ENVIRONMENTAL PARAMETRICS 1
HEURISTIC OPTIMIZATION IN DESIGN

ABSTRACT
This paper presents a workflow called the ‘heuristic optimization workflow’ that integrates Octopus, a Multi-Objective Optimization (MOO) engine with Grasshopper3D, a parametric modeling tool, and multiple simulation software. It describes a process that enables the designer to integrate disparate domains via Octopus and complete a feedback loop with the developed interactive, real-time visualization tools. A retrospective design of the Bow Tower in Calgary is used as a test case to study the impact of the developed workflow and tools, as well as the impact of MOO on the performance of the solutions. Seven optimization runs over two different parametric iterations were conducted with the aim of increasing the Floor Area Ratio (FAR) and thus financial profit, average daylight factor, views score, and decreasing the shaded area and the glare produced by the building. The overall workflow makes MOO-based results more accessible to designers and encourages a more interactive ‘heuristic’ exploration of various geometric and topological trajectories. The workflow also reduces design decision uncertainty, design cycle latency through the incorporation of a feedback loop between geometric models and their associated quantitative data and the exploration of trade-offs of multiple solutions all within one platform.
INTRODUCTION

Early stages of the design process require the various stakeholders to define objectives, iterate multiple solutions, evaluate, and analyze these solutions with respect to the pre-defined objectives and make decisions with a high degree of uncertainty based on the information generated (Gerber et al. 2012). In addition, a central challenge for designers is to design buildings which perform on multiple fronts (i.e. which work economically, socially and technically) using what are often conflicting and competing objectives (Maver 1987). Researchers have used Multi-Criteria Design Optimization (MCDO) methods based on Genetic Algorithms (GA) to rapidly generate and evaluate multiple design solutions through domain integration especially in the early stages of design (Shea et al. 2004; Koeugh and Benjamin 2010; Lin and Gerber 2013; Bradner et al. 2014).

Even with the increasing use of MCDO in the building industry, it has yet to be fully embraced as a vital part of the design process (Evins 2013). There are several reasons for the slow assimilation of MCDO tools in design. Designers must visually and analytically compare solutions resulting from MCDO in order to fully evaluate design trade-offs with regards to quantifiable goals, preferences, and constraints (Michalek and Papalambros 2002; Roy et al. 2008; Haymaker and Flager 2009; Cunha et al. 2011; Marsault 2013). Rigorous analysis and comparison of the design solutions using both quantitative and qualitative criteria becomes essential to identify ‘good/sub-optimal’ solutions, therefore improving decision making (Cunha et al. 2011; Turin et al. 2011; Benjamin 2012). Lack of real-time analysis and feedback latency between performance metrics and geometry in MCDO design is another obstacle that exists in the current tools which invariably leaves a significant area of the design solution space unexplored (Haymaker and Flager 2009; Sanguinetti et al. 2010). In a conventional MCDO process, the majority of the designer’s time is spent managing design information in their task specific format and coordinating solutions. Through poorly designed user interfaces and inflexible data exploration and visualization tools, designers have a difficult time understanding the design solution space (Bradner et al. 2014).

This body of research is unique in aiding the designer to explore and evaluate more quickly and efficiently the design solution space in Grasshopper3D (GH). The aim of the research is to explore sub-optimal solutions with their trade-offs—exploring rather than exploiting or aiming to find a singular optimum solution. The ‘heuristic optimization tools’ enable the designer to sort and filter designs based on performance metrics while simultaneously evaluating the formal qualities of those solutions. Qualitative relationships between objectives can be ascertained from a parallel coordinate plot graph and a radar-based chart which help the designer in addition to the graphical aids in Octopus to carry out the sensitivity analysis.

The workflow presented encourages exploration of alternative topological and geometrical trajectories, enhances the early stages of design and domain integration through rapid generation of design alternatives, allows for better understanding of the
correlation between disparate objectives, provides quick visualization of the cause and effect of quantified trade-offs, takes into account the formal qualities as an implicit objective, and reduces overall design latency.

