Informed Parameterization:
Optimization of building openings generation

VASCO PORTUGAL¹, MANUEL CORREIA GUEDES²

¹ MIT PP— Sustainable Energy Systems, IST, UTL, Lisbon, Portugal
² Departamento de Engenharia Civil, Arquitectura e Georrecursos, Instituto Superior Técnico, UTL, Lisbon, Portugal

ABSTRACT: This paper presents a methodology for parametric design that embeds knowledge from building simulation tools. Current parametric design delivers different solutions throughout the modeling and design process, but in the final stage, it does not allow users to distinguish the optimal solution to develop or how to integrate those solutions into current design process. This paper demonstrates a design strategy for parametric design that embeds knowledge from simulation tools and generates an informed creative process. A specific case study being develop under de Zero + project of the MIT architectural robotics Lab is presented as an example. This approach proposes a performance based exploration of an array of parametric design alternatives (variables) linked with simulation and performance evaluation tools, and combines the results of the performance simulation software with optimization algorithms, to pick solutions for subsequent exploration.

Keywords: Optimization in Design; Genetic Algorithms; Parametric Models; Simulation Software; Building Performance.

INTRODUCTION
The current needs to improve the performance of buildings are leading to the creation of solutions that allow the outline of strategies and carry out of simulations which enable designers to evaluate the performance of digital designs of the buildings. The problem is that current software in general work based on trial error approaches, what reveals to be counterproductive. The search scope is so large that probing for an optimal solution becomes a demanding and time-consuming process, what generally does not justify the outcome.

The principle of developing buildings that are truly effective cannot be just a matter of saving energy. This same performance must also be linked to future occupants, contributing positively to the health and well-being as well. Natural light is not just a case of a desired amenity based on preferences, in fact there are questions of emotional health and comfort [1]. According to the U.S Energy Information Administration (EIA), lighting, cooling and heating are now responsible for the greatest amounts of energy consumption in the building sector [2].

Consequently, we must search for the variables that produce the highest impacts in terms of natural light exposure and energy performance in a perimeter zone. Windows are responsible for a wide spectrum of issues related to the technical performance of an individual zone. These issues, among others, are the focal point of this research study. The window has a relevant role on managing the interaction between exterior and interior conditions, it is responsible for providing adequate daylight, creating a visually stimulating and healthful interior environment, as well as reducing overall energy consumption of buildings. This study intends to address and optimize this relation by allowing the control of its parameters. This subsequently generates a large assortment of design solutions with a wide range of performances. In the analysis of such scope, a stochastic method as the genetic algorithm (GA) process of searching is an efficient technique to explore different design options. There are several previous publications which have proved the potential use of genetic algorithms applied to building design decisions. For example, [3] uses genetic algorithms to evaluate Computational Fluid Dynamics (CFD) in design solutions. Cases of optimal form building [4] and closer to our object [5] and [6] that reconfigure windows openings based on algorithm genetics evaluations to DOE-2 [7] analysis. Yet much of these publications have limitations that we intend to overcome with this new method. Most of these studies developed very specific solutions that cannot dissociate from the contexts and geometry that are under review, thus limiting its applicability. If one wants to do a similar analysis, it would need to reprogram all the methodology related to the technical performance of an individual zone.
applied to its particular requirements. Even if there was access to the code that engendered the results, it would need to master the programing language to change the parameters and adjust them to the user needs.

Thus, the proposed method seeks to address these limitations by merging the geometry under analysis within a framework were, Rhino, Grasshopper, DIVA and Galapagos, are linked into one combined work environment. The aim is to ensure a new design process that can provide immediate quality feedback on building performance, in order to assist the decision making process.

**GENETIC ALGORITHM**

Design problems usually require an analysis with a strong non-linear character. Results in design analysis derive from a fairly large number of preceding parameters, where classical methods do not offer the necessary guarantees for a satisfactory result. Stochastic optimization techniques such as genetic algorithms can be the perfect solution to the problem, as they facilitate the search of a far greater range of solutions to a problem without major costs in terms of time, calculation and complexity.

Usually search algorithms are centered on inquiry of possible solutions by an exhaustive exploration in the default search space. The concept of genetic algorithm transfers the theory of natural evolution to the field of optimization, imitating in a virtual environment a fast forward analogy of the mechanism of evolution in nature. This approach was first introduced by John Holland [8], as a system to solve problems that mimics the process of evolution and natural selection among species. In order to perform a multidirectional search, this process maintains an open collection of solutions (individuals). These subjects are presented as the chromosomes that are in turn composed of genes which represent all the parameters of interest of each individual. Thus the algorithm makes a screening of the fittest individuals, those who present the worst results die according to a pre-defined fitness criterion. The evolution of subsequent generations is controlled by the genetic operators, reproduction, crossover and mutation.

