Proceedings of the IASS-SLTE 2014 Symposium
"Shells, Membranes and Spatial Structures: Footprints"
15 to 19 September 2014, Brasilia, Brazil
Reyolando M.L.R.F. BRASIL and Ruy M.O. PAULETTI (eds.)

Performance-based design of a self-standing building skin; A methodology to integrate structural and daylight performance in a form exploration process

Azadeh OMIDFAR*, Omid OLIYAN TORGHABEHI, Peter VON BUELOW

University of Michigan
2000 Bonisteel Blvd., Ann Arbor, USA
aomidfar@umich.edu

Abstract

This paper investigates the ways in which interdisciplinary integration and performance optimization of a self-standing skin can be synthesized and systematized to efficiently generate and evaluate a diverse range of design options. This research project presents a multi-objective optimization model which is used for form exploration that could assist designers and engineers in creating performance driven design. This research project focuses on the design and environmental performance of a self-standing skin to optimize the performance of existing buildings in New York City. With increased sophistication of digital tools to assess daylight, environmental and structural performance of building skins, a great potential exists to optimize the performance of existing contemporary buildings. This study applies environmental and structural analysis software to optimize the integrated performance of a skin façade of a typical office building located in New York, NY. The geometry of the skin structure is created by a parametric model guided by the performance values associated with structure, daylight, and radiation control. The multi-objective optimization and exploration employs a genetic based method, ParaGen, developed at the University of Michigan.

Keywords: form finding, optimization, daylight simulation, climate based metric, genetic algorithm

1. Introduction

One of the most important methods of saving energy in office buildings is by carefully designing the façade. The performance of the building is strongly linked to the design of the building skin. Thermal properties, acoustic characteristics and daylighting are all affected in the exploration phase of the building skin. Therefore it is necessary to generate, evaluate and optimize building skins during the initial phase of the design process. With the increased sophistication of digital tools to assess given performance criteria, and the need to create buildings that are energy efficient, architects and engineers are more than ever interested in optimization and performance-based design.

There exist a variety of software and tools which are employed by architects and engineers to design, generate, simulate, evaluate, and integrate geometry. However, none of the existing tools have the capability to perform all tasks at hand. Some are dominant at making geometrical surfaces and forms, others are only capable of running simulation, but none are strong at performing both. Although there exists a great potential to design, optimize and evaluate buildings, the challenges are: which tools to use? How to integrate them? When to use them and how? This is a challenge that all architects and engineers face who are interested in interdisciplinary and performative design.

Currently the process that most designers have to implement in order to evaluate the performance of their design is as follows: the initial form is generated in a modeling tool such as AutoCAD, Revit, Rhino, 3DS MAX, among other tools. Once the geometry is created, the form has to be exported in a specific format and imported into another simulation environment for further analyses such as daylighting, acoustics, structural, or thermal analysis. The majority of simulation tools are capable of only a few of these analyses, and therefore it is required to use multiple tools to evaluate the design. If the analysis tool allows for importing forms and geometries for simulation, there are many issues that the designer has to then examine and study such as the complexity of the exported mesh, the materials, the forms, the zones, missing geometry, etc. Frequently in this process, importing a geometry from one software to another software for performance analyses is a task in itself and may not be easily accomplished making it necessary to recreate the geometry. This back and forth process not only causes many issues in the simulation phase, it is also very time consuming and most professionals do not have the time or the budget to spend on this type of exploration process. Therefore it is difficult and time consuming for most professionals to explore a variety of design options and to evaluate their design decisions.

The objective of this paper is to find a more efficient methodology and to systematize the process of design, simulation and optimization. In addition to create a more efficient way of generating and evaluating forms, this project goes a step further to automate the process with a hope to generate a diverse range of design options.

2. Methodology

To integrate all characteristics of architectural design, a comprehensive methodology is required to consider the aesthetic qualities of the façade and the performance behavior of the skin. In order to understand all the possibilities and limitations of creating a performative building skin, a typical office building in New York City has been selected as a case study. The objective was to design a self-standing building skin that wraps around the South, East and West elevation of the office tower.

