UNIVERSIDADE FEDERAL DO PARANÁ

ALEXANDRE BESSA MARTINS ALVES

PARAMETRIC PERFORMANCE-BASED DESIGN FOR CONSTRUCTION: FAÇADE ELEMENTS ENHANCING DAYLIGHTING

CURITIBA

2020

ALEXANDRE BESSA MARTINS ALVES

PARAMETRIC PERFORMANCE-BASED DESIGN FOR CONSTRUCTION: FAÇADE ELEMENTS ENHANCING DAYLIGHTING

Tese apresentada como requisito parcial para a obtenção do título de Doutor em Engenharia Civil, Setor de Tecnologia, Universidade Federal do Paraná.

Orientador: Prof. Dr. Aloísio Leoni Schmid.

CURITIBA

2020

DADOS INTERNACIONAIS DE CATALOGAÇÃO NA PUBLICAÇÃO (CIP)
UNIVERSIDADE FEDERAL DO PARANÁ
SISTEMA DE BIBLIOTECAS – BIBLIOTECA CIÊNCIA E TECNOLOGIA

Alves, Alexandre Bessa Martins
Parametric performance-based design for construction: façade elements enhancing daylighting / Alexandre Bessa Martins Alves. – Curitiba, 2020.
1 recurso on-line : PDF.

Tese (Doutorado) – Universidade Federal do Paraná, Setor de Tecnologia, Programa de Pós-Graduação em Engenharia Civil.
Orientador: Prof. Dr. Aloísio Leoni Schmid

1. Iluminação natural. 2. Algorítimos genéticos. 3. Engenharia de Construção Civil. I. Schmid, Aloísio Leoni. II. Universidade Federal do Paraná. III. Programa de Pós-Graduação Engenharia Civil. IV. Título.

Bibliotecária: Roseny Rivelini Morciani CRB-9/1585

MINISTÉRIO DA EDUCAÇÃO
SETOR DE TECNOLOGIA
UNIVERSIDADE FEDERAL DO PARANÁ
PRÓ-REITORIA DE PESQUISA E PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO ENGENHARIA DE
CONSTRUÇÃO CIVIL - 40001016049P2

TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em ENGENHARIA DE CONSTRUÇÃO CIVIL da Universidade Federal do Paraná foram convocados para realizar a arguição da tese de Doutorado de **ALEXANDRE BESSA MARTINS ALVES** intitulada: **PARAMETRIC PERFOMANCE-BASED DESIGN FOR CONSTRUCTION: FAÇADE ELEMENTS ENHANCING DAYLIGHTING**, sob orientação do Prof. Dr. ALOÍSIO LEONI SCHMID, que após terem inquirido o aluno e realizada a avaliação do trabalho, são de parecer pela sua aprovação no rito de defesa.
A outorga do título de doutor está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

CURITIBA, 28 de Agosto de 2020.

ALOÍSIO LEONI SCHMID
Presidente da Banca Examinadora

Bruno Massara Rocha
BRUNO MASSARA ROCHA
Avaliador Externo (UNIVERSIDADE FEDERAL DO ESPÍRITO SANTO)

ANDREW MARSH
Avaliador Externo (NÃO INFORMADO)

SÉRGIO SCHEER
Avaliador Interno (UNIVERSIDADE FEDERAL DO PARANÁ)

ACKNOWLEDGEMENTS

I would like to express my gratitude to the Federal University of Paraná, for the opportunity to continuously learn and build cientific knowledge. Special thanks to the Undergraduate Program in Construction Civil Engineering, faculty members, staff, and colleagues.

I want to thank CAPES for funding a scholarship during this time, and the international agreement CAPES/COFECUB for funding the exchange in French territory within the *Institut National des Sciences Appliquées – INSA, Toulouse.*

I would like to thank prof. Dr. Aloísio Leoni Schmid, friend and supervisor who guided me throughout the whole process (eight years considering master's degree and Ph.D.) giving me freedom to seek my own paths within the research, always supporting and arguing the decisions. Thanks also to prof. Dr. Marcelo Errera, cosupervisor, always with a motivational and intriguing advise, showing new paths to the research and several contributions to the work. Both professors were responsibles for the foreign experience in France, I am grateful.

Thanks to to my supervisors in France, Prof. Dr. Sylvie Lorente and Prof. Dr. Mathieu Labat. Brilliant and curious minds which I could adquire concepts and experiences applied to this thesis.

I want to register my appreciation with the committee members, Prof. Dr. Bruno Massara, Prof. Dr. Sergio Scheer e Dr. Andrew Marsch, for the analysis and commentaries about this work. The ideias, methods and strategies generated in the academic debates are extremely relevant for building the basis to our society. I wish I keep working improving knowledge and putting ideas in practice.

Special thanks to Luciana Bandeira, my wife and professional colleague. Still, my parents, supporters and encouragers of my whole life. My family and dear friends.

AGRADECIMENTOS

Agradeço à Universidade Federal do Paraná, pela oportunidade ofertada para o aprendizado contínuo e a construção do conhecimento com a pesquisa científica. Em especial, agradeço ao Programa de Pós Graduação em Engenharia de Construção Civil, seu corpo docente, servidores e colegas de doutorado.

Agradecimento à CAPES, pelo financimaneto de uma bolsa de doutorado durante este período, e ao programa CAPES/COFECUB pelo financiamento dos estudos durante o intercâmbio em território francês junto ao Institut National des Sciences Appliquées – INSA, Toulouse.

Agradecimentos ao meu amigo e orientador prof. Dr. Aloisio Leoni Schmid que me guiou ao longo de todo o processo (que já vai a mais de oito anos, contando mestrado e doutorado), dando liberdade para achar os caminhos da pesquisa, e sempre orientando e discutindo as decisões tomadas. Agradecimento ao prof. Dr. Marcelo Errera, coorientador, sempre com um conselho motivador e instigante, mostrando novos caminhos da pesquisa e várias contribuições pertinentes a este trabalho. Agradecimento ainda a estes dois professores pela oportunidade do intercâmbio e toda a experiência adquirida no exterior.

Agradecimento ainda à prof.ª Dr;ª Sylvie Lorente e ao prof. Dr. Matthieu Labat, supervisores do intercâmbio no INSA. Mentes brilhantes e curiosas junto às quais pude desenvolver várias experiências aplicadas nesta tese.

Deixar registrada minha satisfação com a participação dos membros da banca, Prof. Dr. Bruno Massara, Prof. Dr. Sergio Scheer e Dr. Andrew Marsch, pelos importantes comentários e análises do trabalho. A discussão de ideias, métodos e processos que são geradas nos debates do meio acadêmico são de extrema importância pra a construção das nossas profissões e de toda a nossa sociedade. O meu desejo é continuar trabalhando para contribuir com a construção de ideias, construção de conhecimento e de colocá-las em prática.

Agradecimento especial a minha querida companheira de vida e de profissão, Luciana Bandeira de Oliveira. Agradeço aos meus queridos pais, apoiadores, torcedores e incentivadores de toda a vida, aos familiares e amigos queridos.

