of the city of Antalya, specified for the time period from September to October. The geometry is converted into a mesh, which consists of 1500 objects, in order to undertake the calculations. The orientation and tilt angles of individual objects are identified. Based on the relationship between the positioning of one piece and the angle of the sun light, the radiation value of that particular piece is calculated. Thus, the relationship of the objects and the sunlight can be established. The total radiation values ranges from 102992.422 to 871177.938 Wh / m2 (Watt hour/ per square meter) (Table 1). Through the solar access analysis, it is identified that the surface pieces which are almost vertical, which works as a wall, obtain higher radiation values compared to the other pieces. Reducing the area of surfaces closer to verticality is an important parameter in design of the pavilion. The cross section rail of the geometry is slightly adjusted through its control points to accommodate a better solution for the solar access analysis. Therefore, free-form geometry

Solar Access Analysis	Object	Orient.	Tilt	Total Radiation	Total Direct Radiation	Total Diffuse Radiation
ID	Type	(°)	(°)	Wh/m2	Wh/m2	Wh/m2
0000	Wall	-53.32	22.96	750727.000	402232.625	348494.375
0001	Wall	-54.11	25.96	791037.375	429239.906	361797.500
0002	Wall	-55.05	25.01	804416.250	447105.438	357310.781
0003	Wall	-51.04	20.83	703201.875	363437.031	339764.844
0004	Wall	-52.09	23.02	742622.312	394182.375	348439.938
0005	Wall	-52.53	22.57	755208.000	406380.375	348827.594
0006	Wall	-48.36	19.40	679358.250	343629.219	335729.062
...						
0739	Floor	84.37	-62.79	110386.078	230.860	110155.219
0740	Floor	-171.70	-69.03	107279.023	52.300	107226.727
0741	Floor	-174.91	-67.07	106750.359	200.100	106550.258
0742	**Floor**	**-174.07**	**-72.46**	**102992.422**	**0.000**	**102992.422**
0743	Floor	-176.76	-70.85	107836.070	34.500	107801.570
0744	Floor	-179.47	-75.72	103816.391	0.000	103816.391
...						
1481	Wall	-53.18	28.27	824098.125	453647.031	370451.094
1482	Wall	-54.10	28.76	832552.625	457229.000	375323.656
1483	Wall	-54.97	28.07	818652.500	448040.781	370611.719
1484	**Wall**	**-55.73**	**31.58**	**871177.938**	**487550.969**	**383626.969**
1485	Wall	-27.17	33.95	747919.875	350308.875	397611.031
1486	Wall	-54.55	28.96	842044.625	466881.312	375163.344
...						

Table 1
Solar access analysis representing attributes of the objects. The minimum and maximum total radiations are identified.

obtain the advantage of responding to the performance issues related to the solar access analysis better, as well as to the design issues by working both as an urban furniture and a semi-enclosed space.

In order to assess the structural performance of the geometry, Static Structural Analysis by FEM is undertaken with the Scan & Solve plug-in for Rhino. The plug-in works with NURBS surfaces without the need for converting the geometry into a mesh, unlike many other software used for the FEM analysis. Following the assignment of material to the geometry; boundary conditions and loadings are imposed. Numerical stress values and total deformations on the geometry can be identified, by using different materials and altering the geometry. By running the simulation for various scenarios; the geometry can be to be adjusted based on performance requirements.

Comprehensive boundary conditions would have a significant impact on the simulation, such as considering the impact of earthquake in the region. However, the fact that the pavilion is designed to be a temporary and preferably a lightweight structure, only the self-weight of the structure is taken into consideration for the analysis, in order to reduce the time of computation and simplify the simulation. By the FEM analysis, the problem areas on the geometry are identified. Although using different materials such as stainless steel or aluminum would influence the numerical stress values of the simulation, because the boundary conditions are less complicated, in which the geometry is rigidly fixed in three positions to the ground, the geometrical properties obtain the most important role to accommodate the structural performance requirements. Especially, the larger curvature which defines the semi-enclosed