The initial exploration of the geometry was executed in the Rhinoceros CAD environment. Rhinoceros (Rhino) is a stand-alone, commercial NURBS-based 3-d modelling tool, developed by Robert McNeel and Associates (McNeel, [1]). The realization of multiple parameters that control the surface and structural geometry required the geometry to be constructed in Grasshopper as a means to control each variable parametrically. Grasshopper is a graphical algorithm plug-in for Rhino which allows for parametric modelling and scripting (McNeel, [1]).

A building's skin must respond to the particular environmental conditions of its location. For the purpose of this case study, New York, NY (42.35 N, 71 W) is chosen as the testing environment. The New York City - Central Park 744860 weather file will be used for lighting and radiation analysis.

To understand the behaviour of the geometry, STAAD.Pro was utilized to analyse the structural performance of the geometry, while DIVA was employed to simulate the radiation penetration through module aperture using a gridded nodal surface constructed in Grasshopper. Similarly to measure the daylight behaviour of the space, Daylight Autonomy (DA) was measured by calculating the 'climate based metric' in DIVA, which uses Daysim for the back-end calculation. DA is defined as the "percentage of the occupied hours of the year where a minimum illuminance threshold is met by daylight alone (Reinhart and Walkenhorst, [2])." The DIVA plugin for the Rhinoceros and Grasshopper environment supports a series of performance evaluations by using validated tools including Radiance and Daysim (Reinhart *et al*. [3]). DIVA was chosen so that all modelling and daylight simulations could be carried out within the Rhino and Grasshopper environment. Climate based metric is the prediction of various radiant or luminous quantities using sun and sky conditions derived from standard meteorological datasets; the results are dependent both on the locale and the building orientation, in addition to the building's composition and configuration (Mardaljevic, [4]).

The geometry of the skin structure is created with a parametric model guided by the performance values associated with daylight, radiation control and structural behaviour. The multi-objective optimization and exploration employs a genetic based method, ParaGen. ParaGen combines parametric modelling, performance analysis, and a genetic algorithm (GA) together with a SQL database to store and retrieve design solutions for directed exploration of the solution space (von Buelow [5]). Using ParaGen, a range of well performing topologies can be explored.

2.1. Form Generation and Evaluation

The overall definition of a solution generated in Grasshopper can be divided into three distinct groups: *Parametric Variables*, *Geometry*, and *Performance Simulation* (Fig. 1). The *Parametric Variables* are generated by the GA and linked to Grasshopper through an Excel spreadsheet. The values in the Excel sheet are linked to the geometry of the skin which is connected to the DIVA component for Daylight and Radiation simulation of a floor in the office tower. Each new Excel sheet generated by the GA is processed by Grasshopper first to produce a new geometry and then to process the geometry through DIVA to measure the daylight autonomy (DA) and the direct radiation penetration through the skin. The DA calculation measures the amount of daylight that penetrates through the skin falling on a horizontal surface which is placed directly behind the skin at desk level, approximately 2.5 FT (0.7 meters) above finish floor (AFF). The radiation simulation measures the amount of direct radiation that penetrates through the skin apertures falling on the gridded nodal surface placed directly behind the skin.