Subsequently these operators conceive a new generation. They reproduce depending on the individual performance of each chromosome. Crossover is the breeding between two randomly selected individuals from the fittest population, and mutation seeks to look for random parameters outside the previously defined population to reproduce, expanding the search scope and quest for potential lost optimums.

**METHODOLOGY**

The aim of the present study is a two-fold: 1) determine the applicability of a genetic algorithm for the optimization of windows on custom-built perimeter zone. 2) Develop a coherent method that can be applied in different digital models and take advantage of parametric features, considering multiplicity in the design process.

The methodology presented in this paper uses a Rhinoceros plugin called Grasshopper as it allows us to work with each variable parametrically. Grasshopper is a graphical algorithm plug-in for Rhino which allows parametric modeling and scripting (McNell 2010). We use its interface to test all the combinations over a search space of multiple dimensions and to create our own custom components in C# programming language.

It uses GA as the evolution algorithm and DIVA for Grasshopper as the evaluation mechanism. The DIVA plugin supports a series of performance evaluations by using validated tools including Radiance and Daysim (Lagios, et al., 2010). DIVA was chosen so that all modeling and daylighting simulations could be carried out within Grasshopper.

The model runs recursively till the best windows for a determined perimeter area are identified. This eliminates the need for the user to specify, design and design an opening each time an output is required.

This evolutionary design approach creates discrete instances of designs that satisfy the performance targets by providing larger search space for designers to interact with through the integration of GA, Energy and daylighting analysis. To implement the model, a formal representation of the problem was specified. This included a statement of goals (performance requirements) design decisions for achieving those goals, and a mathematical description of any requirements that the design must satisfy. Design decisions are examined against goals using DIVA analysis (Energy and daylighting) software.
The analysis model takes values of design decisions and variable parameters as input, and returns corresponding values of performance as output where GA will drive the search for an optimal solution and the Grasshopper work environment will allow visualizing how the search is evolving. The model is implemented to allow three-dimensional orthogonal geometries to be presented. The initial geometry is executed in the rhinoceros CAD environment a NURBS-based 3-D modeling tool, developed by Robert McNeel and Associates, and then imported inside the grasshopper as a BREP (A solid represented as a collection of connected surface elements). The user then must identify the wall surface where the windows will be located. Following the recognition of these surfaces, the tool automatically generates a grid of points (Fig. 2a) that will be the genes that when compounded in combination of four points create the chromosomes subsequently subjected to an analysis in DIVA and optimized by fitness function running through GA.

Results of the comprehensive research dealing with this optimization process are presented over some already defined shape. Instead of form-finding we are trying to find the best geometry and topology of a set of openings in a structure. The proposed method when compared with previous studies in GA optimization shows a higher degree of flexibility as it is capable of analyzing any digital model, only showing limitations when dealing with organic surfaces without a clear world plan. It is difficult to translate geometry into variables to optimize, to overcome this challenge and smooth the computer processing, this method condenses the number of controlling variables and the complexity of the “individuals” under analysis in the GA.

It is defined by two ‘control’ points and two ‘child’ points automatically outlined by the position of the control points. When the control point moves from the position $a^1(x,y,z)$ to position $a^2(x,y,z)$, that movement also changes the positions of its child points. This method (fig. 2b) allows creating the window form without deforming its shape and with little control points rather than multiple individual points. Two control points are necessary.

Figure 1: Workflow diagram.

Figure 2: (a) Creating a list of points on the surface subject to integrate an opening (b) Select two control points that

(c)
generate the two dependent child points \( a, b, a^1, b^1 = \) window opening. (c) The wall thickness is also a flexible parameter, defined by an offset of the curve in the negative \( z \) axis of the world plan of the working wall surface.

The control point \( a^1(x,y,z) \) and \( b^1(x,y,z) \) are used to define the position of the correspondent two child points, and the four are the points that generate the window under analysis. The child points are located away from the control points with a fixed displacement:

- Control 1 = \((ax, ay, az)\)
- Control 2 = \((bx, by, bz)\)
- Child point 1 = \((bx, ay, az)\)
- Child point 2 = \((ax, by, bz)\)

The window is then computed by subtracting the curve generated by the connection of the 4 created points to the defined surface wall. The wall thickness is also a flexible parameter, defined by an offset of the curve in the negative \( z \) axis of the world plan of the working wall surface (fig.2c). The design representations are specified as a set of variables and parameters. The variable and parameter sets form the genetic elements of the design and define the shape of the design instances. Variables are design attributes that affect design behavior and are varied to find values that best satisfy the evaluation criteria. The term parameter is used to describe other design attributes that also affect design behavior but are assigned fixed values that are not varied during the optimization. The space is evaluated for minimizing energy consumption without sacrificing daylight autonomy for the occupied zone.

