

## BUILDING SIMULATION AND EVOLUTIONARY OPTIMIZATION IN THE CONCEPTUAL DESIGN OF A HIGH-PERFORMANCE OFFICE BUILDING

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### ABSTRACT

This paper outlines a digital design and simulation-based process conceived and tested, for the automation of environmentally responsive building ‘forms’, optimized for Energy and Lighting performance. The process sequences 4 different modeling and simulation programs to evaluate energy loads and lighting levels of a typical office building whose forms are ‘generated’ by an automated script running Rhino + Grasshopper, EnergyPlus, MATLAB and RADIANCE. Deployed in a coordinated fashion, the programs automate the delivery of a building’s overall volumetric dimensions, using a Genetic Algorithm and a Single Objective Function. This is the process whose, development, deployment and testing are discussed in this paper.

### INTRODUCTION

#### **Automated Design Workflow Simulations**

This paper outlines a digital design and simulation-based process conceived and tested, by architecture students in the post-professional Masters of Environmental Building Design Program (MEBD) at the University of Pennsylvania, to advance the conceptual design phase of high performance buildings. The process, devised and executed during a three-week capstone studio exercise, consists of a set of protocols for the automation of environmentally responsive building ‘forms’, optimized for Energy and Lighting. The process sequences 4 different modeling and simulation programs to evaluate energy loads and lighting levels for a typical office building whose forms are ‘generated’ by an automated script running Rhino/Grasshopper, EnergyPlus, MATLAB and RADIANCE, simultaneously. Deployed in a coordinated fashion, the programs automate the delivery of a building’s overall volumetric dimensions, optimized for heating, cooling and lighting using a SINGLE OBJECTIVE FUNCTION. In combination with a Genetic Algorithm, ‘generations’ of building forms ‘automatically evolve’ in response to a set of predetermined performance parameters (Yi, Borin et al, 2012).

This is the process whose development, deployment, testing and results are discussed in this paper. ( See Figure 1)

Designing a workflow that architects and engineers could use at the very beginning of their form-finding exercises, for generating initial building volumes with geometric proportions environmentally responsive to the demands of both energy and light, was the goal of this project. Given the limited resources of time and money experienced by all professionals, this automated process promotes the integration of robust simulations at the earliest stages of a building’s development. While it does not replace the value of more detailed high-level whole building energy simulations completed by engineering professionals during design development stages of a project, it does offer a means for developing initial forms, which when transferred to an expert energy modeler, are sufficiently performative to meet a minimum set of benchmarks. This is precisely the synthetic tool sought by many design firms committed to the adoption of whole building energy analysis in the schematic design phase of high performance buildings.

The particularly innovative aspect of the workflow, completed and tested in May 2011, is the combination of 4 parametric 3D modeling tools (Rhino/Grasshopper), with validated simulation engines (EnergyPlus, RADIANCE), and optimization tools/methods (Genetic Algorithms with Objective Functions) in service to an automated evolutionary method. Certainly, other computational means exist for parametrically associating a building’s form to its energy and lighting performance, however, most do not possess the energy sensitive modeling capacity made possible by this particular method.

The subsequent launch of DIVA for Rhino, for example, has enabled the integration of robust lighting analysis using RADIANCE/Daysim within parametric design as well as one zone thermal energy analysis (Jakubiec, et al, 2011). This functionality is a welcome addition to the designer’s toolbox; however, DIVA’s capacity for modeling energy performance of complex parametric forms remains insufficient for the needs of more complicated multi storey and multi zoned high performance projects.