HEURISTIC OPTIMIZATION WORKFLOW

The workflow (Figure 1) was designed through use of existing plugins for Rhinoceros3D: Grasshopper3D for parametric modeling, Octopus for MOO, DIVA for daylight factor analysis and Ladybug for views and glare analysis. Grasshopper3D (GH) was chosen as a platform for flexible, intuitive and integrated modeling, and for the ability for future extension of the workflow. The unique functionality of the semi-automated workflow is the ability to represent, manipulate, sort, filter and compare visually data of the generated design solutions using GH through the use of the developed tools.

The design generation is carried out in GH and performance evaluation in simulation software respectively. Octopus creates a Pareto ranking to identify potentially well-performing solutions. No bias in the objectives is included as part of the optimization search from the outset to produce the widest possible range of solutions for the given design problem. The solution’s quantitative data and 3D geometry is recorded and stored in GH. When the maximum generations are reached or when the designer stops the optimization run, the stored quantitative results can then be exported into a spreadsheet to be subsequently imported into GH using Lunchbox (a Grasshopper3D plugin). The developed tools can then be used to understand the solutions generated along with the 3D mesh solution. The results are displayed in Rhinoceros3D in gallery format (radar charts, parallel coordinate plot graphs, 3D solution space graphs (Pareto graph), ‘form-based’ sorting and, subset and generational searches).
Using the developed tools, an analysis can then be conducted to explore the resultant solution space and fundamentally aid the designer in reaching a decision based on both quantitative and qualitative (formal qualities) analysis. A selection of the satisfactory/pREFERRED solutions by the designer could be further optimized in Octopus by mating them to create more sub-optimal solutions (i.e. ‘optimizing creatively’) or alternatively can be used for design development. The proposed tools are intended to be used by designers at the early stages of design, to integrate MOO with simulation and data visualization tools. The scalability of the workflow is in its ability to be used for any design exploration whether skyscraper design or curtain wall optimization due to the flexibility of GH.

The Bow Tower
The ‘Bow’ Tower in Calgary (Figure 2) designed by Foster and Partners is used as the test case to evaluate the effect of the workflow and to critically examine the influence of the number of objectives on the optimization process. At 236m, the Tower is the tallest structure in Calgary, Canada. Several performative design features exist in the Bow Tower, such as the concave south-facing façade that maximizes daylight exposure and heat gain forming a crescent shaped floor plan (Foster 2013).

A replica of the Bow Tower (Figure 2) was parametrically modeled using GH with the exact realistic plot dimensions, building height, number of floors, orientation of the building and the respective areas of the two main program functions: retail and office. Seven optimization runs were conducted with the aim of increasing the Floor Area Ratio (FAR) and thus financial profit, average daylight factor, views, and decreasing the shaded area and the glare produced by the building. These objectives were chosen because they are relevant to this building and its context. The bias in the choice of evaluating which combinations of objectives was determined based on the sensitivity analysis carried out from the first optimization run, in which directly related and conflicting objectives were identified. Not only that, but these objectives are easy to evaluate at this stage of the design process where the design lacks geometric complexity needed, for example, for structural analysis and optimization. Ultimately though, as in any office tower, the main aim is to maximize spatial efficiency and financial revenue/profit. The same optimization settings such as the mutation rate were used for all optimization runs to ensure consistency across all runs.

The optimization runs are divided into two main categories: three optimization runs using the same parametric setup as the original Bow Tower design consisting of two main arcs joined by two non-tangential arcs and four optimization runs using a slightly different parametric definition of the two main arcs joined by tangential arcs (Figure 3). The objectives used for each optimization run are presented in the table below (Table 1):
The Parametric Model

The financial model is based on the difference between the cost of building the Bow Tower and leasing it on a 25-year lease plan. The profit generated over 25 years is used as an objective and is calculated as per the lease agreement that is between the current owners and the leasing company at a rate of $36 per square foot, at the annual rent escalation of 0.75% of office space (HR Reit 2012). The financial equation used is as follows:

$$\text{Profit generated} = ((x^{*}((1+0.0075)25) + (x^{*}25)) - ((\text{Retail area}*$250) + (\text{Office area}*$325)),$$

Where $x = (\text{gross leasable area}*$36) & gross leasable area = building gross floor area * 0.7

The financial model is adaptable relative to the program types and location, and can accommodate real world profit calculation methods such as net present value and internal rate of return equations.