### Table 1: Selected materials values.

<table>
<thead>
<tr>
<th>Components</th>
<th>Reflectance</th>
<th>R-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor/Slab</td>
<td>20%</td>
<td>12</td>
</tr>
<tr>
<td>External Walls</td>
<td>50%</td>
<td>12</td>
</tr>
<tr>
<td>Roof</td>
<td>80%</td>
<td>20</td>
</tr>
<tr>
<td>Adiabatic Walls</td>
<td>50%</td>
<td>--</td>
</tr>
</tbody>
</table>

CASE STUDY

The case study for this analysis is a Fireman’s Dormitory for Somerville Fire Department; it is one of the pilot projects from an MIT initiative called Zero+ that is developing a fabrication logic that uses thermoplastic panels applied to construction, and this research is currently being refined through prototyping and pilot projects at the MIT Robotic Lab headed by Prof Mark Goulthorpe. A part of the research is to also develop a software for those who want to design and optimize their own buildings; in either case, the ‘output’ is essentially to provide digital instruction to numeric command machines to allow for the direct and automated fabrication of structural thermoplastic panels that will subsequently be attached together to form a highly integrated structural building enclosure. For the purposes of this study we will focus only in one of the rooms of the building.

The research and experiment is based on the use parametric tools and custom coding and linking of these tools to simulate and evaluate a real world conditions like daylight and energy loads. Through background literature review and survey we have not found an existing tool and methodology able to optimize efficiently the complex interaction proposed.

Figure 3: Proposed design for the Fireman’s Dormitory for Somerville Fire Department.

The location is in Somerville, MA (42° N, 71° W). To obtain the lighting and energy simulations we used a weather file with equivalent meteorological conditions to our site, the Boston Logan International Airport AP 725,090 (TMY3). The wall surfaces that will receive the windows are facing west, double glazed with 0.45 of \( U \)-value, Solar Heat Gain Coefficient (SHGC) and visible transmittance (VT). The perimeter area is 3.56 meters wide 4.57 meters deep 2.65 meters high with a pitched roof with 4.90 meters high from the floor and an inclination of 50°. For this test we estimated a schedule of occupied hours from 8AM to 6PM.

Then within the algorithm, the windows variables are connected to the daylighting analysis component, DIVA for Grasshopper version 2.0 which uses Radiance as the daylighting calculation engine. Results are passed simultaneously to an evaluation function of the
algorithm to calculate daylight autonomy. Daylight Autonomy (DA) is an annual daylight metric, commonly referred to as ‘dynamic daylight metric’. It is represented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level [9] [10]. These values are filtered based on the Illuminating Engineering Society of North America (IESNA) recommendations for illuminance levels in residential spaces which range from 300 lux to 1500 lux, depending on the type of tasks (IES North America 2000). The algorithm then evaluates how much nodes are within the desired illuminance range (300-1500 lux). All values are then sent to the genetic algorithm. These values are then sorted in a descending order. The target of the optimization is to bring at least 60% of the 20 sensors placed at 0.5 meters from the floor, into the defined range for acceptable luminous environment. After we extract the values of the nodes inside the space; Considering the 20 sensors and the 60% threshold the minimum acceptable scheme must have at least 12 sensors within the desired range. Anything below this figure is considered negligible.

The thermal simulations are performed using a DIVA component called VIPER, this component runs thermal analyses from Grasshopper using EnergyPlus, a simulation engine developed by the U.S. Department of Energy. It can provide several outputs but for this exercise is programed to calculate heating and cooling loads according to the parameters determined by each individual chromosome. The fitness function is set to minimize these calculations, what subsequently pursues the most efficient solution.

CONCLUSION
The paper presented a new methodology for integrating parametric features and simulation tools in the design decision process. The focus of the analysis is intentionally simplified in order to streamline the understanding of the results and calculation. The case study clearly indicates the potential of developing a system to manage the simulation and evaluation of building digital models during the conceptual design stage of the project. It allowed the consideration of a larger scope of possible design solutions without extra work or need to reprogram the software. This is a pertinent step towards the integration of performance analysis in earlier stages of design.

This same methodology can be adjusted to diverse contexts and objectives and there are several other outputs which can be obtained within the process of performance analysis of each one of the design variants. The fitness function can also be adapted for either minimize or maximize the objectives. Further work should focus on calculation of several zones at the same time, incorporation of additional objectives in the fitness function and especially improve the interactivity with the user by leaving space for a further informed design exploration after the GA results.

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