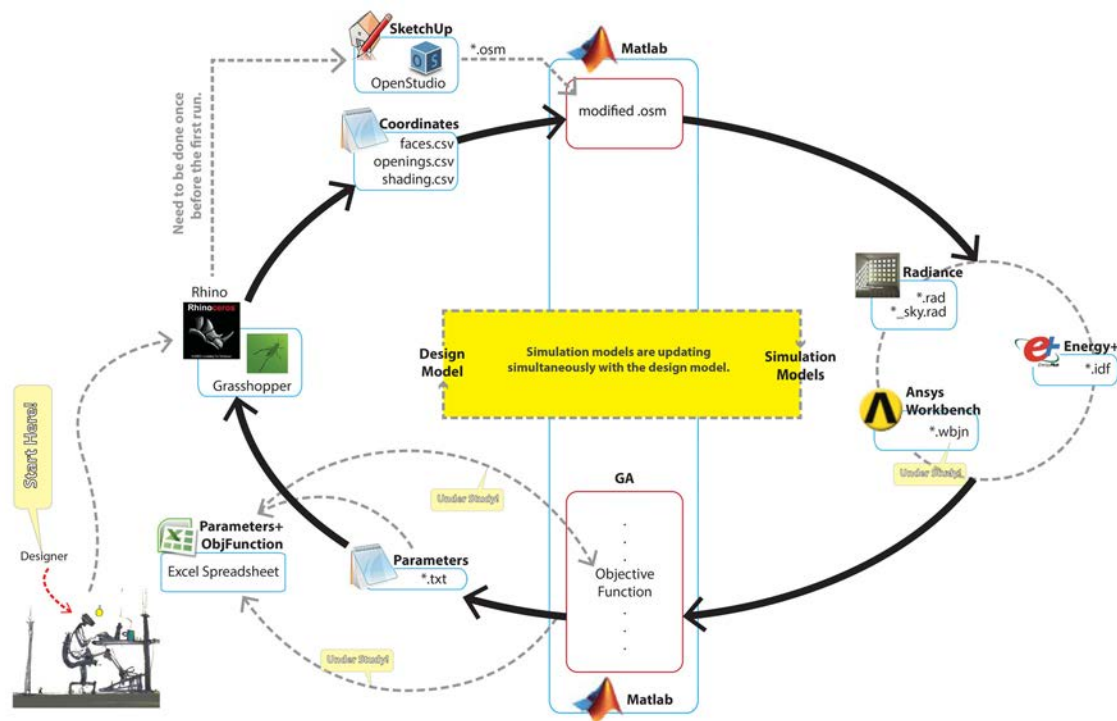


Figure 1 . Workflow Diagram for Automated Optimization

The custom scripting required of the project here described, could not have been subtended within the thermal model capabilities of DIVA.

### Project Brief: High-Performance Office Buildings

The brief tasked participants with more than the mere design of a building. Required was the design of a repeatable and verifiable process for delivering high performance energy efficient buildings. The architectural program consisted of 250,000 square feet of office space, including ground floor retail, for a vacant site in the Philadelphia Navy Yard. The project was originally conceived in the context of the new Energy Efficient Building HUB, a United States Department of Energy funded regional incubator for advancing the market of advanced energy retrofits. Program and site were chosen in alignment with HUB initiatives for achieving 50% reductions in the operation of mid size office buildings in the Mid Atlantic region. And while the building program was based on an expansion of EEBHUB activities, the site was a parcel of land to the east of future EEBHUB headquarters.

To this end, an integrated design process was outlined which foreground the coordinated use of computational tools for achieving the called for levels of performance. To leverage the full spectrum of available modeling tools, the use of digital simulations for solar insolation, shading, energy consumption, lighting design and airflow was promoted. And to maximize the synergistic potential

of a building's program, site, climate, engineering systems, energy consumption and materials, the development of new simulation aided design processes was required.

### Modeling Architectural Atriums using DesignBuilder

Following a rigorous climate based analysis of the site using industry standard weather tools such as Climate Consultant, the team developed the following architectural concept. Building volumes, organized around the introduction of architectural atriums offer significant opportunities for long-term energy savings in the operation of buildings. Atriums typically used for consolidating a building's circulation, can also be used to naturally ventilate a building during the summer, increase solar heat gain during the winter and maximize the amount of light that penetrates through the building's section. Hence, the team's initial modeling concept included the siting of three parallel but separate building blocks on the site, with the resultant two atriums identified as buffer zones for maximizing heat game in the winter and natural ventilation in summer. The atriums were oriented and designed with differing heights to maximize desirable heat gain, while building volumes were given different depths to minimize the effects of cold winter winds from the northwest and to maximize cool summer winds from the southwest. At the level of building details, responsive shading devices were introduced for controlling the solar radiation and diffuse lighting

allowed to penetrate within atrium interiors. For the spring and fall, the atrium was designed with an operable skin to take advantage of natural ventilation, with a specialized curtain wall detailed as part of the overall design.