The views are calculated using a 'view analysis' component in Ladybug that evaluates the visibility of the geometry under test from a set of key viewing points. The surrounding context is modeled accurately in both shape and size to represent the buildings surrounding the Bow Tower. The component evaluates the view objectively in all directions and outputs the percentage of viewpoints seen by the geometry under evaluation. The daylight factor percentage is the average of all the values for the whole building using the DIVA daylight factor analysis component.
The glare points are tested using ‘bounce from surface’ component in Ladybug which turns the test geometry into a specular surface to reflect sunlight vectors. It is necessary to consider glare as parabolic shapes tend to dangerously focus sunlight at certain times of the day. The number of vectors reflected onto the immediate surrounding public spaces either from direct or indirect sunlight reflection is tallied and used as the objective.

The shaded area is calculated using ‘mesh shadow’ component where a shadow is cast onto a ground plane based on projected sunlight vectors. The total area cast by shadow is summed up for the summer equinox from 10 am to 4 pm according to the Calgary Land Bylaws.

**ANALYSIS RESULTS**

**Original Geometric Definition**
The following optimization runs involve the use of the original geometry of the Bow Tower (*Table 1*). The hypothesis is that a larger range of solutions can be generated with the relaxation of objectives (i.e. fewer objectives) which ultimately will lead to better performing design solutions.

<table>
<thead>
<tr>
<th></th>
<th>1st Run_6 Obj.</th>
<th>2nd Run_4 Obj.</th>
<th>3rd Run_3 Obj.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypervolume Indicator</td>
<td>0.22</td>
<td>0.52</td>
<td>0.64</td>
</tr>
<tr>
<td>Generations</td>
<td>41</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Population</td>
<td>3192</td>
<td>2224</td>
<td>2318</td>
</tr>
<tr>
<td>Individual Run Time</td>
<td>19 seconds</td>
<td>12 seconds</td>
<td>10 seconds</td>
</tr>
</tbody>
</table>

*Table 2*
MOO properties of the original Bow Tower optimization runs.

The Hypervolume Indicator (HI) was never able to go beyond 0.22 (1 being the maximum possible value) for the first run (*Table 2*). The HI of the second and third runs reached 0.52 and 0.64 respectively which indicates that the solution space was significantly larger for both compared to the first run. The first part of the hypothesis proved correct, as with the relaxation of the search space (i.e. less objectives), a larger range of solutions was found.
Sensitivity analysis of the solutions shows that there is a direct relationship between FAR, profit and shaded area. There is an inverse relationship between FAR and daylight factor, and an inverse relationship between views and glare, and an unclear correlation between views and glare with the rest of the objectives (Figure 5). These relationships are reiterated in both the second and third runs.

Some of the best overall performing solutions are identified in the 99th percentile of daylight factor of the first run. The formal qualities of the solutions vary, with three solutions out of nine sharing the same elliptical shape of the floor plan, rotated somewhat to both reduce the shaded area and glare while increasing the views (Figure 6).

In the second run, the 90th percentile of profit resulted in lower than average daylight factor, average views and above average shaded area (Figure 7). The formal language is different compared to the same percentile of the first run. There is a larger variation in the formal definition which arguably results in more interesting forms (Figure 8). Upon exploration of the form in the third run, irregular shaped floor plans resulted in higher than normal daylight factor yet poor formal qualities (Figure 9). Overall, the 3D form of the ‘good’ performing solutions share similarities in both shape of the floor plan and orientation to the original Bow Tower design.

**Modified Geometry Definition**
The following optimization runs involved the use of the modified parametric definitions (Table 3). The hypothesis is that a different geometric definition would improve the formal qualities of the solutions as an implicit objective.

<table>
<thead>
<tr>
<th>Hypervolume Indicator</th>
<th>Generations</th>
<th>Population</th>
<th>Individual Run Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4th Run_4 Obj.</td>
<td>0.46</td>
<td>25</td>
<td>1390 seconds</td>
</tr>
<tr>
<td>5th Run_3 Obj.</td>
<td>0.57</td>
<td>25</td>
<td>1335 seconds</td>
</tr>
<tr>
<td>6th Run_2 Obj.</td>
<td>0.94</td>
<td>25</td>
<td>1352 seconds</td>
</tr>
<tr>
<td>7th Run_1 Obj.</td>
<td>1.00</td>
<td>1</td>
<td>100 seconds</td>
</tr>
</tbody>
</table>

Table 2
MOO properties of the modified Bow Tower optimization runs.