RESUMO

Desde os anos 90, teorias sobre a evolução começaram a se tornar mais frequente como forma de estudar o design de elementos naturais e artificias de uma forma interdisciplinar. O entendimento de como a natreza gera formas vivas e inanimadas permitiu que os processos de projeto imitiassem ou simulação um processo evolutivo de design em coisas desenvolvidas pelo ser humano, como processos, sistemas, configurações e objetos, ou seja, artefatos. Este trabalho pretende discutir como o *design* evolutivo pode melhorar o desempenho de edifícios. Para detalhar e explorar este tema, o escopo é focado no problema da iluminação natural baseada em desempenho. Através da linguagem visual de programação, este trabalho busca elaborar um esquema que trata de otimizar sistemas modulares de sombreamento de fachadas, buscando potencializar o desempenho quanto à iluminação natural. O método consiste em condicionar uma geometria a funções associativas, estabelecendo parâmetros, métricas de desempenho quanto a iluminação natural, simulação de performance e otimização por meio de algoritmo genético. A intenção é criar um código flexível e genérico que possa ser aplicado para desenhar diferentes elementos de fachada, variando a orientação, a geometria dos elementos e os materiais. O elemento construtivo explorado aqui é o cobogó, um elemento vazado que permite ventilação natural, sombreamento e distribuição da luz solar quando aplicado numa fachada. Esse elemento é uma típica solução da arquitetura brasileira. Os cobogós irão melhorados em termos de Exposição Solar Anual (ESA), coeficiente de distribuição de iluminância (CDI) e economia de material. A abordagem prática desta pesquisa é discutida no contexto do projeto arquitetônico, do paradigma da *Design Science Research* (*DSR*), *design* evolutivo, desenho e modelagem paramétrica, gramática da forma, *design thinking* e Lei Constructal. O objetivo é criar um códico como artefato, que permita uma multiplicidade de possibilidades em plataforma validada de simulação. Os resultados demonstraram que o desenho tradicional do cobogó já é uma boa solução de sombreamento de fachadas quando comparado a outras soluções típicas. E através dos estudos, o artefato apresentado aqui pode melhorar o desempenho do cobogó em até 6,6% em termos de distribuição da iluminância. Diferentes graus de liberdade são estudados aqui, aumentando a possibilidade de novos *designs* serem testados. O processo de design evolutivo é também analisado, e seus parâmetros são avaliados quanto aos requisitos de performance de suas configurações. O uso do Radiance junto com o Daysim para realizar a simulação anual impôs limitações na tarefa de buscar objetos otimizados, pois a resolução do modelo para captar pequenas mudanças na geometria deveria utilizar outros métodos para resentar a distribuição da luz de forma mais precisa. Esta conclusão é discutida ao final deste trabalho.

Palavras-chave: Iluminação natural, elementos de fachada, cobogó, linguagem de programação visual, projeto paramétrico, algoritmo genético, modelo evolutivo.

ABSTRACT

Since the 1990's theories of evolution in the design of natural and artificial things start to become clearer as an interdisciplinary way of thinking in the development of things. Understanding how nature shapes animate and inanimate things allowed design processes to imitate and simulate the evolutionary process in the design of human-made processes, systems, configurations, and objects, i. e. artifacts. This work aims to discuss how evolutionary design may enhance the performance of buildings. The scope focuses on the daylighting performance-based design problem in detail and explores this theme. Through the visual programming language, this work looks for a schema that deals with optimal modular shading elements and seeks to enhance daylighting performance. The method consists of conditioning the geometry to associative functions, setting the parameters, establishing the daylighting metrics, simulating the performance, and optimizing it through a genetic algorithm. The intention is to create a generic and flexible script that can be applied to the task of designing different façade elements by varying orientations, the geometry of the elements, and the materials. The building element explored here is the *cobogó*, a hollowed element that allows natural ventilation, shading, and natural light distribution when applied to façades. It is a typical solution for Brazilian tropical architecture. The c*obogós* will be improved in terms of shading performance (ASE), luminous distribution (UDI), and economy of material. The practical approach of this research is discussed in the context of architectural design, Design Science Research (DSR) paradigm, evolutionary design, parametric design, shape grammar, design thinking, and Constructal Law, and has the aim of building a script as an artifact that allows a multiplicity of possibilities in a validated platform. Results have shown that the traditional design of the cobogó is already a good solution to be applied in façades if compared with other solutions. Additionally, the artifact presented here improved the performance of these elements by 6.6 % in terms of illuminance distribution when the script is applied. Different degrees of freedom are studied here, enhancing the possibility of new designs to be tested. Evolutionary design is studied, and as it is intended to support designs that search for performance requirements, some exploration of its parameters is also explored. The use of Radiance with Daysim to perform annual analysis imposed limitations in the task of searching for optimized objects since the resolution needed for daylight simulations to capture small changes in the geometry requires the use of more refined methods to represent the light distribution correctly. This is addressed at the end of this work.

Keywords: Daylighting, façade elements, cobogó, visual programming language, parametric design, genetic algorithm, evolutionary design.

RESUMO EXPANDIDO

Neste trabalho, apresentado em língua estrangeira por incentivo do Programa de Pós-Graduação da UFPR e, que também é uma sequência de intercâmbio de um ano realizado junto ao Instituto de Ciências Aplicadas de Toulouse, França através do Programa CAPES-COFECUB, o objetivo é estudar como os modelos paramétricos e sua lógica de processo podem influenciar no melhor desempenho de edifícios. O recorte da pesquisa é para o campo da iluminação natural.

Além da importante necessidade de se pensar os edifícios quanto a questões de orientação, distribuição da geometria e da relação com contexto urbano em busca de edifícios mais inteligentes e integrados com o contexto, elementos construtivos de menor escala têm, da mesma forma, potencial de contribuir para melhorar a performance da iluminação natural em edifícios. Ao mesmo tempo em que são representativos da paisagem construída, seja ela urbana ou não.

Neste trabalho o elemento escolhido é o cobogó. Este elemento tem longa tradição na história da arquitetura moderna e contemporânea brasileira. É também um elemento construtivo presente em grandes obras da arquitetura e, ao mesmo tempo, distribuído por diversas construções vernáculas. A modularização deste elemento potencializa sua pré-fabricação, contribuindo de antemão para uma produção racionalizada e mais limpa. Além disso, ele pode tanto ser produzido de forma escalada atendendo às demandas mercadológicas por produtos de baixo custo, quanto mesmo de forma mais individualizada e adaptada a uma situação específica, já que as novas tecnologias de fabricação auxiliadas por computador tendem a facilitar esse tipo de processo.

A intenção deste trabalho é a discussão sobre as potencialidades e a viabilidade da aplicação deste tipo de método durante o desenvolvimento do projeto ou do elemento de fachada em si, e

não um cobogó otimizado como resultado. O método aplicado é o script associativo, ou modelo paramétrico, criado a partir da linguagem de programação visual. O modelo associativo será avaliado através de algoritmo genético quanto aos requisitos de iluminação, insolação direta e economia de material.

Todos estes conceitos são pontuados e contextualizados durante o texto deste trabalho assim como as condicionantes que compõe o método. Uma parte introdutória compõe os capítulos de 1 a 4, falando do contexto da pesquisa, do tratamento da iluminação natural na arquitetura, as representações e métodos de cálculo para iluminação natural, a interpretação das formas para o ambiente da programação visual e o paradigma de pensamento em projeto paramétrico, além do modelo paramétrico sujeito ao algoritmo genético. No capítulo 5, a estrutura do método é apresentada e as ferramentas utilizadas são detalhadas, enquanto que o capítulo 6 apresenta os resultados e discussões do trabalho. Finalizando com uma discussão mais ampla nas conclusões, onde também são sugeridos temas para trabalhos futuros e aprofundamentos desta pesquisa.

Este trabalho é fundamentado em técnicas de simulação computacional e buscou utilizar plataformas validadas e amplamente utilizadas em outros trabalhos científicos similares que são apresentados ao longo da revisão bibliográfica. A base da modelagem tridimensional acontece no programa Rhinoceros 3D em conjunto com o plug-in Grassshopper, nativo nesta versão do software, onde a modelagem é então baseada na linguagem de programa visual e torna-se associativa/ paramétrica. Este conjunto permite flexibilidade de forma e desenho aos elementos estudados. As simulações de iluminação acontecem no Radiance, software validado e amplamente utilizado para fins profissionais e acadêmicos, assim como no Daysim, para simulações anuais baseadas em dados climáticos. Ao longo do trabalho essas ferramentas são devidamente detalhadas.