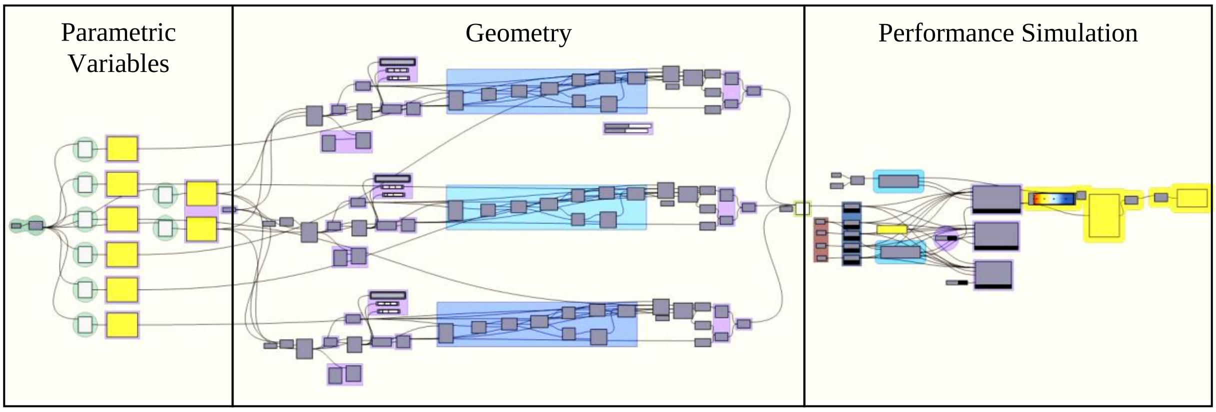

Figure 1: Overall definition and structure in Grasshopper- Parametric Variables, Geometry of the Panels, and Daylight and Radiation Simulation.

2.1.1. Parametric Variables

Rather than controlling the geometry parametrically in Grasshopper by using 'sliders', as mentioned earlier, the geometry is instead controlled by an Excel sheet which is connected to the Grasshopper model. The *Parametric Variables* section in Grasshopper is the connection between the Excel sheet and the Grasshopper file. Once the location path of the Excel file is defined, the component displays the values of each cell in the Excel sheet. Fig. 2 shows the variable names and example values used (columns A and B respectively). Columns C through E give the range of each variable maintained by the GA. The Module Width and the Module Height variables control the size of each module, and the Horizontal and Vertical Pitch variables are the horizontal and vertical rotation of the unit geometry which control the rotation and thus the depth of each unit module. Lower, Middle and Upper refer to horizontally banded zones of the modular panels used for each story height. Depending on the values of the variables, there can be between three and six bands of panel modules per story height.

	A	B	C	D	E
1	Variables	Values	Min Value	Max Value	STEP
2	Modual_Width	2	1	4	1
3	Modual_Height	4	2	4	1
4	Horizontal_Pitch_Lower	-10	-10	-30	10
5	Horizontal_Pitch_Middle	60	-10	-50	10
6	Horizontal_Pitch_Upper	-20	-10	-70	10
7	Vertical_Pitch_Lower	50	-60	60	10
8	Vertical_Pitch_Middle	-30	-60	60	10
9	Vertical_Pitch_Upper	40	-60	60	10

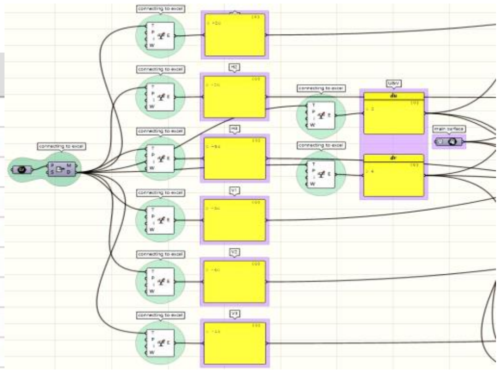

Figure 2: Excel sheet designed to control the parametric variation of the geometry in Grasshopper

The values in the Excel sheet are generated by the GA component of ParaGen. The initial population of values are generated randomly. Once the database contains a sufficient number of solutions, the GA switches over to breeding. ParaGen uses Half Uniform Crossover with sets of two parents. It can also occasionally mutate one parent or as mentioned above it initially generates random data sets. The maximum and the minimum values for the sizes of the modules are shown in Fig. 2 to be between 1 FT (0.3m) and 4 FT (1.2m). There exist three horizontal and three vertical rotational angles for each floor to ceiling segment of the building skin. The angle of the horizontal rotation ranges from 20 degrees to 60 degrees. The angle of the vertical rotation ranges from 0 degrees to 120 degrees. All values produced either randomly or through breeding are constrained to the ranges shown in Fig. 2.