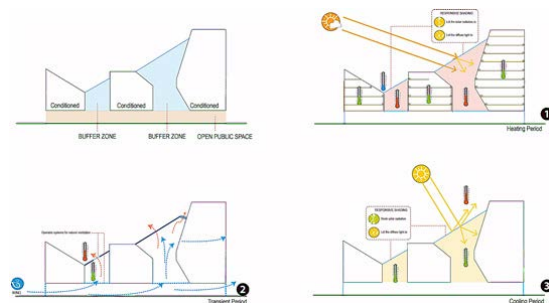


Fig 2. Initial Performance Criteria ( in Section) for 3 Buildings and 2 Atriums

Prior to, and simultaneous with, the running of the detailed 4-program coordinated simulation process described here below, preliminary whole building energy simulations were completed using DesignBuilder to identify overall guidelines for organizing the dimensions of each building and atrium. A base case was defined as a plan configuration of 3 fully conditioned 12.75 meter wide buildings, and 2 fully conditioned atriums, also 12.75 meter wide. Two sets of energy tests were completed; the first, evaluating whether the atrium was more effective for energy performance as a conditioned or unconditioned space; the second, identifying which building plan dimensions were most effective at maximizing energy performance. Against the base case, an unconditioned atrium 12.75 meter wide contributed to a 5.4 % energy reduction. When the dimensional ratio of building to atrium was altered to 16.75 meter and 7.75 meter respectively, with both spaces remaining conditioned, a 3.5 % energy reduction was registered against the base case. And lastly, with the ratio of building to atrium remaining 16.75m /7.75m and the atrium now unconditioned, projected energy consumption was reduced by 10.6%, over the base case.

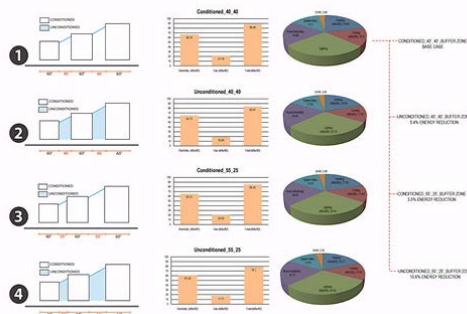


Figure 3. Initial Results of DesignBuilder Simulations

Five additional variables were tested against this final, best performing combination (conditioned buildings at 16.75 meter and unconditioned atriums at 7.75 meter); including availability of shading, type of glazing, type of materials, building occupancy schedule, and green roof designs, with the following energy reductions recorded;

Most striking is the combination of all five variables, which resulted in a 36.9% energy reduction over the initial base case of 12.75 meter wide conditioned buildings and 12.75 meter wide conditioned atriums.

However, given the team's more ambitious goal of identifying the optimized configuration for both building and atrium, this could not be fully achieved using only DesignBuilder because of the complex and interconnected relationship that dimensions have on each other when calculating overall energy performance. Assuming projects with more variegated and complex sectional profiles for achieving maximum airflow and light penetration, DesignBuilder is incapable of calculating the simultaneous effect of deploying more than 10 variables in evaluating energy performance. As such, an automated and reiterative computational process was designed for more robustly evaluating the hundreds of possible combinations of building to atrium dimensions. This necessitated the rejection of more typical trial and error methods, for the adoption of a highly detailed multi-variable evolutionary algorithm capable of computing a critical path to the most optimal energy performance.

## SIMULATION

### Workflow of an Evolutionary Algorithm ( Steps 1 to 4 )

Five programs and four steps were required to formulate the evolutionary computational algorithm used in this design project. ( see Figure 1)

#### Step 1 – Generating the parametric model using Rhinoceros and Grasshopper

The initial step involved generating a parametric model using architectural modeling software in which the geometric dimensions of the three buildings and two atriums were codified for computational purposes. Albeit, the overall width of the site, within which the 3 buildings and 2 atriums were to be located, was fixed, variables labeled 'A' through 'K' were parametrically defined as geometric points whose final location the energy performance optimization process would secure. Each of the points identified a critical location in either of the 3 buildings or 2 atriums. ( see Figure 4).

Table 1 - Initial DesignBuilder Results					
	Office Building Info		Atrium Info		Energy Results
	Dimensions (m)	Conditioned	Dimensions (m)	Conditioned	
Sim 1 - BASE CASE	12.75	Yes	12.75	Yes	
Sim 2 - Atrium Unconditioned	12.75	Yes	12.75	No	-5.40%
Sim 3 - Dimensional Changes	16.75	Yes	7.75	Yes	-3.50%
Sim 4 - Dim. Change and Atrium Unconditioned	16.75	Yes	7.75	No	-10.60%
Sim 5 - Sim 4 with Shading Strategy	16.75	Yes	7.75	No	-11.20%
Sim 6 - Sim 4 with Glazing Strategy	16.75	Yes	7.75	No	-10.80%
Sim 7 - Sim 4 with Materials Strategy	16.75	Yes	7.75	No	-15.30%
Sim 8 - Sim 4 with Scheduling Strategy	16.75	Yes	7.75	No	-31.50%
Sim 9 - Sim 4 with Green Roof Strategy	16.75	Yes	7.75	No	-10.70%
Sim 10 - Sim 4 + Sim 5-9 combined strategies	16.75	Yes	7.75	No	-36.90%