Como o trabalho foi desenvolvido na Universidde Federal do Paraná, a cidade escolhida para validar o uso do artefato é a cidade de Curitiba, capital do estado do Paraná. Os resultados deste trabalho demonstram que o formato mais simples e comum na paisagem urbana, que aqui é chamado de o cobogó padrão (the standard cobogó) apresenta excelentes resultados como elemento de proteção solar e de distribuição da iluminação no interior dos ambientes construídos. Ele é comparado aqui a outras soluções padrão aplicadas a fachadas de edifícios, como janelas comuns, fachada envidraçada, brises comerciais, e prateleira de luz. O cobogó teve um bom desempenho se comparado a estas outras situações. O cobogó padrão é também testado em função de outras orientações, e se mostra uma solução consistente quando aplicado em diferentes fachadas, se demonstrando um elemento construtivo versátil, que pode manter uma unidade estética na composição de fachadas em edifícios e ter um bom desempenho na relação proteção solar x distribuição da iluminação.

Neste trabalho, diferentes graus de liberdade para a adaptação da forma dos cobogós são definidas e chamadas de graus de adaptação (degrees of adaptation)*. Um primeiro grau de adaptação se refere a mudanças nas proporções da topologia inicial; um segundo grau de adaptação se refere a acrescentar ao anterior a possibilidade de distorção do perímetro interior do cobogó; e um terceiro permitindo uma distorção tridimensional das peças.*

O esquema paramétrico e suas possibilidades de geração de formas associado ao uso do algoritmo genético também é explorado e relatado, sendo o foco principal desta tese. O dimensionamento de uma população inicial e alguns critérios para conduzir uma simulação evolutiva com o uso deste artefato são aqui discutidos. O uso do algoritmo genético com fins de otimizar o desempenho destes elementos se mostrou uma ferramenta com potencial, visto que o cobogó já apresentou bons resultados iniciais quanto ao aproveitamento da iluminação natural.

A técnica de modelo evolutivo tem sido aplicada a algumas décadas no campo da arquitetura, em pesquisas acadêmicas e na produção de edifícios icônicos, como explorado durante o trabalho. Associar as propriedades de geração de formas inovadoras com a análise da performance dessas formas, a fim de buscar soluções otimizadas dentro de um contexto, é uma possibilidade que vai de encontro com as necessidades de edifícios mais eficientes e com melhor aproveitamento dos recursos naturais, dessa forma, este trabalho tenta explorar esse potencial permitido pelas ferramentas e conceitos através dos modelos evolutivos.

Os resultados demonstraram que o cobogó pode ter seu desempenho melhorado em até 6,6 % para distribuição da iluminação no ambiente quando sujeitado ao processo de projeto evolutivo, se compaado a solução padrão de cobogó. Porém, o uso da simulação computacional com Radiance e Daysim para o estudo anual da iluminância no ambiente impôs certas limitações quando utilizado com geometrias pequenas fazendo a transição entre a porção externa e interna da cena, como uma veneziana ou um cobogó. Para uma representação ainda mais refinada da distribuição luminosa e da percepção de pequenas modificações nas formas dos cobogós, métodos de simulação em fases podem ser considerados em futuros trabalhos. Esses métodos têm sido desenvolvidos nos últimos anos e aplicados de maneira mais efetiva no Radiance mais recentemente.

LIST OF FIGURES

LIST OF TABLES

SUMMARY

1. INTRODUCTION

Throughout years of evolution, nature has been shaping all the things we see regardless they are natural, artificial, animate, or inanimate (BEJAN and LORENTE, 2008). Nature is the environment where these things are subjected to certain conditions and stimuli, and where they interact with other things and elements. Natural or artificial things also have their properties that describe what they are and how they might change when subjected to the environment or to other elements. This is a process of evolution, a process of evolutionary design of things. Understanding the processes through which natural things are transformed allows us to describe the essence of the design in things.

Designing is an act of nature, which for years drives the evolution of things in time. However, designing is also a human act, where one works driven by an unwitting goal to develop things or ideas that are inexistent in nature but are subjected to it as well. Both designing processes, of natural and artificial elements, are subjected to the same universal laws. Thus analyzing, describing, and teaching about the design of things and how they are conceived in nature or by man-made is a matter of science. Yet, to distinguish both, man-made things are usually referred to as artifacts (Simon, 1996).

To design things with a scientific approach, it is first required to identify the essential features that even inadvertently will guide the design evolution process. Therefore, three main ideas must be kept in mind to design: the first is to have precise goals and objectives for the development of an artifact; the second is to understand, describe, and simulate the outer environment which will rule the behavior of this artifact; and finally to understand, describe, and simulate the artifact internal behavior which is the structure that defines its essence and will respond to the outer environment through its internal relationships (Simon, 1996).

The design of plants, animals, landscapes, hydrographic basins, and soils can orderly be represented by relationships and as a living system they are, they evolve in time. Bejan and Lorente (2008) describe the design in nature by one law, the Constructal Law of design. This law states that the design of things in nature must allow easier and easier access to a certain current (of energy, flux, ideas) in time, i.e. minimizing hindrances, and keeping living systems alive. In their own words:

> *For a finite-size flow system to persist in time (to live), its configuration must change in time such that it provides easier and easier access to its currents (fluid, energy, species, etc.) (BEJAN and LORENTE, 2008).*

The design of artificial things or man-made things, considering it through time, like in living systems in nature, tend to also let the current flow easier in order to live (Bejan, 1996; Bejan, et al., 2014; Lorente, et al., 2012; Errera, 2018). Therefore, predicting the design of things is a matter of identifying these flows and explore how they shape and structure this particular system in an evolutionary path (Reis, 2011).

In nature, the variability of systems and phenotypes, for animate or inanimate things, contributes to the equilibrium of the ecosystems and may represent experimentation done by nature. Each species has its internal structures, size, and shape, even if subjected to the same conditions in the same environment, for instance, like the whole variability of species we can find in a coral reef. What is interesting is that nature does not set an optimal design as a general rule to all systems, if it happened every living specie would have the same size, shape, and structure. Nature works with evolutionary design to keep systems alive considering its internal organization, the outer environment, and the necessity to keep systems alive (BEJAN and LORENTE, 2008).

Understanding, describing, and designing with these ideas propose us working with complexity and dealing with different answers to similar problems. When studying or generating the design of things based on evolutionary principles, it is thus necessary to describe and correlate the environment, the internal structure, and the goals in known domains and tools.

In parallel with a wider theory of morphogenesis, thirty years of work among computers and evolutionary architectural design are described in Frazer (1995) where the logic of working with topological changes in the computational environment to achieve evolved models is discussed. Among translating topology generation to computer language, creating correlations between these topologies with shape grammar concepts (Stiny & Gips, 1972), and generating designs from that correlations in time with evolutionary architecture, Frazer's work explores the concepts, tools, and potentialities of designing with computers that are present until today[1]. Computer logics have helped model creation to be responsive and they converged as associated techniques to explore evolutionary design.

When working with responsive modeling, defining what variables to work with will define the whole model's structure. Designing with parameters, i.e. parametric design, is a designing process in which geometrical and topological changes, in a model, become effortless. Therefore, it replaces singularity with multiplicity in the designing process (Barrios Hernandez, 2006). The parametric design is also defined as setting and adjusting the parameters of a model through mathematical equations to rule a geometry. These mathematical equations may be also subjected to physical phenomena like, in the building context, structural conditions (Turrin, et al., 2011; Gan, et al., 2019), energy-saving requirements (Qingsong & Fukuda, 2016; Gan, et al., 2019) or daylighting performance (Kirimtat, et al., 2019; Yi, 2019; Caldas & Santos, 2016;

---

[1] An additional understanding about translate building components to computer logics is expressed in (Mitchell, 2008).