2.1.2. Geometry

As previously mentioned, this case study is comprised of an office tower and a free-standing building skin which wraps around the East, South and West façade of the tower and connects to it at each floor level for structural support. The geometry and the shape of the tower is not a focal point of this research, as the aim is to consider solutions for existing office buildings located in New York City. Although the geometry of the skin is important as it impacts the overall performance of the building, due to the overall objective of this research to find the ways in which the process of form generation to evaluation and optimization can be synthesized and systematized, a simple geometry was chosen as a case study.

The overall design of the skin is comprised of intersecting oval apertures that are rotated in both the horizontal and vertical direction (Fig. 3). The horizontal and vertical rotation of the apertures in the vertical axis creates the depth of the skin; the horizontal rotation create surfaces that perform similar to light shelves, and the vertical rotation generates surfaces that behave similar to fins. The depth (thickness) of the unit modules is important in order to block the unwanted radiation as well as allow daylight to penetrate deep into the occupied spaces. The size (height and width) of the unit modules ranges from 1 FT (0.3m) to 4 FT (1.2m); while depth (thickness) varies depending on the angle of rotation in the vertical axis. The size and the horizontal and the vertical rotation of the modules are controlled by the parametric variables in the Excel sheet as described above. Each solution bred in the GA produces a new set of values in the Excel sheet, which becomes a new geometry inside of Grasshopper. Each time the values in the Excel documents are changed, the form and the size of the skin also changes.

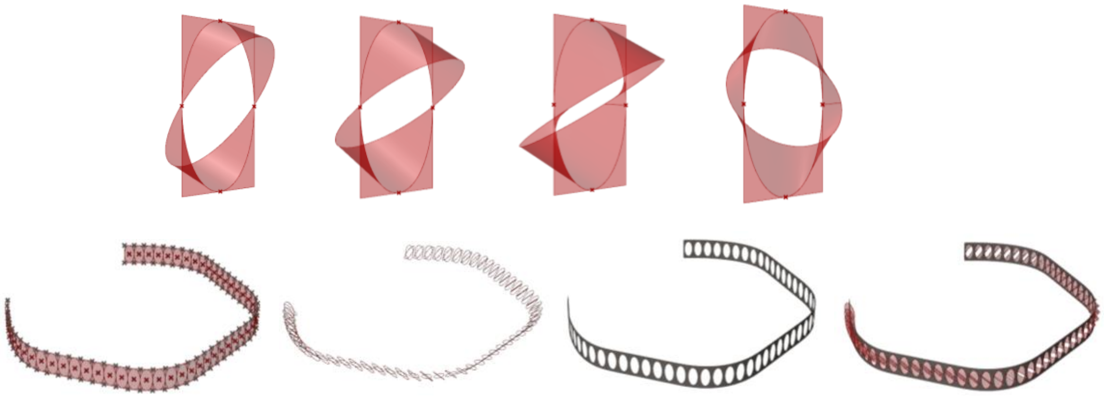

Figure 3: Building skin components and construction

The overall skin is approximately 48 FT (14.6m) tall. Each floor level is assumed to be 12 FT (3.6m) tall. Each level is divided into three 4 FT (1.2m) bands of skin that each have a different unit module with a different angle of rotation (Fig. 4). The free standing building skin wraps around the tower to protect the building from direct radiation and allow for light penetration deep into the spaces. The horizontal rotation of the intersecting ovals creates a small scale overhang that protects the interior space from direct radiation, while the same rotation also creates a small scale light shelf that re-directs daylight into the space beyond.