Table 1 - Initial Design Builder Results

- A. Roof angle of building #1 relative to atrium #1
- B. Roof angle of building #2 relative to atrium #2
- C. Roof angle of building #3 relative to atrium #2
- D. Vertical angle between the ground and building #3
- E. Width of atrium #1 ( at the ground)
- F. Width of atrium #2 ( at the ground)
- G. Width of atrium #1 ( at the roof )
- H. Width of atrium #2 ( at the roof)
- I. Difference in length between building #3 and #2
- J. Difference in length between building #2 and #1

Additional to the above Geometric parameters, the following material and lighting parameters were also included;

- K. Glazing percentage on each Building face
- L. Size, spacing and angle of Shading for each Atrium

## Step 2 – Parametric alignment of geometry, light and energy

The second step involved associating the parametric model produced in Rhinoceros/ Grasshopper with the energy modeling capacity of EnergyPlus, the lighting analysis operations of RADIANCE, as well as with the technical computing capabilities of MATLAB. To this end, a highly customized method was developed in which the following steps were followed;

- a) The first step was to identify a number of geometric points (coordinates) for each of the variables “A” through “L”, that would be the same in an architectural model, an energy simulation model and a lighting model.

- b) To this end, an energy model was built in OpenStudio and a lighting model was built in RADIANCE with the exact same coordinates as the architectural design model .
- c) Thereafter, the coordinates of the architectural model were exported as a list from Grasshopper to a text file .
- d) Subsequently, MATLAB was used to replace the number based coordinates on the list, with names. Such as for example, point 0, 0, 0 was renamed Point1\_X, Point1\_Y, Point1\_Z and so on. This renaming of the coordinates was only required once in the process.
- e) In so doing, the energy and lighting models were both parametrically bound to the list of architectural coordinates produced by Grasshopper. And this connecting of models was also only required once in the process.
- f) However, in order to track any geometric changes that may occur in the Grasshopper list, another script was developed in MATLAB that re-writes the parameterized energy and lighting files should the list of geometric points change. This script is repeatedly used in the process of simulation/optimization every time the location of a variable changes its coordinates. In this way a loop has been created between the architectural model and the simulation models. Anytime a parameter is changed in Grasshopper, a new list of coordinates is exported and the MATLAB script runs new energy and lighting models to evaluate the altered geometry.
- g) However, in the steps outlined above, the process has not yet been designed to include optimization.