Cunningham, et al., 2014), in the final stages of design or in the early stages (Membrini, et al., 2014) when major impact in the quality of the building is achieved with a low resource spenditure. Therefore, parametric design becomes a parametric performance-based design that requires additional and interdisciplinary input data to reach better and better solutions in time.

Designing is inherently a parametric process (Gerber, 2007). However, setting up the parameters to work automatically, generating options, and consequently obtaining better designs requires nontraditional tools and methods that are nowadays available through the evolution of computation applied to construction, the so-called Computer-Aided Design (CAD) software. On the other hand, parametric design is more about an attitude of the mind than any particular software. It is a way of thinking that seeks to express and explore relationships (Woodbury, 2010).

Mastering the design process with the parametric design thinking means that the designer no longer solves a static model, but rather keeps looking for relationships between parts of a model, and creates a hierarchy with flexibility allowing future changes in the model.

Many authors have applied parametric design to enhance daylight in buildings, and these works show us that mixing parametric design with daylighting control is an attractive direction for research and improvement of building performance (Eltaweel & Su, 2017; Ekici, et al., 2019). It must be remembered that designing bioclimatic solutions for buildings using natural resources is something that has been made for decades. Even so, the addition of parametric tools is now a possibility to enhance bioclimatic aspects of contemporary buildings and explore complex integrated design solutions. Although some authors believe that parametric design, as a process of creating and evaluating design solutions, is a trend that will overcome traditional processes of design (Oxman, 2017), it came to increase the quality of designs and to add flexibility to the design process.

In this work, evolutionary design is discussed and presented as a possibility to improve daylight performance in buildings. The context is within the design thinking, parametric modeling, shape grammar, artificial science theory and Constructal Law, computer simulations, and genetic algorithms. Following this thought, the question addressed here is how we may build evolutionary performance-based schemata that may generate solutions for improving performance in buildings. The internal spaces are daylit through the building envelope elements and its composition of openings, opaque surfaces, shading devices, and solar orientation. Therefore, how may an evolutionary parametric-performance based design applied to façade elements improve the daylight performance of buildings?

The objective of this work is to propose and evaluate a parametric schema for designing performance-based façade elements that improve daylight performance.

The façade element that was chosen to study is the *cobogó*, a modular cast-made element that shades the façade at the same time it allows natural ventilation. It is an iconic building element of the Brazilian modern architecture and it is widespread from vernacular to institutional buildings in Brazil. The application of evolutionary design for this element has the intention to contribute to optimized solutions for different cobogós shapes and different façade orientations or locations.

In the subsequent section, the purposes and the approach adopted in this work will be presented, and the strategy of this research will be explained.

1.1. RESEARCH STRATEGY

The objective of this work is to propose and evaluate a parametric schema for designing performance-based façade elements that enhance daylighting. This objective is contextualized and justified by the theories of natural and artificial systems (Holland, 1992), evolutionary architecture (Frazer, 1995), artificial science (Simon, 1996), and Constructal Law (Bejan, 1997; Bejan & Lorente, 2008), all complementary theories among themselves that emerged in the 1990s and that are the basis to evolutionary models and designs for applications in academia today.

The theoretical basis was considered from that point to today's researches, to understand the whole theory of evolutionary design for animate, inanimate, and man-made things. All this contextualization has here the cutout of the daylight performance in buildings.

The professional practice of architectural design usually contemplates sundry of complementary conditions to subject the design, like the historical context of the site, cultural aspects, social impact of design decisions, landscape views, construction restrictions, materials restrictions, legal constraints, the efficiency of solutions, aesthetics concerns, costs, maintenance, etc. Many of these restrictions are objective but many are subjective as well. For clarity purpose, a heuristics was assumed to conduct and exemplify the concepts and discussions introduced before. And instead of proposing a whole building development for daylight performance, the intention is to focus on a daylighting problem related to façade elements.

Some researchers have been recently applying the Design Science Research (DSR) paradigm (Dresch, et al., 2015) to deal with design problems as science. Even if some similarities may be pointed out between the case study and DSR, last one aims at developing things, also named artifacts. Artifacts are identified as man-made things that stand for a purpose and show evidence of being human artifices. Simon (1996) would call it the science of the artificial.

> *"Engineering, medicine, business, architecture, and painting are concerned not with the necessary but with the contingent not with how things are but with how they might be in short, with design. The possibility of creating a science or sciences of design is*

> *exactly as great as the possibility of creating any science of the artificial. The two possibilities stand or fall together." (Simon, 1996)*

Moreover, like any scientific approach, it needs academic accuracy, methodological rigor, the possibility of debate, and verification of results and conclusions. Additionally, the research steps and the research conditions had to be carefully described and the process of development becomes a basis for further or complementary works to other researchers. Therefore, an artifact is everything that is developed by the human being to solve problems or accomplish requirements.

Instead of analyzing and describing a phenomenon, the DSR method meets the requirements of design-related disciplines, like industrial design, graphic design, medicine, management, architecture, or engineering. The objectives are solutions to problems by modification or creation of systems.

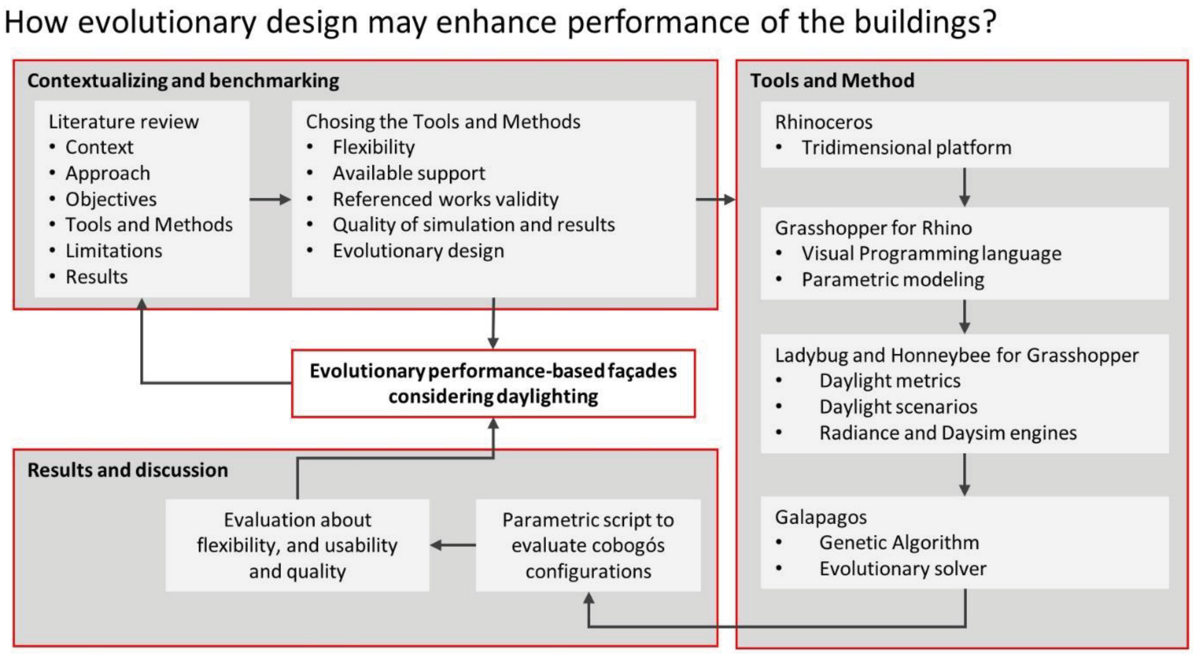
The steps assumed and the protocol to conduct this research were as follows:

