



Combining parametric modeling and interactive optimization for high-performance and creative structural design

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Abstract

In architectural and structural design, current modeling and analysis tools are extremely powerful and allow one to generate and analyze virtually any structural shape. However, most of them do not allow designers to integrate structural performance as an objective during conceptual design. As structural performance is highly linked to architectural geometry, there is a need for computational strategies allowing for performance-oriented structural design in architecture. In order to address these issues, the research presented in this paper combines interactive evolutionary optimization and parametric modeling to develop a new computational strategy for creative and high-performance conceptual structural design. Parametric modeling allows for quick exploration of complex geometries and can be combined with analysis and optimization algorithms for performance-driven design. However, this methodology often limits the designer's authorship, since it is based on the use of black-box optimizers. On the other hand, interactive evolutionary optimization empowers the user by acknowledging his or her input as fundamental and includes it in the evolutionary optimization process. This approach aims at improving the structural performance of a concept without limiting the creative freedom of designers. Taking advantage of the two frameworks, this research implements an interactive evolutionary structural optimization framework in the widely used parametric modeling environment constituted by Rhinoceros and Grasshopper (Robert McNeel & Associates [15], [16]). The implemented design tool capitalizes on Grasshopper's versatility for geometry generation but supplements the visual programming interface with a flexible GUI portal, increasing the designer's creative freedom through enhanced interactivity. The tool can accommodate a wide range of structural typologies and geometrical forms in an integrated environment. The paper includes a description of the tool and demonstrates its applications and benefits through several conceptual design case studies.

Keywords: conceptual design, exploration, interactive evolutionary optimization, parametric modeling

1. Introduction

Recent years have seen the development of increasingly powerful modeling and analysis tools that allow architects and engineers to generate and analyze virtually any structural shape. Both generating complex geometries and performing advanced analyses now require less manual effort and computational time

than ever before. However, such tools have generally failed to integrate architectural and structural design. Specifically, existing tools epitomize a design paradigm that excludes structural considerations from the earliest stages of architectural design. Since the performance of a structure is highly attributed to its geometry, such an approach will likely result in poorly performing structures. Furthermore, integrating structural design during the conceptual design phase has the potential to reconcile structural form and architectural geometry, resulting in efficient and architecturally expressive forms.

Several classes of experimental tools and computational techniques have recently emerged to bridge the gap between structural and architectural design: for example, interactive (Van Mele, et al. [19]) and constraint-based (Fivet and Zastavni [7]) graphic statics, thrust network analysis (Block and Ochsendorf [5]), form-finding (Killian and Ochsendorf [8]), and other related approaches. In order to capitalize on the opportunities offered by computational power while overcoming the issues previously highlighted, these structural design tools have been developed to integrate structural performance into conceptual architectural design. They are very powerful for specific structural types but do not define a comprehensive framework for creative conceptual structural design more generally. There is thus a need for general computational frameworks that go beyond structural typologies and offer guidance-based exploration of architectural and structural forms.

2. Background

Two computational design strategies, parametric modeling and interactive evolutionary optimization, offer compelling alternatives to the previously mentioned techniques. Indeed, these approaches are naturally oriented towards creative exploration, are theoretically applicable to any design problem and are well-suited to make ill-defined criteria meet quantifiable objectives in architectural design,.

Parametric modeling combined with optimization algorithms has emerged as one of the most widely used computational methodologies for conceptual structural design. Recently, it has organically grown from the development of interrelated tools. Specifically, 3D modeling software, such as Revit (Autodesk [3]) or Rhinoceros, can be combined with visual programming interfaces, supplementing the modeling workspace to constitute parametric modeling environments.

These allow the user to script complex generative algorithms without prior programming knowledge and can help steering design space exploration. Exploring different solutions can be done in a timely manner as the parametric design process is by essence non-destructive, meaning that one model contains all the previously explored solutions as well as the ones yet to evaluate. Furthermore, these parametric modeling environments can be used in combination with analysis and optimization components to constitute integrated design environments. Thus, such environments are not solely dedicated to computer-aided drawing but benefit from the numerous available plug-ins to assess the performance of architectural designs according to a wide range of criteria, from building envelope performance to daylighting availability.