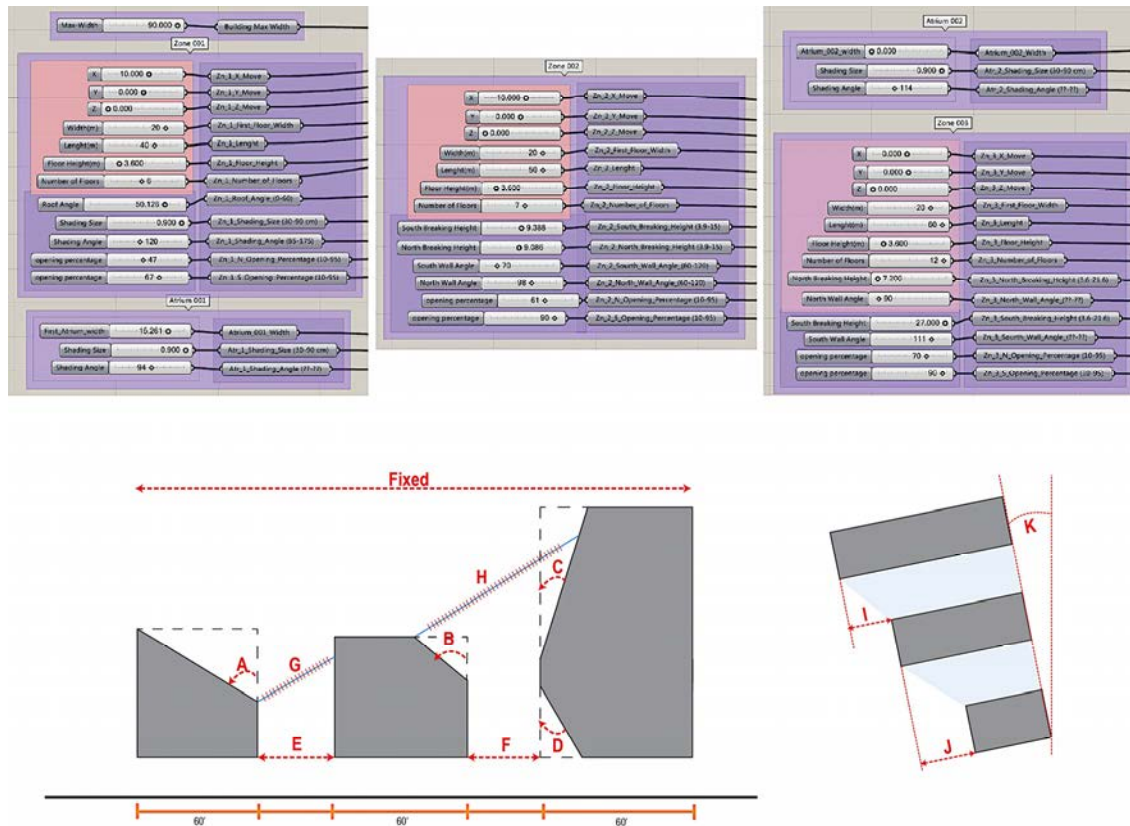


Figure 4 . Identification of the Parameters

Regarding the use of MATLAB, this was the technical computing platform, which in May 2011 was the best suited to completing the operations. It read the coordinates delivered from Grasshopper, generated the EnergyPlus and RADIANCE files, executed the simulations, incorporated the set of parameters identified by the Genetic Algorithm, offered results for the whole “generation”, ran the optimization, and exported the needed parameters for the next generation of simulations. At the moment, however, other means exist for doing the same, as it is fairly easy to setup a similar process when using a multiple objective optimization algorithm.

### Step 3 – Integrating the Genetic Algorithm (and running the Objective Function).

The third step in the development of this process, involved activating a method for “evaluating” the results produced by the automation sequence just described. Given the parametrically associated relationship between a building’s geometry, and it’s energy and lighting performance, the MATLAB sequence was susceptible of generating a near infinite number of possible responses to the question of high performance.

In order to create “value” within the script’s generative capacity, the identification of select

performance criteria was required in order to organize the possible variations of coordinates “A” through “L”. This involved the introduction of a Genetic Algorithm, a main stay of computing intelligence, which when deployed within a computational process initiates a set of interrogative functions that resemble nature’s own evolutionary processes. Genetic Algorithms (GAs) are typically used to ‘generate’ optimal solutions to stated problems in mathematics, engineering, and physics. And in matters of architectural design, they are typically introduced in the search for optimized formal responses to a set of given performance goals. (Jones , 2009)

The original computational sequence which connected the building’s geometry to its combined energy and daylighting performance was augmented with the introduction of a Genetic Algorithm, from the *Genetic Algorithm Toolbox for use with MATLAB®*. Its introduction was tasked with ‘generating’ a series of geometric coordinates which over time – were “bred” to be most responsive to the following combined criteria:

- maintaining to a minimum the building’s annual heating load
- maintaining at a minimum the building’s annual cooling load



- ensuring an average lighting level at the first floor of all buildings between 300 and 800 lux.

This set of prescriptive yet highly interrelated design targets defined the algorithm's Objective Function; the set of computational requirements towards which the algorithm sought optimization.

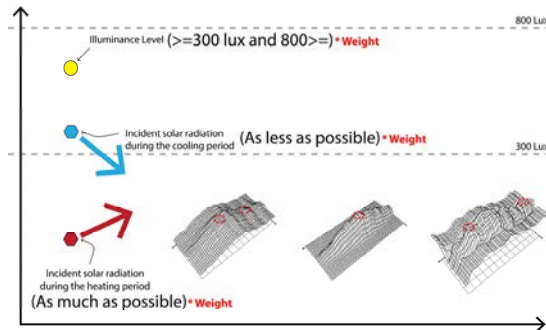


Figure 5. Single Objective Function

To this end, the Genetic Algorithm resulted in 'generations' of formal families descriptive of 3 office buildings and 2 atriums according to the following methods;