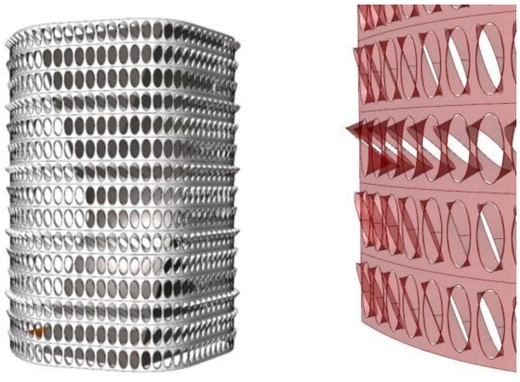

Figure 4: Building skin components and construction

2.1.3. Environmental Performance Simulation

As previously mentioned, in the *Performance Simulation* section of this project, DIVA-Grasshopper is employed to measure Daylight Autonomy (DA) and Radiation (RAD) penetration through the skin. The overall geometry of the skin and the geometry of the first level of the tower was connected to the DIVA plug-in. Each modeled surface was assigned a specific material such as walls (60% reflectance), glazing (87% visual transmittance), ceiling (80% reflectance), floor (20% reflectance) and exterior surface material (90% reflectance). Two sets of sensors or nodes were generated: one for the DA which was located above finish floor at approximately 2.5 FT (0.7m) high, and second was located on the exterior walls directly behind the skin to measure Radiation penetration through the unit modules (Fig. 5).

The surfaces, materials and the nodes were all linked to the DIVA plug-in for both DA and RAD analysis. The DA measured the amount of daylight penetrating through the skin from 8:00 am to 6:00 pm for the entire year; while the RAD only measured the peak summer week from July 27th to August 2nd.

The Daylight Autonomy for the majority of skin designs ranges from 43% daylight to 75% daylight; which suggests that the space is lit at 500 lux for 43-75% of the occupied hours by daylight alone. This is very critical as it reduces the use of electrical lighting, and therefore the overall energy consumption of the building.

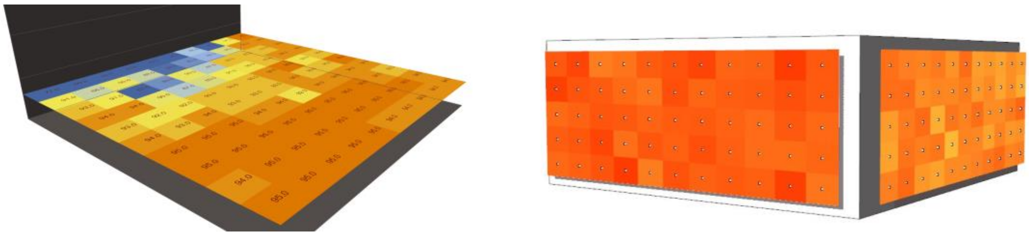

Figure 5: Example of Daylight Autonomy and Radiation Map generated in Grasshopper

The RAD measurement during the peak summer week without the skin was approximately 1790 Kwh/m^2 while the RAD penetration through the skin during the peak summer week ranges from 83 Kwh/m^2 to 530 Kwh/m^2 depending on the skin design and aperture depth rotation. This is roughly 70% to 96% reduction in direct radiation which would ultimately reduce the overall cooling demand of the office tower, and therefore reduce the energy consumption during the summer months.

2.1.4. Structural Performance Analysis

The structural framework is a regular rectangular grid based on the dimensions of the skin modules. The geometry is exported as a DXF file and imported into STAAD.Pro software. Pipe sections with rigid connections are used as structural members for the frame. The skin structure is supported by pinned supports at the ground level and also restrained at each floor level with a simple bracket connection. Pinned supports have been used to model the bracket connection of the skin to the tower. The skin frame structure is illustrated in Fig. 6.