Such integrated environments constitute a compelling common ground for architects and engineers. However, little to no control on the optimization process is left to the user and parametric models are optimized using black-box solvers - Galapagos (Robert McNeel & Associates [14]) and Goat (Rechenraum [13]) for Grasshopper for example - yielding a single near-optimal solution. As a result, parametric modeling as implemented in existing environments lacks of guidance features and design space exploration, usually remaining limited to manual manipulation of sliders and initiation of

computational search. As automated optimization procedures fail to take advantage of the designer's expertise (Scott, Lesh and Klau [17]), they do not capture the complexity of architectural design.

Another strategy, interactive evolutionary optimization, lately has gained popularity for nuanced exploration in structural design. While standard evolutionary algorithms seek to find the optimal solution using heuristic methods in a closed loop workflow, interactive optimization incorporates the designer's input in the optimization process for the selection of parent solutions. This approach accounts for ill-defined objectives, such as aesthetics, which makes it very suitable for applications in architectural and structural design where design complexity goes beyond quantifiable metrics. Moreover, it can capitalize on the designer's intuition to interact with evolutionary parameters (Mueller and Ochsendorf [12]) and control the design space exploration. This strategy may lead to sub-optimal solutions which are more valuable to the designer in terms of ill-defined criteria such as aesthetics. This strategy has proven to be successful for guidance-based exploration of the design space and was implemented in structureFIT, a web-based tool for interactive evolutionary optimization of 2D trusses developed by Mueller [11].

Given the advantages of the strategies discussed above and their complementarity, there is a clear potential for connecting interactive evolutionary optimization and parametric design. Previous work has illustrated the benefits of combining parametric modeling, genetic algorithms and designer's for design space exploration. Specifically, ParaGen, developed by von Buelow [20], has shown the benefits of combining parametric modeling and interactive evolutionary optimization on a wide variety of design examples such as trusses, folded-plate structures, and roofs (Turrin, von Buelow and Stouffs [18]). While the aforementioned tools prove the relevance of parametric design and optimization for architectural and structural design, there is an unmet need to extend existing work, focusing simultaneously on user-friendliness, versatility, and extensibility. This paper presents a new tool that addresses this need, proposing a design environment that integrates guidance-based exploration of the design space for any problem with user friendliness and versatility.

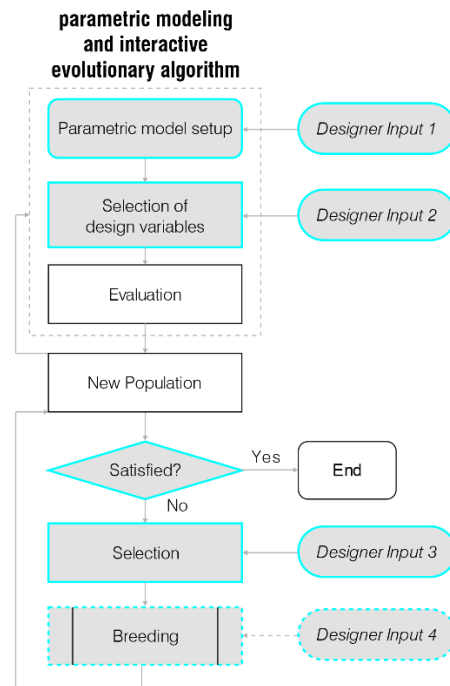


Figure 1: Framework workflow

3. Framework

3.1. Connecting Interactive Evolutionary Optimization and Parametric Design

This paper develops an approach that seeks to connect interactive evolutionary optimization to parametric design in such a way that all the features offered by parametric design in terms of geometry generation can be used to explore innovative structural systems. Consequently, interactive evolutionary optimization must not be limited to a set of structural typologies or design problems. Instead, it should