1. To begin with, 15 different building designs were devised using a particular combination of parameters ("A" to "L"). The aim of whose selection was to ensure that the 15 resultant buildings were as different as possible from each other, and as such representing the widest range of formal possibilities. The particular combination of values for each of the parameters is generated by the MATLAB script that generate a series of numbers between minimum and maximum values for each of the parameters, referred to as a uniform random distribution.
2. In the language of GAs, this collection of 20 buildings is referred to as a 'Generation', and each building within a Generation, an Individual.
3. Once the 15 Individual (buildings) are generated, their coordinates are run through parametrically associated energy and lighting platforms, and their results gathered and ranked for "Fitness" to the Objective Function; that is, according to their simulated levels of performance.
4. Once the ranked list of 15 simulation results is complete, the GA selects the best Individuals in a process called (Selection), a binary method, which randomly interrogates two Individuals and compares them to each other; the better Individual going on to the next generation.
5. The creation of the next Generation is called (Breeding), (in which A to L parameters are recombined) based on the assumption that the next (second) generation of 15 buildings will perform better than the previous because they are offspring (Child), whose mixed parameters (Genes) come from already better high performance Parents.
6. This new collection of offspring is once more evaluated for its energy and lighting performance and the results ranked as previously mentioned.
7. The process continues until the optimization algorithm generates the desired number of Generations.

#### Step 4 – Evaluating the Results

The final steps in the Algorithm involve returning to the architectural model and re-generating new values for the parameters based on previous optimization results. When the initial set of simulations are run for the first 15 Individuals (1<sup>st</sup> Generation), the Genetic Algorithm summarizes the results, evaluates them and generates a new set of coordinates. This new set of coordinates will be read back into Grasshopper to generate the new Generations to be simulated and evaluated in a similar way.

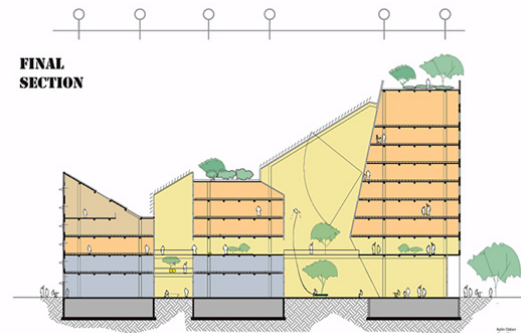


Figure 6. Final Section (3 Buildings + 2 Atriums)

## ANALYSIS OF RESULTS

### Convergence

The entire Simulation process can be brought to an end in one of two ways. More arbitrarily, one can stop the process by choosing a priori a number of Generations for the script to run – in our case 12 Generations were run. Alternatively, the process of optimization can be stopped when the targeted design objective, encoded in the Objective Function, is achieved. Simulation results are said to Converge when future "generations" do not improve on the performance targets of the Objective Function. At the moment of Convergence, the GA has found the best combination of Genes (values for parameters A to L).

Convergence, did occur during our process, albeit for a local and not a global minima. (See Figure 8) On the one hand, the Objective values over the final 3

Generations, 10, 11 and 12 are effectively the same and the average objective value for the last generation is almost the same as the best option. These results can lead us to conclude that the solution is partially converged, having found the best possible

results for this particular set of simulation runs (local minima). However, this does not imply that the GA found the most optimal solution for a larger set of criteria (global minima). The GA only converged for

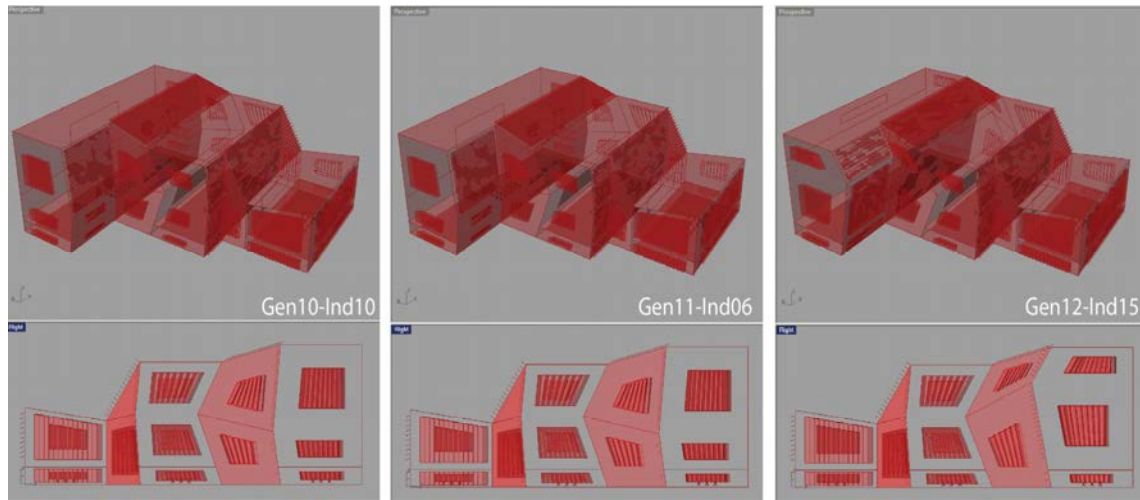


Figure 7. Best Individuals from Generations 10, 11 and 12

this particular run and it is assumed that better options exist for which this optimization method would need to be run multiple times.