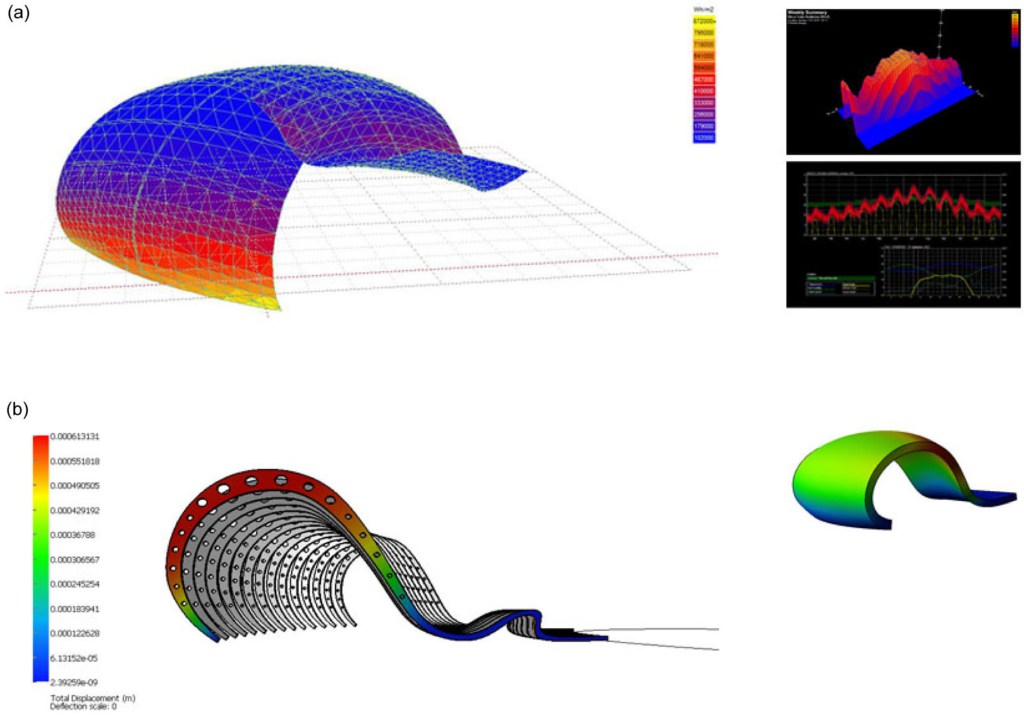


Figure 2
(a) Solar access analysis undertaken for the initial study of the free-from surface, by specifying the weather data of Antalya. (b) FEM analysis is undertaken for different geometry options by specifying material, boundary conditions and loadings.

space plays the critical role for the overall form with its height exceeding 3.00 m and span of approximately 5.40 m.

In order to generate the semi-enclosed space, a symmetrical geometry, which can be constructed by two rail curves, is selected for this study. If there is no symmetry; the structure would be unstable, require comprehensive structural solutions and additional structural issues may need to be addressed in the design process, which are considered against the design intent. If the section of the semi-enclosed space is closer to a circle, then the stresses on the geometry are equally distributed. By modifying the cross section rail of the geometry through its control points, the numerical stress values can be adjusted. Altering the geometry has also a significant impact on the panel layouts of the cladding, in terms of the panel sizes and numbers

One of the proposed structural elements obtains varied thicknesses in profile ranges from 0.07 m to 0.40 m in order to increase the strength of the structure on the necessary parts, such as the larger curvature which defines the semi-enclosed space. Additionally, in order to obtain a lightweight structure, the sections of these structural elements are enhanced by introducing holes in them (Figure 2).

Fabrication Scheme of the Pavilion

Because the pavilion is a temporary structure, pavilion pieces are designed to be easily demountable and light. Geometrical description of form is clearly identified for the fabrication purposes. In terms of constraints related to the transportation and assembly, structural elements are considered to be fabricated in pieces. Because of this reason, two material systems are tested for the structure; as steel and wood. These structural systems are compared in terms of their performances, as well as their lightness.