build upon parametric modeling environments versatility and built-in features. Doing so, the designer's input goes beyond selection of solutions and manipulation of evolutionary parameters, as she or he is also in charge of the setup of the parametric model with total freedom, as shown in Figure 1. Interactive evolutionary optimization must thus be connected to parametric design in the most lightweight way possible and should only know about the geometry, the performance index, and the design variables of a given problem, thus allowing the designer to explore any problem easily and interactively. Connecting evolutionary optimization and parametric design inherently extends the designer's input by not limiting it to the modification of predefined parametric formulations of design problems.

3.2. Implementation and User Interface

The new tool – called *stormcloud* - is written in C#.NET (Microsoft [9]) and uses Windows Presentation Foundation (Microsoft [10]) for its user interface. Helix 3D Toolkit (Bjorke [4]) is used for the 3D visualizations of generated structures. The tool is implemented for Rhino/Grasshopper (Robert McNeel & Associates [15], [16]) as a single component placed on the Grasshopper canvas (see Figure 2). Double clicking on

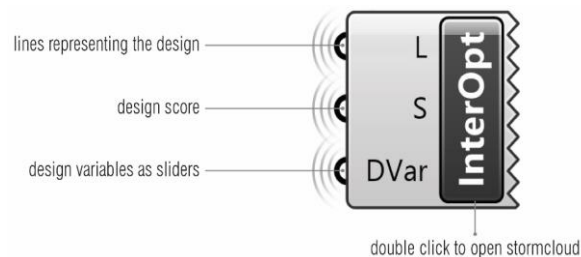


Figure 2: Interactive evolutionary optimization (IEO) component

the component raises an event that opens a WPF window. The component takes three different inputs – geometry (in the form of lines), an evaluation method that produces a numerical score, and design variables - and has no output parameter. The score is normalized according the initial solution score. The code-behind of the WPF window generates populations of candidate solutions by re-computing the Grasshopper script solution after setting the design variables, i.e. sliders, to new values obtained after cross-over and mutation operations. The geometry, values of design variables, and score of each solution state are collected by the component at every iteration and are stored in the data context of the window. Since the graphical user interface supplements Rhino/Grasshopper, it takes advantage of the versatility offered by the parametric modeling environment both in terms of analysis and geometry generation. The IEO component only knows about geometry, score and design variables, which makes the WPF application extensible to any problem. In other words, the component is blind to the nature of the parametrized model. This means that *stormcloud* is not bound to any predefined parametric formulation (e.g. trusses) and can be used on a variety of design problems. While this paper illustrates the benefits of *stormcloud* with structural design examples, it can be used for any design problem for which a fitness function can be set. It can also be used for pure subjective exploration through the use of a constant fitness function.

In order to address the need for effective design visualization and selection, two crucial aspects of the interactive evolutionary optimization process, the user interface (see Figure 3) include the following features:

- (i) Synchronized 3D viewports

Static thumbnails of designs are replaced by 3D viewports whose cameras are synchronized for better comparison of candidate solutions. Enforcing a camera binding between the viewports allows the user

to easily and effectively compare the different solutions for subjective selection. Simultaneously visualizing the different designs dramatically increase the design space exploration capabilities of the parametric environment

(ii) Selection of design for detailed visualization

Each candidate solution displayed on the design grid can be selected for detailed visualization on the main viewport. This allows the user to assess more easily subjective features of the top designs. Selecting a design for detailed visualization also changes the solution state in Grasshopper to correspond with the selected solution, thus allowing for geometry generation in Rhino.

(iii) Generation of geometry in Rhino viewport

The user can save the preferred solutions as geometries stored in Rhino. Each solution is assigned a different sublayer of a common 'exploration' layer.

(iv) Recording of exploration

The designer is offered the possibility to record his exploration by saving the characteristics of each solution explored, i.e. the values of the design variables and the score, as a comma-separated values (.csv) text file. The file can then be used by the user to extract more knowledge about the design space.