For Figure 8 – The Y axis shows the Objective value resulting from this calculation:

% Daylighting objective value

Lighting\_ObjV = ((average illuminance - 200)^2)/2

if 150 <= average illuminance <= 250 then

Lighting\_ObjV = Lighting\_ObjV/2;

% Cooling\_ObjV

Cooling\_ObjV = Cooling Load

% Heating\_ObjV

Heating\_ObjV = HeatingLoad

%Solar heat gain during heating period

SummerGain\_ObjV = Radiation during the summer period

% Solar heat gain during cooling period

WinterGain\_ObjV = -Radiation during the winter period

% Total ObjV

ObjV = Lighting\_ObjV /100 + 2 \* Cooling\_ObjV +  
2 \* Heating\_ObjV + SummerGain\_ObjV/2 +  
WinterGain\_ObjV/2

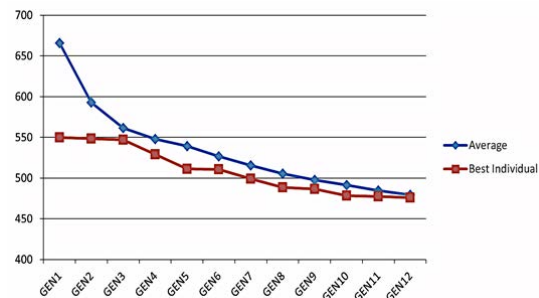


Fig 8. Objective Value Results from the GA over 12 Generations

### Energy Performance

As previously noted, and visible in Figure 8, the final 3 Generations converged with the following performance results. Against an initial Base Case, the optimized final 3 Generations demonstrate an average of 28% reduction in the total energy load. Option 3 is of particular interest; given a 10% increase of its Heating Load, because of its 55% better performance in Cooling, its combined Energy Reduction remains 29% over the Base Case.

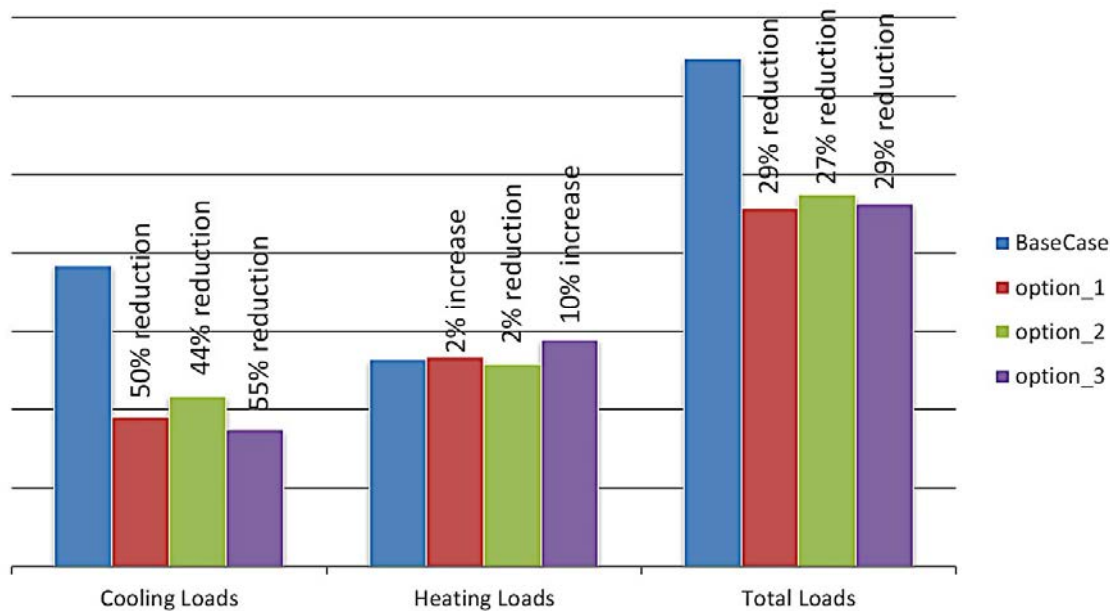


Fig 9. Heating, cooling and total loads Comparison between the base case, and the three best options

## CONCLUSIONS

This paper has described an automated work flow process which can be used to optimize the operations of a Genetic Algorithm that generates formal possibilities for a set of building forms and their adjacent atriums, calibrated against an Objective Function, that has integrated energy and lighting performance.