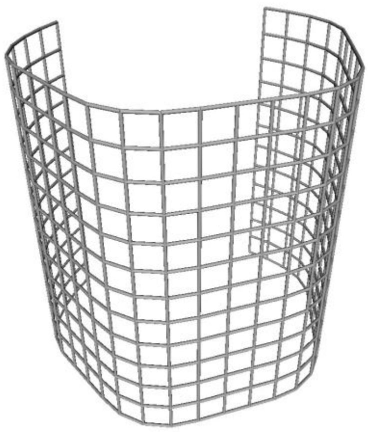

Figure 6: The skin frame structure

The skin is designed to resist the self-weight of the structure and skin and also a wind load. To account for the self-weight of the skin the frame structure is designed to resist twice the weight of the frame which is an approximation of the skin material weight on the frame. Wind loading has been calculated based on the

ASCE 7-02 for the project site situated in New York (42.35 N, 71 W). The wind load pressure is calculated based on Equation. 1.

$$q_z = 0.00256\ K_z\ K_{zt}\ K_d\ V^2\ I \qquad (1)$$

The site specific and structure specific parameters are tabulated in Fig. 7.

Kz (pressure exposure)	Kzt (topographic factor)	Kd (wind directionality factor)	V (basic wind speed)	I (importance factor)
1.169	1.0	0.85	106	1.0

Figure 7: Wind pressure parameters

Considering wind load in two perpendicular horizontal directions the structure is analyzed using the combination of self-weight and wind loading. Using AISC building code, STAAD.Pro defines the appropriate pipe sizes for each structural member to resist the load combinations. The analysis and design results are stored in an output file created by the software.

Using the output file, the structural performance parameters are extracted. The main performance criteria which have been used in this research are explained in this section. The total weight of the frame is a good criterion for material use and material efficiency. The maximum deflection is the deflection of the frame which must be limited to avoid collision with the skin and tower in strong winds as well as binding of the skin modules embedded in the structural frame. The maximum size of the members should be limited due to the size of the module aperture. The performance parameters and structure images are extracted and eventually uploaded to the server.

2.1.5. Automation process

To automate the parametric process of the different runs, AutoHotkey (AHK) is employed. AHK is an open-source scripting utility and automation software that allows users to automate different tasks in Microsoft Windows. It is a custom scripting language which uses keyboard shortcuts or hotkeys to run and automate different functions. AKH script is used primarily to link the various software packages being used (Excel, Rhino, STAAD.Pro), and in some cases issue menu commands within the software. Additionally, inside each software package VBA macros are written to perform different tasks. Once the Grasshopper file is initiated by AHK, it launches DIVA to initiate a simulation run for both DA and RAD as well as exporting a DXF file for the STAAD analysis. Once the simulation is finalized for a specific geometry, it saves three pre-set views in Rhino, then Rhino is exited. Then AHK launches an Excel macro which begins the calculation of the DA and the RAD simulation for each sensor. The script then opens STAAD.Pro for the structural analysis. After all of the aforementioned operations, the last AKH script takes all images and values associated with the geometry and it uploads them to the server where all the other information is stored. Once all information is uploaded to the server, it is purged from the client PC and the cyclic process begins again using new values generated by "breeding" function of the ParaGen GA on the server. This automated method allows for numerous and efficient form generation and simulation cycles.

3. Results

Once all of the files and data relating to a solution have been uploaded to the server, the data is then placed in a SQL database with an identification code that connects all of the associated images and data files (von Buelow, [5]). Through a graphic interface of the ParaGen webpage, all images and the data can be accessed, filtered and sorted based on their performance values or aesthetics (Fig. 8).