(v) Exploration visualization

As with other optimization plug-ins for Grasshopper, geometries that are computed in Grasshopper can be visualized live – changing in real-time – in the Rhino viewport which provides additional information to the designer about the possible structural forms that are being explored.

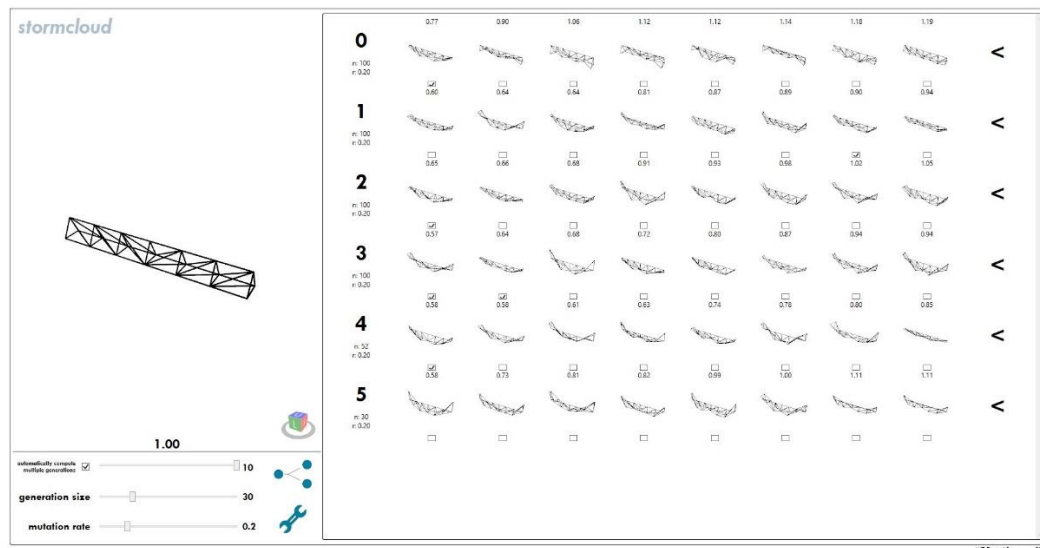


Figure 3: Graphical user interface of *stormcloud* (exploration of the case study developed in 4.1)

4. Case Studies

This section illustrates the applications and benefits of *stormcloud* through several conceptual design case studies. In both case studies, the performance metric is the required structural material volume under a given loading condition. Member sizes are determined to limit stresses to the allowable value and prevent member buckling, modeled using Euler's column buckling formula. Internal forces are calculated using Karamba (Preisinger and Bollinger-Grohmann-Schneider ZT GmbH [6]). While these examples are chosen in the realm of structural design, *stormcloud* can be used for any discipline in architectural design.

4.1. 3D Truss

The truss example developed is defined with a parametric model which includes 8 design variables, controlling the vertical and horizontal positions of the nodes, bound to a specified range. The structure is symmetrical, spans 10 m and is supported at both ends by 3 pin supports. It is subjected to vertical loads applied on all of its unsupported nodes (see Figure 4). A sample of the designs found using *stormcloud* are shown in Figure 5. Diverse performant and unexpected solutions are found, illustrating the intended benefits of the design tool.

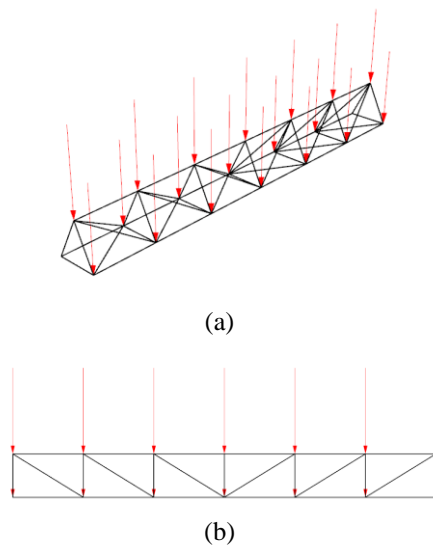


Figure 4: Initial geometry and corresponding loading: perspective (a) and side (b) views