The HI for the optimization runs is not greater than second and third runs from the previous iteration. The reduced number of manipulated genes (15 compared to 19) manipulated may have resulted in a lower HI as the possible number of solutions is reduced.

The sensitivity analysis shows that the same relationships exist between the objectives as in the first iteration. The formal qualities appear to be considerably better with this parametric definition and there is a tendency for the solutions to have the same shape.
of the floor plan as the original design of the tower (Figures 10, 11). An elliptically shaped floor plan was a recurrent, as an efficient way to minimize the shaded area and to maximize the views; yet, the profits were significantly lower than in the generated solutions that were similar to the original Tower. There were solutions that performed slightly better than the original Tower but with less profit (Figure 12). The design's concave feature faces south east instead of south west, with improved daylight factor and slightly better views percentage. The views are better score-wise but with this orientation, it does not necessarily mean better views as the building’s concave feature faces away from the mountains.

For the fifth and sixth run, there are a greater number of solutions in the 90th percentile of daylight factor than the fourth run. The concave feature of the building form tended to face south east rather than south west as of the original Bow Tower design. A comprehensive exploration of the solutions shows that this trend is seen throughout the different subsets of the different objectives.

**Comparison Between Original and Modified Geometry**

The use of an already built design helped contextualize MCDO results and identify whether generated solutions are indeed performative improvements or not. The results show that there is no conclusive answer, as in general, some iterations did show improvements and some did not (Table 4). The challenge in improving the performance of what was already an efficient design proved a difficult task for the MOO engine.

For the first run, there were improvements across all objectives, except for the views which remained the same. The second and third runs showed slight improvements in all objectives except profit, which decreased and remained the same for the second and third runs respectively. These results partially prove the hypothesis for the first iteration, which is that the performance of the generated solutions would improve.

*Figure 9* 90th percentile profit of 4th run (4 objectives).

*Figure 10* 90th percentile profit of 5th run (3 objectives).

*Figure 11* Original (red) versus solution ID 254 (blue) (overall performs better than the Bow parametric replica).

*Figure 12* Strange parametrically generated solutions that cannot be used for further design development even if they perform well.
### Table 4
Comparison of Bow Tower optimization runs vs Bow Tower replica (MG: Modified Geometry).

<table>
<thead>
<tr>
<th></th>
<th>Iteration 1 Original Geometry</th>
<th>Iteration 2 Modified Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profit</td>
<td>$269,796,148</td>
<td>4.4%</td>
</tr>
<tr>
<td>Daylight Factor</td>
<td>6.2%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Shaded Area</td>
<td>240770 m²</td>
<td>-12%</td>
</tr>
<tr>
<td>Views</td>
<td>20%</td>
<td>0%</td>
</tr>
<tr>
<td>Glare</td>
<td>429</td>
<td>-20%</td>
</tr>
<tr>
<td>FAR</td>
<td>21.44</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

The fourth run resulted in improved profit and a reduced area covered by cast shadows; the daylight factor, however, was reduced on average by nearly 4%. Profit improved significantly for both the sixth and seventh runs, with the seventh run having the best improvement of all the optimization runs.

There are no parallels in the results between the first iteration and the second iteration, even though there were no significant changes to the base geometry. The results indicate a surprising trend: the more objectives, the better the overall performance of the solutions. It is somewhat counter-intuitive that more objectives would lead to better performing solutions. This is not a conclusive statement as there are multiple domains that are not considered and the forms generated may not be more formally pleasing overall. Not only that, but some solutions may exhibit improved quantitative results yet they cannot be used for further design development as their spatial properties are poor or they would not work well in the given context (Figure 13). Hence, the overall average performance metrics of the optimization runs are only indicative until further extensive exploration is carried out.
ANALYSIS AND DISCUSSION
An important tool that was vital for this research was Octopus, an EA-based open-source MOO engine that works natively in Grasshopper3D. It is one of the many useful tools that are accessible to the design community in the Grasshopper3D ecosystem but the only one that can carry out MOO. With this in mind, other commercial software tools such as modeFrontier, ModelCenter and Optimus do not offer automatic linkage with Grasshopper3D unless the designer codes or programs a plugin that would allow for such a linkage (Keough and Benjamin 2010). Another disadvantage of these robust tools is that they are not readily accessible for most designers. They have a steep learning curve and lack the great support community that exists for Grasshopper3D and its associated plugins such as Octopus.