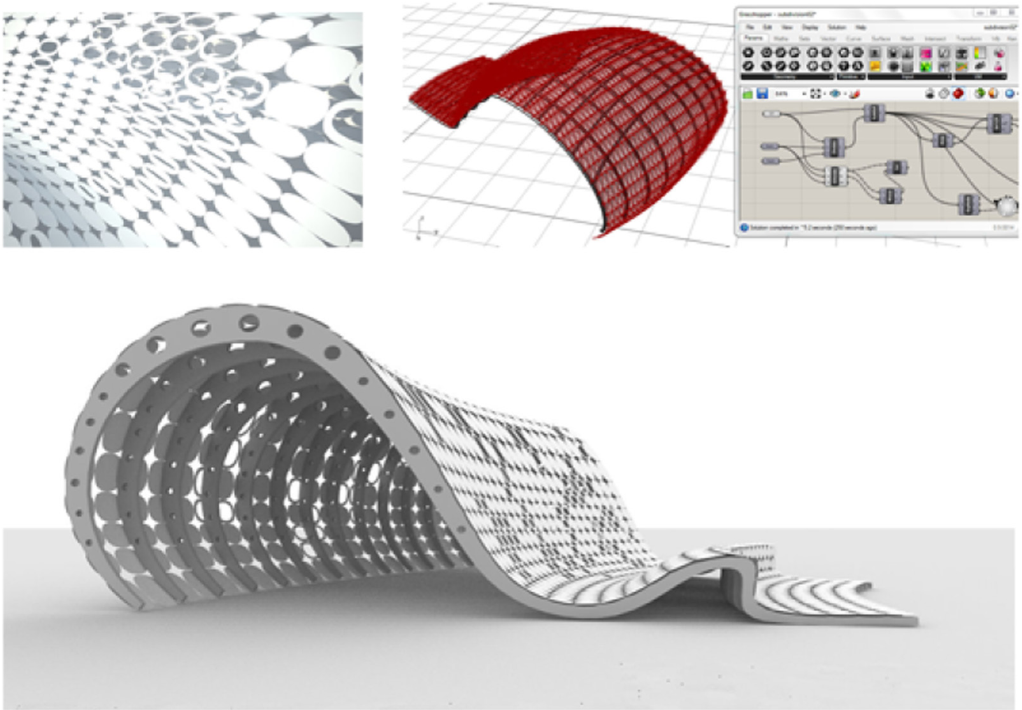
One of the options is using steel profiles for the structure, which is feasible in terms of achieving a lightweight structural system. Steel tubes are proposed to be bended according to curvature specified in the NURBS geometry. The diameter of the circular cross section of major structural elements is d=10 cm. There are 9 steel tubes which work as major structural elements, positioned according to the V curves of the NURBS surface. The spacing between these tubes ranges from 70 cm to 176 cm based on the V curves. Additionally, 21 horizontal steel tubes with d=5 cm are used to bind the major structural elements by following the U curves of the NURBS surface. The spacing between these tubes ranges from 59 cm to 65 cm based on the U curves. Material proposed for the cladding of steel structure option is opaque, acrylic glass with thickness of 3 mm. The idea is to use flat panels for cladding and mount them to the curvilinear surfaces. The acrylic pieces are considered to be fabricated by laser cutting machine, of which size is 80 cm * 60 cm. It is critical how to attach the flat panels to the structure. Therefore, a particular detail is developed in which the components are assembled in groups and then mounted to the structural elements which define the surface curvature.

The other option is using wood as the structure, which is considered to be manufactured by the Computer Numerical Controlled (CNC) machine. The fact that a complex geometry can be generated with a number of differentiated and highly articulated components by digital fabrication tools, the geometry is developed further to accommodate the fabrication constraints. The use of digital fabrication is preferably selected, because of reducing the waste material and obtaining advantages for a more sustainable design solution. The CNC machine available is able to handle maximum sizes of 200 cm * 400 cm wood sheets, with standard of 5 cm material thickness. The micro laminated wood is proposed because of its strength for a structural system. The number of major structural elements is 15, used with holes in the sections to reduce weight of the elements. The spacing between these elements is dense, ranging from 40 cm to 92 cm, because their thicknesses are considered very slim. There are also horizontal wooden binding elements, being implemented with the same principles as in the steel structure. Because of the constraints related to the machine, structural elements are proposed to be produced in pieces. The cladding of the wooden structure is 2D CNC cut plywood sheets with thickness of 3 mm, which can be used both flat or curved, because they are flexible to be bended to accommodate curvature on the surface. The maximum sheet size of the machine, which can handle sensitive tasks such as highly curvilinear surfaces, is 180 cm * 300 cm.