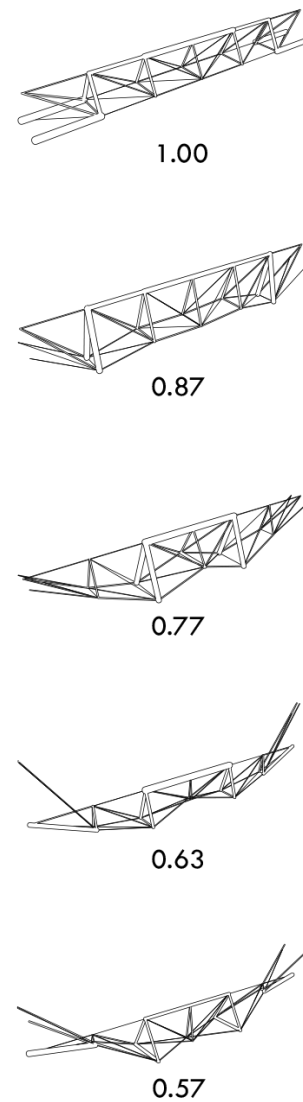


Figure 5: Sample of designs found using *stormcloud* with normalized required volume scores

4.2. Space Frame

The structural system explored here is a three-dimensional truss canopy covering an area of 60 m x 60 m. This case study is inspired by the “Earth Canopy” designed by Feilden Clegg and Atelier One (see **Error! Reference source not found.**6), a timber space frame with a free-form set of bottom chords and upper chords arranged on a flat plane where arrays of solar panels are installed (Atelier One [1]). 9 design variables (see Figure 7) determine the vertical position of the 12 control points – symmetry is enforced - of the bottom surface. The structure generation process is described in Figure 8.



Figure 6 : Earth Canopy, designed by Feilden Clegg and Atelier One (Atelier One 2015)

Parameters

Dimensions

Side Length

Depth

Surfaces: Number of Iso-parametric subsets

U Divisions

V Divisions

Space Truss: Number of Modules

U Divisions Truss

V Divisions Truss

Design Variables
Bottom Surface Control Points Z

Number

Number

Number

Number

Number

Number

Number

Number

Figure 7 : Design parameters (including design variables)

The structure is designed to resist gravity loading which is applied through vertical point loads applied on every node. Since the control points can only move vertically, the tributary area of each node is equal – except for the edge nodes – and the loading condition is realistic (see Figure 9).

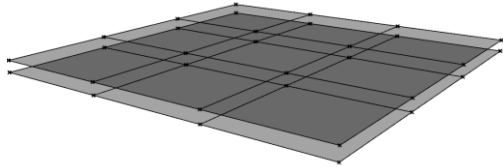
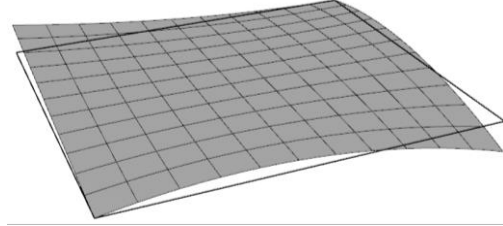
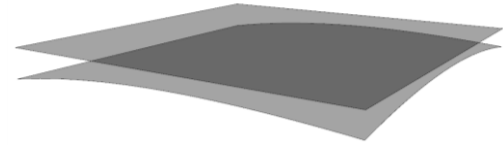
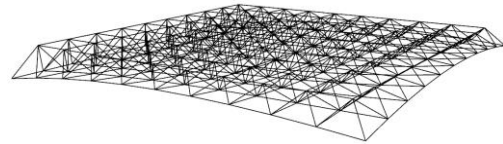
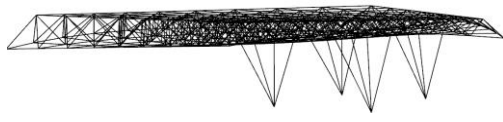
<i>Geometry</i>	<i>Step</i>	<i>Parameters</i>
	rectangular surfaces generation	side length depth
	Bottom surface manipulation through vertical translation of control points	$x_i \in \mathbb{R} \mid -3 \leq x_i \leq 3$ with $i=1,2,\dots,18$
	surfaces used as input for the space truss component	
	lines describing space truss output by component	u divisions truss v divisions truss
	4 supports points are connected with bars to the four closest truss nodes	support points positions