The developed workflow with its associated tools played a crucial role in identifying multiple issues. The Pareto graph in Octopus does not always show potential errors or deceptive bottlenecks in the optimization runs as a result of the way parametric definitions are setup. Secondly, the sensitivity analysis carried out using the parallel-plot graph highlighted strange or unpredictable relationships and thus made the trade-offs of the solutions on the Pareto graph more understandable.

The change in the geometric definitions expanded the horizon of discovering interesting yet mediocre performing designs. The ability of the developed workflow and tools in helping the designer better understand the limitations of the site and the design proved fruitful. The encouragement of exploring multiple alternative parametric definitions may not necessarily lead to better quantitative results but may lead to more interesting formal qualities, i.e. it could help designers ‘optimize creatively’. The use of optimization tools in design is not to generate the highest performing solution, but rather to gain a better understanding of the design space and to explore alternative formal trajectories if necessary (Bradner et al. 2014).

In order to contextualize the solutions that are to be explored, it is necessary to first exploit and identify the ‘best’ possible solution(s) for a given design. Exploitation and exploration therefore have a symbiotic relationship and even though one of the aims of this research was to encourage exploration of the solution space, exploitation is equally important.

The trial runs of the test case and its variances show that poor parametric definitions can greatly influence the final results. Quick test runs are necessary at first to comprehensively understand how each parametric definition works and, the limitations of each of the parameters and how they correlate. It is therefore essential to predict how a design will perform and within what ranges so not to be tricked by the software with ‘impressive’ results.
During the optimization runs technical difficulties were experienced and resulted in slow runs. This is due to the inability of Grasshopper3D to handle large amounts of data. Thus, part of the setup was to streamline and optimize the parametric definition while limiting the level of detail of the geometry to basic elements to reduce simulation run-time. The effectiveness of the workflow can only be directly compared to ParaGen, which was developed in-house at the University of Michigan (Von Buelow 2011). The software is not available to the general public which hinders the possibility of a real-time operative comparison. The disadvantage of ParaGen’s workflow is in the inability to explore solutions in 3D form unless through a tedious process of exporting a VRML file for each individual solution.

CONCLUSION

The ‘heuristic optimization workflow/tools’ enable qualitative interactions by the inclusion of formal qualities as an implicit objective. The overall process is analogous to the design process itself and in this case, where MOO is used, the design decisions are not solely based on quantifiable metrics such as financial performance. The use of the developed information visualization tools helped make sense of the data generated with the 3D solutions. The tools also aided in prioritizing objectives which helped refine the search and optimization run times.

One of the main goals of this research is to reduce the design cycle latency through the integration of parametric design, MOO, simulation, and feedback loops. By using and tightly integrating off-the-shelf software and by semi-automating the workflow using a common platform, some of the commonly encountered data exchange and interfacing issues were avoided. The exploration of the design solution space, however, increased the design latency which would affect the overall design cycle latency. In other words, design cycle latency was reduced from one perspective but increased from another. A future research trajectory is to explore the impact of the workflow on a hypothetical design case that has ill-defined objectives and geometric parameters using a similar approach to Lin and Gerber (2013).

We believe the potential of the described workflow is significant early in the design development. It can be made more efficient, smart and flexible with additional tools for Grasshopper3D that can be used by practitioners and students. The intent of these tools is to allow designers to explore and evaluate a large number of alternatives quickly through domain integration.
REFERENCES


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Yassin Ashour is currently a Masters student at the University of Calgary, Faculty of Environmental Design. His current research is on introducing new techniques of integrating multi-objective optimization into the architectural design process through the use of information visualization tools to improve the performance of buildings. Before joining the University of Calgary, Yassin worked as a teaching assistant at the British University in Egypt. He acquired his Bachelor’s degree in Architectural Engineering with honors from Loughborough University, UK.

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