Although the structural elements made out of steel obtain the advantage of being lightweight, the fact that bending procedure of steel tubes reflects the quality manual operation, the precision to the 3D geometry may be problematic. The wooden structure has the advantage of fabricated with a small tolerance by the use of CNC machine. However, the weight of the wooden structure can cause problems. Additionally, because the structural elements made out of wood are considered to be fabricated in pieces, the assembly of the pieces can be challenging as well, by maintaining its structural strength. As a result, both options obtain advantages and disadvantages to be considered for the fabrication.

In order to create cladding, the NURBS surface is converted into panels by using a parametric definition at the Rhino Grasshopper. The opacity of the cladding is driven through series of design concerns and through the intent of controlling the sunlight. A gradient of surface opacity is generated to control sun radiation. It is possible to identify specific ratios between the opaque and/or transparent areas of the cladding and total surface area, towards finding the optimal solution based on climatic conditions of Antalya. First of all, the surface is subdivided based on UV curves on the surface. Following the genera-

Figure 3
The panel layout of the pavilion is generated parametrically by considering the performance requirements.



tion of individual pieces by UV parameter, the surfaces are exploded. The extracted points are evaluated and used for regeneration of the panels. The panels should be unrolled to be fabricated in 2D by laser cutting or CNC machine. The panel sizes range from 23 cm to 52 cm and the total number of panels are 2000, based on the design intent. A relatively denser pattern increases the number of panels by alteration of the U-V curves of the surface. Although, various panel shapes such as quadrilateral, triangular or curvilinear panels can be created via the definition, curvilinear panels are selected and developed for the pavilion, due to its possibility for creating better design solutions for the opaque and transparent areas of the cladding. The panels should obtain flexible connections to allow movements. The connection elements are introduced in four sides of each panel. Because the panels are considered as non-structural parts, they are designed to be mounted on feasible positions of the actual pavilion structure (Figure 3).

RESULTS AND EVALUATION

The proposed method of the performance based pavilion design exposes how different performance requirements can influence a design project. The solar access analysis has proven that there is a direct relationship between the geometry and the solar radiation. For the given free-form surface, the vertical surfaces gain the most of the sun radiation for the time period from September to October for Antalya. Therefore, the geometry needs to be slightly altered to reduce those affected areas. Working with a free-form NURBS surface enables to modify the geometry through its control points, by maintaining its coherence and continuity. In addition to the solar access analysis, static structural analysis by FEM has indicated the importance of developing the geometry though the requirements of structural performance. The curvature, which defines the semi-enclosed space, plays the most important role due to the proportions of its height and span. In order to work as an installation unit, shading element and urban furniture, the surface profile needs to be continuous and fixed from at least three points to the ground for being stable.

The pavilion geometry can be enlarged or shrank, by adjusting the rail curve which is a part of a larger circle. This possibility brings also a systematic approach towards the construction of the pavilion. Additionally, the panels of the cladding can be informed by the climatic requirements, thus their opacity and transparency can be increased or decreased though the environmental data and solar radiation analysis. Therefore, the proposed pavilion accommodates requirements related to the both formal and performance issues.

Although, the proposed method integrates issues of the free-form pavilion from design towards construction, additional limitations may be confronted during its implementation.

SUMMARY AND CONCLUSIONS

In general practice, performance assessments of a design are usually undertaken in a later stage of the design process, as an engineering input which influences design radically and reduces the efficiency in the design process. In order to integrate formal and performance issues in an early stage, the design process of a temporary pavilion is identified. The aim is challenging the conventional form and fabrication techniques. A free-form NURBS surface is created as an installation unit, shading element and urban furniture, located in Antalya, Turkey. Two structural systems, as steel and wood, are investigated in order to accommodate the design requirements of the pavilion project. Structural performance and environmental performance assessments, including Solar Access Analysis and Static Structural Analysis undertaken by FEM, are operated in order to inform the geometry. The cladding scheme is generated via a GH definition, by designing opaque and transparent areas on the surface. The proposed method in this paper integrates form, performance, material and fabrication constraints. It exposes how structural and environmental performances may inform a design project.

The intent for the future work is to study the integration of various performance requirements with architectural form further. A model may integrate different types of performance requirements, form, material and fabrication techniques into one parametric system, where they are equally important and inform each other. This would increase efficiency in the architectural design process radically.

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