Figure 8: Space truss generation process

While the problem parametrization is limited – node positions are changed indirectly - and will not yield the absolute optimal solution, the design example shows that the tool allows to explore very diverse and expressive forms which are also high-performing (see Figure 10). This case study also illustrates the benefits of the different user interface features implemented. Indeed, given the complexity of the structure, the 3D visualization and selection interactions are necessary to assess designs effectively. In this case, control surfaces governing the truss geometry are visualized to improve legibility. Finally, it

presents the potential of integrating parametric modeling and interactive evolutionary optimization for structural design: a very complex design can easily be explored quickly and result in both performant and creative designs.

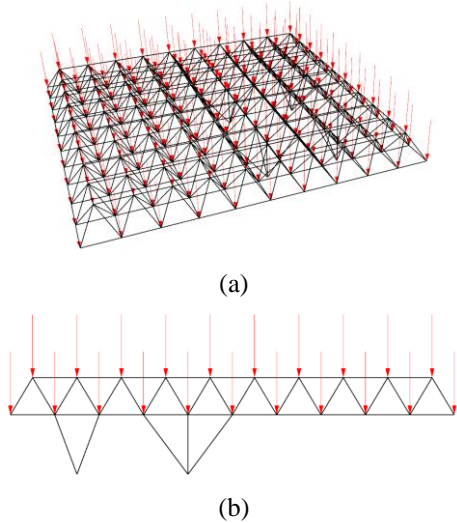


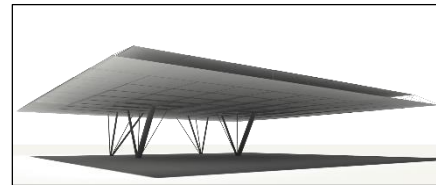
Figure 9: Initial geometry and corresponding loading: perspective (a) and side views (b)

5. Conclusions

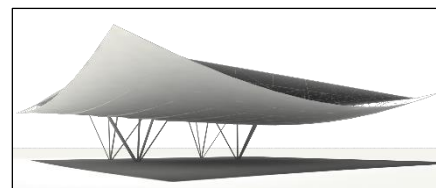
5.1. Discussion

This paper has introduced a new theoretical framework and implemented a tool for linking interactive evolutionary exploration with rich, flexible parametric design models. The implemented tool works in the Rhino/Grasshopper environment, but could also be implemented in other environments, such as Revit/Dynamo (Autodesk [2]), in the future. The tool can accommodate a wide range of structural typologies and geometrical forms in an integrated environment.

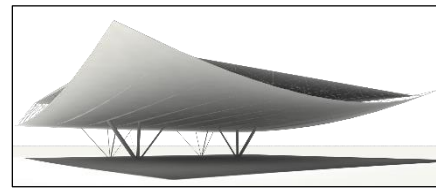
The framework developed in this research has the potential to make designers adopt interactive evolutionary optimization as a performance-oriented methodology for design. Indeed, the framework