- Literature review: daylighting in buildings, parametric design thinking, parametric performance-based design, evolutionary design;
- Defining the limitations and potentials of tools and strategies;
- Defining the tools to conduct the work;
- Benchmarking on the daylight performance of traditional façades elements;
- Writing the parametric schema in a visual programming language;
- Conducting preliminary simulations and identifying misleading procedures or parameters;
- Writing the parametric schema for the studied topologies;
- Exploring façade elements designs with parametric tools;

- Seeking for optimization process with genetic algorithm approach;
- Evaluating and quantifying the benefits of evolutionary method;

The work is conceptually structured according to Figure 1. Some of the choices made are described and will be further detailed in the subsequent chapters. Briefly, three points structure the conception of this thesis, contextualization and benchmarking to define the problem and situate the necessity for tools and methods, then choosing these tools and methods considering the aspects raised in the literature, and finally the treatment of the problem, running the simulations and treating the collected data.

Figure 1 - Thesis strategy.



About the selection of tools, the ease of access to them, the flexibility they allow, and the quality of the referenced work using them ascertain which tools, metrics, and methods to use in the development of this research. It is also relevant to consider the quality of support from online forums for discussion with other users and researchers, the developer's support, and the surrounding researchers' opinion.

It is important to notice that the purpose is not only an optimized object, construction element, or design solution, but rather a system to find one, therefore this thesis is about identifying the potentials and disadvantages of doing so, reporting, and discussing the relevant aspects of the present method.

1.2. RESEARCH CONTEXTUALIZATION

This thesis was conducted in the Federal University of Paraná under the Graduate Program in Civil Construction Engineering and belongs to the research field of Built Environment and Sustainability. The thesis was thus conducted in association with the Built Environment Laboratory (*Laboratório de Ambiente Construído – LAC*) of the Department of Architecture in the same university.

During the years of the Ph.D., I spent one year in exchange at the French institution *Institut National des Sciences Apliquées – INSA*, in Toulouse under the international agreement CAPES-COFECUB. The contribution of that experience to this thesis was to deal with physics-based computer-aided simulation and the Constructal Law approach presented earlier. The work there had been carried out under the supervision of Professors Sylvie Lorente and Matthieu Labat and the coordination of Professor Marcelo Risso Errera. Thereby, part of this thesis was presented as an extended abstract in the Constructal Law and Second Law Conference 2019 (Alves & Schmid, 2019).

In the Graduate School of Civil Construction Engineering at UFPR, there are some works worth referring here, since they have equivalences in subject or field of study, like Uehara (2018) and Schmid and Uehara (2017) that evaluate the daylighting efficiency when applying photovoltaic membranes in windows for office buildings. Yet, the work of Schmid (2004) describes a simulation system for light visualization in Java Language used for teaching architecture students.

In Brazil, some recent Latin American conferences had works dealing with daylighting and façade elements (Cartana, et al., 2017) and daylighting associated with cobogós (Cordeiro, et al., 2017). A work that is related to regulatory prospects is the illuminance chart proposed in (Fonseca, et al., 2017) for the Brazilian territory in terms of natural illuminance.

In the international literature, the work of Zani *et al.* (2017) is worth notice due to the similarity with the daylighting performance study of an innovative modular shading device made of concrete in Italy. Also, the work of Vazquez (2017) identifies and describes the shape grammar of typical brick facades as shading devices.

The Brazilian technical standards for daylighting have been revised and discussed in recent years. Some of them are still based on international standards and some researchers discuss the necessity to implement local regulatory aspects that have been made in these last revisions (ABNT, 1992; ABNT, 2005; ABNT, 2013).

In the next chapter more references and relevant topics will be presented.

2. DESIGNING WITH DAYLIGHT

In this section, I will present a review on the influence of daylight in architecture. Yet, I will include some explanation about the sun and the sky as light sources and how they are mathematically represented in computational simulations. I will also delineate some illuminance requirements for buildings, by sun exposure, and the metrics to design with when dealing with natural light. The final section will explore some types of shading devices and their performance in some related works in the literature.

2.1. NATURAL LIGHT AND THE ARCHITECTURE

One important moment in the history of western architecture, that demonstrates the excitement with natural light inside buildings was the Crystal Palace[2] by Joseph Paxton in the London Great Exhibition in 1851[3]. This building, according to some authors, signaled the beginning of modern architecture (Tietz, 2008) due to the industrial fabrication of the glass, the advancements with the iron structure (Addis, 2006), and the lack of ornaments (Figure 2). At that time, the electrical lighting was not a commercial product yet[4] and the transparency of the building allowed sheltered meetings in a fully natural lit ambient.

Long before this pavilion, the excitement with natural light was materialized in religious architecture mostly, and shaped tombs, temples, churches, and cathedrals over the centuries among a subjective significance of natural light crossing different cultures spread in the world.

After the availability of affordable electrical light and mostly after Nikola Tesla's fluorescent lamps in the 1940s, the importance of daylight significantly decreased for the public in general.

---

[2] The excitement was also due to technological advancement with the cast plate glass windows and cast iron structure.

[3] The building was transferred to Sydenham in 1855 and was burnt to the ground in 1936.

[4] The first public demonstration of the incandescent bulb lamp by Thomas Edison occurred in 1879, 28 years after the Crystal Palace exhibition.

Still, with the oil crisis in the 1970s, governments, designers and the public started paying attention to energy efficiency in buildings, and the natural lighting strategies in buildings seemed an opportunity to reduce energy consumption with artificial lighting and to reduce cooling loads with shading devices (Reinhart, 2014).

Figure 2- The Crystal Palace at Sydenham Hill, 1854. Photo by Philip Henry Delamotte

Source: (Merin, 2013)

Although electrical light could replace the daylight on allowing human tasks to happen, the benefits of daylight in buildings are greater than only the luminous efficiency for working. Daylight allows a view to the outside, contributes to the ambiance aesthetics, helps on the quality of the internal air, decreases artificial light needs, and creates daylit spaces where many electric lights would be needed to meet the same results.

Besides that, daylight helped human evolution since the circadian rhythm is synchronized with the solar day through the retinal photoreceptors (Berson, 2003). These photoreceptors are not the cones and rods, discovered 150 years ago but ganglion cells directly connected to the brain and responsible for physiological control of the body functions in response to the environmental illumination. They have lower sensitivity than cones and rods and start producing melatonin at the end of the day and cortisol from the morning.

Throughout the history of architecture, most of the important buildings were conceived considering natural light as a design element. Although the public in general diminished the importance of daylighting in the early 1940s, when electric light became accessible, Le Corbusier was introducing the *brise soleil*, which became an identity of the modernist architecture onward. The *brise soleil*, or louvers, are linear, mostly pivoting shading devices that carried the aesthetics from industrial facilities to the civil buildings, representing the excitement with the possibilities of mass production (Corbusier, 2004), as in the *Unité d'Habitation*, Marseille, 1952.

In Brazil, the *Petrobrás* headquarters in *Rio de Janeiro*[5] is a representative building using the louvers as the shading device shaping the building and performing a functional façade element. In this building, the east and west façades have vertical louvers, while the north façade, facing the equator line, has horizontal louvers. In the south façade, glazed panels have no solar protection. This building is a didactic example of using louvers and solar charts. Additionally, Gustavo Capanema's Palace also in *Rio de Janeiro* by Oscar Niemeyer, 1943 with ideas and proposals of Corbusier, and the mixed-use building *Copan* in *São Paulo,* 1966 also by Niemeyer also make use of louvers. The *brise soleil* thus became representative of the international style.