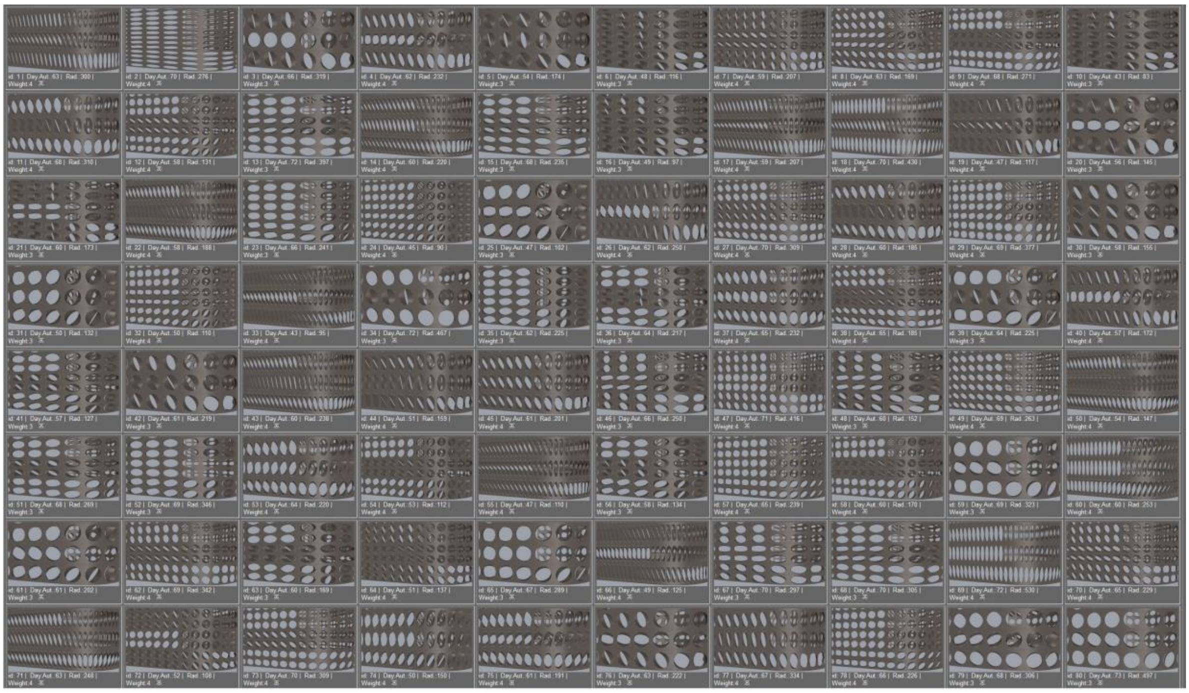

Figure 8: A display of solutions taken from SQL database

Solutions can be viewed side by side, as a single image, or an image with all data associated with it. Each image is labeled with appropriate variables. The software allows for upper and lower limits to be set on any of the parametric or performance data in order to filter and control the solutions displayed. This is an interactive process that is ideal for designers and engineers to evaluate a design both aesthetically and performativity.

In addition any sets of values can be chosen and plotted. This is an effective way to find solutions with particular relationships to others in a set. The graphing function can also be used to determine Pareto front solutions. Fig. 9 shows a graph which compares the Daylight Autonomy to the Radiation values for a set of solutions. The solutions found on the Pareto front generally represent the best "trade-off" values for the two chosen objectives, for example, skins that block direct radiation while allowing maximum light penetration into the space beyond. By clicking points on the graph, images of the solutions are shown. This allows the designer to make qualitative as well as quantitative comparisons. Fig. 9 also shows a comparison of three solutions picked from the Pareto front. The ParaGen webpage displays both small thumbnail images and all key performance values for each solution. By activating an image, a larger image along with all data values will be displayed (Fig. 10).

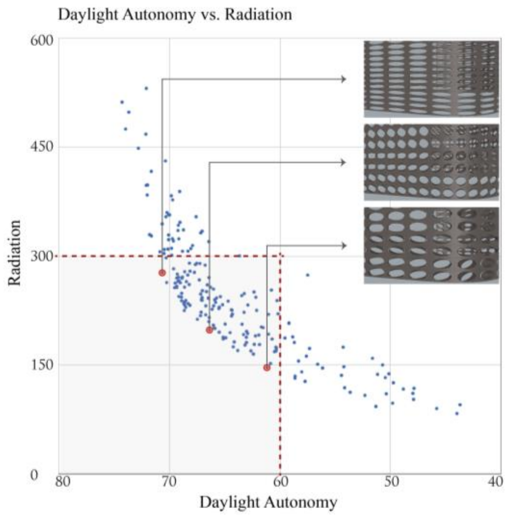

Figure 9: The graph of Daylight Autonomy vs. Radiation. The Pareto front values are on the lower left boundary.