In conclusion, a set of observations are herein offered regarding the selection of parameters, the definition of Objective Functions, the degree to which the Energy model subtending the algorithm is validated, the computing infrastructure required for such a workflow, and lastly, how Algorithms can best integrate the analysis of qualitative objectives.

### Choosing Parameters

Selecting the initial parameters - as in ours labeled A to L - that most conclusively contribute to the measurement of a building's energy performance requires some consideration. Given the design concept of our particular project, which involved the overall dimensioning of 3 buildings and 2 contiguous atriums, choosing parameters related to the size and orientation of key boundary planes was assumed to be the most effective. In the process of running the optimized genetic algorithm, should any of the chosen parameters have had only minor effects on the performance of the building, such parameters would have been rejected and neglected during the Breeding and Selection process.

Being able to reduce the total number of active parameters whose values require computing is important for reasons of efficiency. Having too many reduces the speed and productivity of the algorithm, having too few assumes too general a set of behaviors. Decidedly, the fewer the number of parameters, the sooner the algorithm's solution will Converge. To this end, a worthwhile approach is to run sensitivity studies prior to running the entire algorithm, in order to assess which of the parameters have the greatest effect on performance results. Having these high priority parameters identified, others of lesser consequence can be fixed as constant for computing purposes.

### Single vs Multiple Objective Functions

When the project was first run in May 2011, a single objective function was used to evaluate the performance of each building for heating loads, cooling loads and daylighting. This offered certain limitations which can be overcome when using a multi-objective evolutionary algorithm. Design is, by definition, a multi-objective problem. Simplifying all its objectives into one single objective, is not easy or recommended. Multiple-objective optimization provides a variety of optimized solutions which offers the designer an opportunity to explore different design solutions in the process of taking a final decision.

### Validated Energy Model for the Atrium's Behavior

The initial energy model should be a validated model. In the case of this paper, due to the limited amount of time available for developing the full



sequence of the workflow, little time was dedicated to completing a validated energy model. Because of the complex performance of the atrium, being partly conditioned and partly unconditioned, a detailed study of the airflow would have been useful. As such, the energy modeling would have required greater accuracy and more substantial CFD modeling, being able to account for extreme conditions such as the atrium's exposure to excessive amounts of radiation. However, given the project's primary goal, which was the proof of concept of a particular integrated design workflow, the variability of the energy modeling was deemed less important to the conclusions of whether the genetic algorithm resulted in a convergent solution.

### Computing Infrastructure

Initiating the optimization of genetic algorithms with single or multiple objective functions requires a significant amount of computing power. In the case of this project, the use of a single CPU to run all of the studies proved to be a hindrance to the process. It slowed down the automation and discouraged the running of more iterations. The use of Cloud computing can in fact decrease the calculation time and increase the opportunity for conducting more simultaneous studies. (Sadeghipour Roudsari et al , 2012)

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### REFERENCES

- Jakubiec, Alstan and Reinhart, Christopher. "Diva 2.0: Integrating Daylight And Thermal Simulations Using Rhinoceros 3d, Daysim And Energyplus" in Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.
- Jones, Nathaniel Louis. Master of Architecture Thesis, May 2009, Cornell University, "Architecture as a Complex Adaptive System." The use of Genetic Algorithms in design optimization.
- Sadeghipour Roudsari, Mostapha, Yi, Yun Kyu, Drew, Christopher. "Applying Climate-Based Daylight Modeling for a Macro Scale Master Plan Design; Case study: The Great City in China." In Proceedings of the 1st Asia conference of International Building

Performance Simulation Association Held in Shanghai, China Nov25-27 2012.

Yi, Yun, Borin, Joung. "Agent-Based Geometry Optimization with Genetic Algorithm (GA) for Daylighting", In Proceedings of the 1st Asia conference of International Building Performance Simulation Association Held in Shanghai, China Nov 25-27, 2012.

Yi, Yun Kyu, Malkawi, Ali. "Site-Specific Optimal Energy Form Generation Based on Hierarchical Geometry Relation," In: Automation in Construction, Elsevier, Vol 26 77-91 2012.

Additional script authored Sadeghipour Roudsari – LadyBug Plug in –  
(<http://www.grasshopper3d.com/group/ladybug>)

Additional Grasshopper Scripts: Galapagos  
(<http://www.grasshopper3d.com/group/galapagos>).

Octopus for a multi –objective evolutionary algorithm  
(<http://www.grasshopper3d.com/group/octopus>).

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