---

[5] By Roberto Luis Gandolfi, Jose H. Sanchotene, Abraao Assad, Luis Fortes Netto. (1963)

Still in Brazil, due to our tropical climate and the necessity of natural ventilation associated with natural daylight, a hollowed modular building element created during the 1920s became also seminal in the architecture of the country, the so-called *cobogó*[6]. This element is also historically representative since it is derived from the Portuguese colonial architecture (Vieira, et al., 2013). An expressive appearance of this element was the long façade of the Brazilian Pavilion in the World Fair of New York, 1938 by Lucio Costa and Oscar Niemeyer. However, this element is also scattered in vernacular buildings all over the country.

Expressions like sustainability, energy efficiency, environmental responsibilities, and green solutions were unknown for the most of human production of buildings during eras, although the concepts were perhaps embedded in the designing culture. But after the oil crisis and on the second wave of excitement with technology, the High-Tech movement in architecture, showed some prominent production towards these concepts and was the basis to a new aesthetical language with some remarkable solutions like the Arab World Institute in Paris by Jean Nouvel, 1987 were presented, with its mechanical solar sensitive façade[7]. A more recent building from a notorious High-Tech architect is the California Academy of Science by Renzo Piano, 2008. In this building, the holes in the roof and the movement of the structure allow a well-daylit space, which becomes a seminal building, an example of a sustainable approach as well.

The ability to work with natural light is also represented by the Swiss architect Peter Zumthor by whom natural light becomes a “building material” (Figure 3). In his studio, daylight is consistently evaluated from the subjective point of view. The process of producing physical models of its designs to seek the path of natural light and its aesthetics together with building

---

[6] Three engineers, Amadeu Oliveira **CO**imbra, Ernest August **BO**eckman and Antônio de **GÓ**is, created the building element. In reference to these authors the hollowed modular façade element is known as COBOGÓ (G1, 2013). Although the three engineers developed this element, it was totally modified in terms of design and conception along the years. The original model is presented in the patent 18431 (Vieira, et al., 2013).

[7] Unfortunately it does not work anymore, at least until the publication of this volume.

materials has projected Zumthor as one of the most important contemporary architects that know how to create atmospheres using building construction (Zumthor, 2006).

Figure 3 - Thermas de Vals, Vals in Switzerland by Peter Zumthor

Source: (Los Angeles County Museum of Art, 2013) Photo Credits: Margherita Spiluttini. © Margherita Spiluttini

When designing a new building, architects must be concerned with façade orientation, building materials, shading devices, and openings to define interesting views, aesthetic requirements in façade composition, daylight performance and perception in interior spaces for human requirements, as same as thermal performance in the final building. Therefore, the understanding of the sun and sky behavior is fundamental to design considering daylight.

2.2. LIGHT, SUN, SKY, AND THEIR REPRESENTATIONS

In this section, some physical aspects of the light, and its behavior in the environment will be discussed, as same as how its represented and simulated with computer software. Thereforen, it is important to firstly define light and understand some concepts like luminous flux, illuminance, luminous intensity, reflectance, and luminance (Hopkinson, et al., 1966).

Light is a portion of the electromagnetic spectrum of radiant energy. The visible light by the human vision range in this spectrum between the wave-length of 390 to 750 nm from which we see the colors in the environment. However, the light coming from the sun carries a wider range of wavelengths, including values below 390 nm, which are the Ultra-Violet (UV) rays and above 750 nm, which are the Infra-Red (IR) rays. Visible light from a led lamp and the sun also have different levels of brightness and the human eye can distinguish these levels as same as the different colors in objects.

This visible radiant energy we call light is measured by its transference rate and its effect in the human visual sense. The total amount of emitted energy is what we call the luminous flux, measured in lumens (lm). For instance, a 1W led lamp can produce a luminous flux of 25 to 120 lm, while the sun produces $3.562*10^{28}$ lm (Mook, 2018).

When we consider an area of interest, like a portion of a desk or a kitchen countertop, the amount of radiant energy reaching that area of the surface is then expressed in lm/m^2, also known as lux[8], which is the definition of illuminance. In a clear sky day in Abu Dhabi (EnergyPlus, 2020), for a TRY, the outside illuminance may reach 99,900 lux from direct illuminance and 12,600 from indirect illuminance, while with overcast sky 12,500 lux come from direct illuminance and 62,600 lux from indirect illuminance, the sunlight scattered in the

---

[8] This is the International System of units (S.I.) and are the units adopted in Brazil. For the English speakers countries these units become lumens per square feet (lm/ft^2) or foot-candle. 10,76 lux = $1lm/ft^2$

clouds creates diffuse lighting coming from all direction. In Curitiba (LABEEE, 2018), for a TRY, 54,578 lux is the higher value of direct illuminance in a clear sky day[9], almost the half found in Abu Dhabi.

As light has direction, it is possible to measure the amount of radiant energy within a specific solid angle. This measure is called luminous intensity, measured in candela (cd). And, if the luminous flux of a lamp is concentrated in the same direction, which some light fixtures do to have more focused illumination, light becomes denser in a certain direction with the same total luminous flux, increasing the luminous intensity.

For the human eye to perceive the light and see an object its surface must reflect the light rays received. The portion of the luminous flux wich is diffusely reflected by a surface is the reflectance, which is dimensionless and usually expressed as a percentage. White or clearer surfaces are more capable of reflecting light, while darker surfaces do not and because of that, they are less visible.

There is a difference that needs to be distinguishing here, between the human perception of the reflected light and the measured amount of reflected light. The human vision is capable of adapting the sensibility to different brightness in an entire scene, which in many cases, for the same absolute values of luminous flux the human eye has different perceptions of brightness. On the other hand, this absolute brightness can be measured with a photometer and it is called luminance, measured in cd/m². Therefore, the human perception of light could be the same for different values of luminance, depending on the whole brightness of a scene.

---

[9] Considering a Test Reference Year (TRY) climatic data, which is representative averaged climatic year. Absolut measured values could be above these values.

The sun is the main source of natural light on Earth. But when its rays reach the atmosphere, with air, dust, and water vapor the light is scattered and two main light sources can be considered. The first is the sun itself as a focal source of luminous flux, and the second is the sky reflecting and spreading the sunlight.

The luminous flux of the sun is something independent of the atmospheric condition, but its perception from the Earth surface is influenced by it. Therefore, sky conditions will define the illuminance in a surface, and the representation of these sky conditions with the sun and the sky luminous flux has been studied for a long time (Reinhart, 2014).

Scale models are a traditional recognized method to achieve both qualitative and quantitative analysis of daylight in buildings (Hopkinson, et al., 1966). The reliability of scale models, which reaches accuracies of measurements within 20%, at its best scenario (Cannon-Brookes, 1997), allows it to aid students, designers, and researchers to understand the light distribution and measure it in different solutions. For analyzing physical scale models, the outside daylight is a valuable light source that has all the weather variables and the dynamic changes of the sky conditions. For that, 1:1 scale models can also be used, like the one used in the mockup for the New York Times Headquarters[10] offices, or 1:10 to 1:20 models that yet have enough scale of magnitude to collect satisfying results (Bodart & Deneyer, 2006).

Indoor measurements may have yet the aid of a heliodon, a tool that simulates the sun position during the daylight hours relative to a plane, or yet an artificial sky composed of a mirror box with diffuse light from above. These indoor environments have the potential for controlled situations but usually increase the error in more than 25% due to the scaled representation of the sky and the sun, which results in the so-called parallax error (Mardaljevic, 2002).