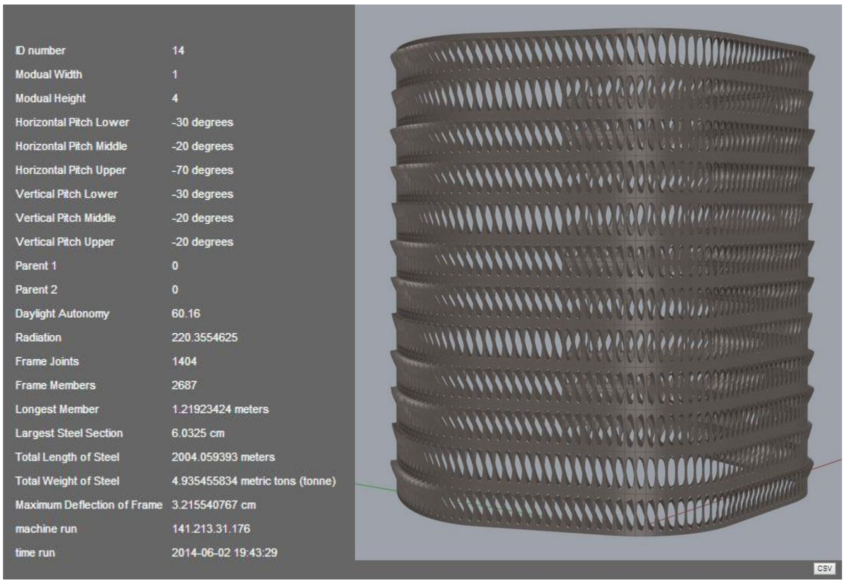

Figure 10: Detailed data and files available on the website

3. Conclusion

The aim of this paper was to investigate the ways in which interdisciplinary integration and performance optimization of a self-standing skin can be synthesized and systematized to efficiently generate and evaluate a diverse range of design options. This project presented a multi-objective methodology to efficiently study parametric design of a building skin. Considering that in the present day we have more than one hundred tools, software, or plug-ins that all aim to design, model, evaluate, generate forms and geometry, we are still in search of ways in which to either find a tool that does all tasks at hand or find ways to integrate tools and software to efficiently perform the multi-faceted tasks needed to design and optimize forms.

This integrative methodology connects multiple software, to efficiently design a performance-based building skin. The use of ParaGen allows users to analyze and select the most desirable and performative solutions. The form exploration and selection process is enhanced by means of the interaction of the designer with the process particularly in the early stages of design. This process introduces an integrated methodology that allows designers to find solutions which yield good performance over a range of criteria including qualitative judgments.

Acknowledgement

The authors would like to thank Taubman College at the University of Michigan for support of the Hydra Lab.

References

[1] McNeel R. Rhinoceros: Nurbs Modeling for Rhino. (Version 4.0 SR 8) [Computer Software]. Robert NcNeel and Associates. 2010. Retrieved from www.rhino3d.com

[2] Reinhart C.F. and Walkenhorst O. "Dynamic RADIANCE-based Daylight Simulations for a full-scale Test Office with outer Venetian Blinds." *Energy and Buildings* 33(7): 683-697, 2001.

[3] K Lagios, J Niemasz, C F Reinhart, "Animated Building Performance Simulation (ABPS) - Linking Rhinoceros/Grasshopper with Radiance/Daysim", *Proceedings of SimBuild 2010*, New York City, August 2010.

[4] Mardaljevic, John. Climate-Based Daylight Analysis for Residential Buildings. N. p., 2008.

[5] von Buelow P, ParaGen: Performative Exploration of Generative Systems, *Journal of the IASS*, vol. 53, no. 4, pp. 271-284, 2012.