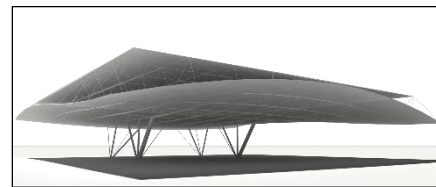
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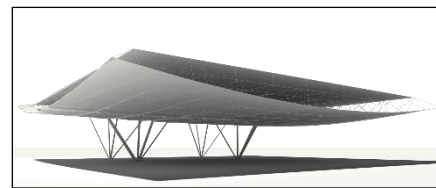
0.70



0.65



0.63



0.62

Figure 10: Sample of designs found using *stormcloud* with normalized required volume scores.

developed not only goes beyond what is available in parametric environments in terms of design space exploration but, for the first time, interactive evolutionary optimization is actually implemented in a widely used environment that has the potential to make the strategy adopted by architects and engineers.

5.2. Future Work

The framework and the tool can be improved in many ways to incorporate more features for increased interactivity and design space exploration. It also must go beyond single-objective optimization to address problems like constructability and be more relevant to the complexity of architectural and structural design. Of course, such developments offers many challenges and opportunities in terms of computational speed, selection, and visualization that need further investigation.

References

- [1] Atelier One. 2015. *Projects - atelier one*. Accessed May 2, 2015. <http://www.atelierone.com/projects/>.
- [2] Autodesk. 2015. *Dynamo BIM*. <http://dynamobim.com/>.
- [3] —. 2015. *Revit*. <http://www.autodesk.com/products/revit-family/overview>.
- [4] Bjorke, Oystein. 2015. *Helix 3D Toolkit*. <https://github.com/helix-toolkit>.
- [5] Block, Philippe, and John Ochsendorf. 2007. "Thrust Network Analysis: a New Methodology for Three-Dimensional Equilibrium." *Journal of the International Association for Shell and Spatial Structures*.
- [6] Preisinger, Clemens, and Bollinger-Grohmann-Schneider ZT GmbH. 2015. *Karamba 3d*. <http://www.karamba3d.com/>.
- [7] Fivet, Corentin, and Denis. 2013. "Constraint-Based Graphic Statics: New Paradigms of Computer-Aided Structural Equilibrium Design." *Journal of the International Association for Shell and Spatial Structures*.
- [8] Killian, Alex, and John Ochsendorf. 2005. "Particle-Spring Systems for Structural Form-Finding." *Journal of the International Association for Shell and Spatial Structures*.
- [9] Microsoft. 2015. *C#/NET*. <https://msdn.microsoft.com/en-us/library/67ef8sbd.aspx>.
- [10] —. 2015. *Windows Presentation Foundation*. <https://msdn.microsoft.com/en-us/library/ms754130%28v=vs.110%29.aspx>.
- [11] Mueller, Caitlin. 2015. *structureFIT*. <http://www.caitlinmueller.com/structurefit/>.
- [12] Mueller, Caitlin, and John Ochsendorf. 2015. "Combining structural performance and designer preferences in evolutionary design space exploration." *Automation in Construction* 52 70-82.
- [13] Rechenraum. 2015. *goat*. <http://www.rechenraum.com/en/goat/overview.html>.
- [14] Robert McNeel & Associates. 2015. *Galapagos*. <http://www.grasshopper3d.com/group/galapagos>.
- [15] —. *Rhinoceros*. <https://www.rhino3d.com/>.
- [16] —. *Grasshopper 3D*. <http://www.grasshopper3d.com/>.

- [17] Scott, Stacey D., Neal Lesh, and Gunnar W. Klau. 2002. "Investigating Human-Computer Optimization." *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. New York, USA. 155-162.
- [18] Turrin, Michela, Peter von Buelow, and Rudi Stouffs. 2011. "Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms." *Advanced Engineering Informatics*.
- [19] Van Mele, Tom, Philippe Block, Claudia Ernst, and Lukas Ballo. 2015. *eQUILIBRIUM*. <http://block.arch.ethz.ch/equilibrium/>
- [20] von Buelow, Peter. 2012. "Paragen: Performative Exploration of Generative Systems." *Journal of the International Association for Shell and Spatial Structures*, December 4.