---

[10] By Renzo Piano Building Workshop (2007) shown in (Reinhart, 2014, p. 170)

To help increase the precision of a scale model, it is necessary to increase the quality of geometry and detailing of the model, as same as the reflective properties of interior materials. In comparison, computer-aided simulations easily achieve this kind of geometric and material quality since all numeric values are inputted into the model. Besides, computer simulations have an overall precision of 20%, and they are becoming more and more accessible at low cost (Reinhart, 2014). Computer-aided interfaces have also several possibilities for visualizing results of daylight and irradiation.

For studying the range of daylight efficiency in a design solution, the two CIE extreme skies are commonly used: The overcast sky and the clear sky[11]. The overcast sky model presented by Moon and Spencer (1942) introduced the model of the first non-uniform sky. Later, the clear sky model was introduced by Kittler (1967). Additionally, the CIE classification allows at least fifteen different types of skies, considering the intermediary illuminance between these two extremes (Darula & Kittler, 2002). Although the CIE skies do not consider climatic data it is possible to set a location and calculate the illuminance at specific predetermined conditions. The equations handling with sky calculations in CIE standards work dividing the sky luminance between the horizon and the zenith according to the sun position. Still, the CIE skies predict an idealized version of sky conditions (Matsuura, 1987), with predetermined coefficients from a table (Figure 4) and you can end up using a sky generated from default geographical parameters that are not appropriate to the intended location (Ward & Shakespeare, 2003).

---

[11] Usually, architecture rendering software also have these two standard skies, since they usually want to illustrate a design. From the performance point of view they evaluate two extremes, but in between conditions are usually more common.

Figure 4 - Sky classification according to CIE standards and its coefficients

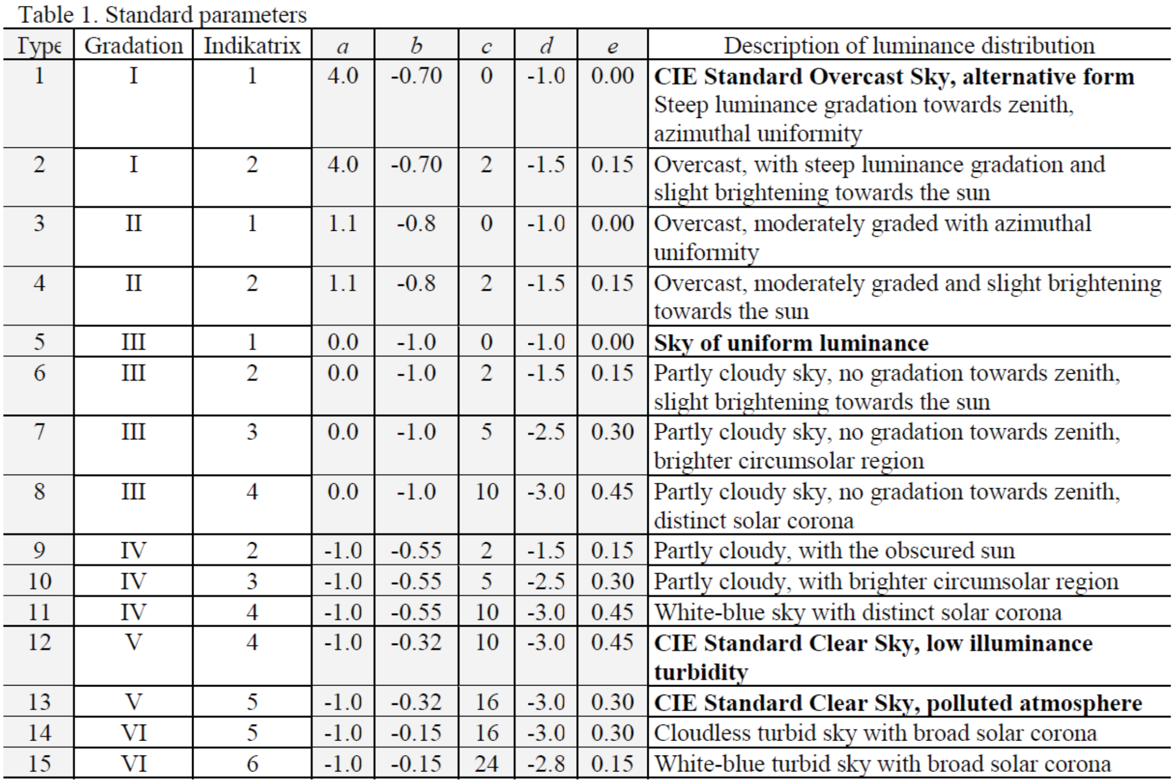


Table 1. Standard parameters

Type	Gradation	Indikatrix	*a*	*b*	*c*	*d*	*e*	Description of luminance distribution
1	I	1	4.0	-0.70	0	-1.0	0.00	**CIE Standard Overcast Sky, alternative form** Steep luminance gradation towards zenith, azimuthal uniformity
2	I	2	4.0	-0.70	2	-1.5	0.15	Overcast, with steep luminance gradation and slight brightening towards the sun
3	II	1	1.1	-0.8	0	-1.0	0.00	Overcast, moderately graded with azimuthal uniformity
4	II	2	1.1	-0.8	2	-1.5	0.15	Overcast, moderately graded and slight brightening towards the sun
5	III	1	0.0	-1.0	0	-1.0	0.00	**Sky of uniform luminance**
6	III	2	0.0	-1.0	2	-1.5	0.15	Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun
7	III	3	0.0	-1.0	5	-2.5	0.30	Partly cloudy sky, no gradation towards zenith, brighter circumsolar region
8	III	4	0.0	-1.0	10	-3.0	0.45	Partly cloudy sky, no gradation towards zenith, distinct solar corona
9	IV	2	-1.0	-0.55	2	-1.5	0.15	Partly cloudy, with the obscured sun
10	IV	3	-1.0	-0.55	5	-2.5	0.30	Partly cloudy, with brighter circumsolar region
11	IV	4	-1.0	-0.55	10	-3.0	0.45	White-blue sky with distinct solar corona
12	V	4	-1.0	-0.32	10	-3.0	0.45	**CIE Standard Clear Sky, low illuminance turbidity**
13	V	5	-1.0	-0.32	16	-3.0	0.30	**CIE Standard Clear Sky, polluted atmosphere**
14	VI	5	-1.0	-0.15	16	-3.0	0.30	Cloudless turbid sky with broad solar corona
15	VI	6	-1.0	-0.15	24	-2.8	0.15	White-blue turbid sky with broad solar corona

Source: *(Darula & Kittler, 2002)*

Therefore, measured data with direct and diffuse radiation values are preferable when modeling a realistic sky. The dynamic changes that occurred in the sky throughout the year are difficult to represent or simulate. Even so, the Perez all-weather sky model (Perez, et al., 1993; Perez, et al., 1990) simulates all-sky conditions, from clear to overcast, through partially cloudy, skies. The Perez model can predict illuminance values for different sky condition from irradiance measurements, which is a data available for many locations[12], by considering the mean instantaneous sky luminance angular distribution. This is the context for the climate-sky based models. The Perez model also considers coefficients “a, b, c, d, e” which are, respectively, horizon-zenith gradient, gradient intensity, circumsolar intensity, circumsolar radius and backscattering effect (Marsch, 2018). Thus, the simulations that evaluate daylight conditions

---

[12] At moment this thesis is written, we have two climatic data available for Curitiba, one from the TRY of 2005 with no illuminance measured values, and one from the TRY of 2008 which is used further in this work and carry these data.

through a whole-year round achieve better results with this model (Ward & Shakespeare, 2003). The formula for the clear sky, considering a relative luminance *lv*, is the basis for both models CIE and Perez, and it is as follows (Eq. 1):

$$lv = f(\zeta,\gamma) = \left[1 + a\exp\left(\frac{b}{cos\,\zeta}\right)\right]\left[1 + c\exp(d\gamma) + e\cos^2\gamma\right] \qquad \textit{(Eq. 1)}$$

Where, *lv* is the ratio between the luminance in the sky element *Lv* of interest and the luminance in any arbitrary reference sky element[13]. ζ is the zenith angle of the considered sky element and γ is the angle between the sky element and the sun.

The Perez all-weather sky model contribution is to treat the five coefficients as a function of the solar zenith angle, the sky clearness, and the sky brightness according to measured irradiance data (Perez, et al., 1993). Therefore, this model is the one utilized in many works dealing with sunlight problems under real sky conditions.

For feasible calculations of daylight illuminance inside buildings, the Daylight Coefficients are a technique that can compute the illuminance in a scene with dynamic sky conditions in simulation tools (Mardaljevic, 2000a). Daylight Coefficients are a technique to compute the incident direct and indirect daylight based on the properties of the sky and the room:

> *"The core principle behind Daylight Coefficients is that the daylight directly or indirectly incident on a surface inside a room can be accounted for by considering two independent factors: luminance of the sky and the geometry and the optical properties and geometry of the surrounding surfaces." (Subramanian, 2017)*

Mathematically, Daylight Coefficient is defined as:

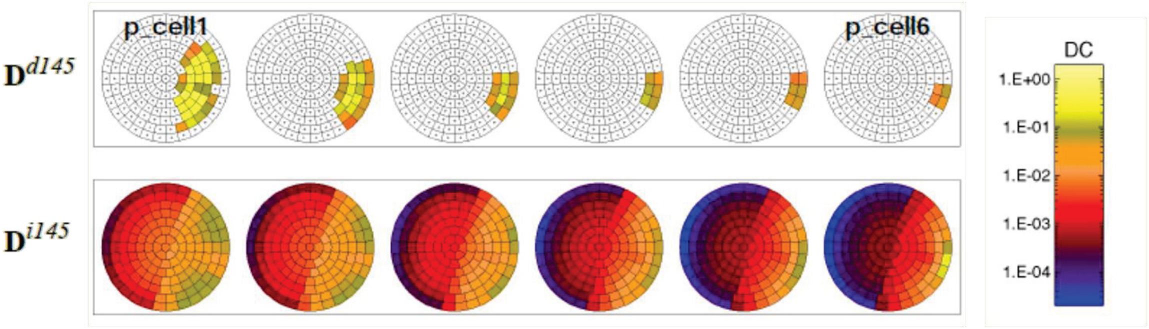
---

[13] Usually the zenith luminance is adopted *Lz.*

$$DC_{\propto}(x) = \frac{E_{\propto}(x)}{L_{\propto}\Delta S_{\propto}}$$

Where, x is a point and orientation in a building, S_α is a sky segment or sky patch, ΔS_α is the angular size of S_α, $E_\alpha(x)$ is the illuminance at x due to S_α, and L_α is the luminance of S_α. The equation above works for compute one sky patch, thus to calculate the total illuminance in a point is the sum of the contributions that must be considered.

Figure 5 - Sky patching for direct and indirect components



Source: (Mardaljevic, 2000b)

Therefore, about the sky representation, the idea is to divide the skydome into smaller patches and calculate the luminance in each patch considering the sun position and sky condition as a resulting vector from four components – direct sky, indirect sky, direct sun, and indirect sun (Figure 5), this resulting vector is obtained through (Eq. 2):

$$E = (D^{d145}c^{145}) + \left(D^{i145}c^{145}\right) + \left(D_{\beta}^{d5010}S^{sun}L^{sun}\right) + (D_{\beta}^{i145}S^{sun}L^{sun}) \qquad \text{(Eq. 2)}$$

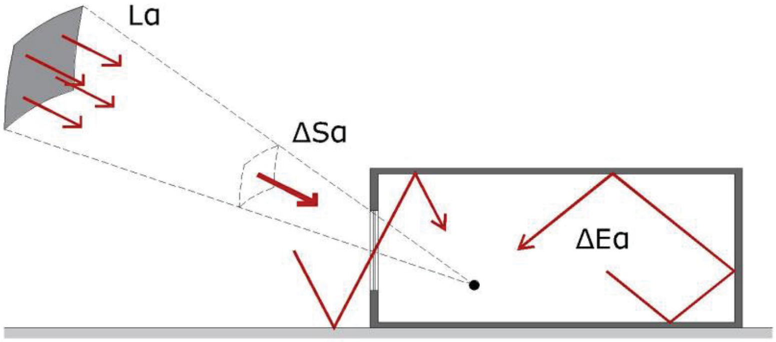
where, the two first expressions refer to the sky luminance (direct and indirect), and the following two to the sun luminance (direct and indirect). The expression accounts for a total 145 patches of sky and indirect sunlight and 5010 patches to indicate the sun position at a given time and angle β. The influence of this technique is visible in Figure 5.

For a given point in the space, the luminance emitted from one patch and represented by a resulting vector will be computed. The final illuminance in that given point is the integral of all resulting vectors. If this given point is inside a room, or if it is partially blocked by a wall, a roof, a shading device at the window, these elements will influence the final illuminance reaching this point (Figure 6). At the interior of a building, the sunlight bounces according to the material properties and the geometry configuration, contributing to final illuminance on a surface.

Although the analogy with a resulting vector, the technique used for daylight calculations uses the backward ray-tracing method. In this method the light is calculated from the test point, or from a point in a surface of the scene. This point emits sample rays that will be reflected in the space and transmitted by materials until they reach a source of light, be that source the sky (in which case the average sky patch luminance is used), or an artificial light source (in which case the source luminance is used).

A validated software working with these techniques is Radiance. It has the purpose of daylight simulation and has been used for practitioners and researchers since it is a physical-based validated platform (Ward & Shakespeare, 2003) with continuous improvements. It considers both the CIE standard skies model and Perez all-weather model and it is integrated with Daysim as well when performing annual matrix-based simulations (DEFuller; AMcneil, 2017). Radiance with Daysim use stochastic and deterministic calculations to predict illuminance distribution as same as the Daylight Ccoefficients technique.

Figure 6 - Resulting patching vector and its influence in global illumination indoor



Source: Adapted from Mardaljevic (2000b)

The stochastic approach is implemented throuhgt a backward ray-tracing method to solve the light rendering equations based on the Monte Carlo method (Tregenza, 1983). This method proposes that if a ray that reaches the eye of the observer (or the camera) also reaches the light source (the sun, or any artificial light source) this ray will be computed in the simulation, otherwise, it is not considered. This technique spares calculations that would not contribute to the scene or specified test points in a mesh. Additionally, contributions of reflective surfaces and refracted rays are treated separately, optimizing the solver performance.

The deterministic solution traces the same resulting rays every time, and the rays are directed to the light source, to the mirrored surfaces, reflective surfaces, and transparent materials. The result is clean and quick but not as accurate as the result of the stochastic method when considering complex scenes (Ward & Shakespeare, 2003).

Therefore, the simulations blend deterministic and stochastic raytracing techniques to achieve the best balance between speed and accuracy in its local and global illumination methods (Ward, 1994). To solve the illuminance calculations and a scene rendering a general integral equation is presented (Ward & Shakespeare, 2003):

$$L_r(\Theta_r,\phi_r) = L_e(\Theta_r,\phi_r) + \int_0^{2\pi}\int_0^{\pi} L_i(\Theta_i,\phi_i)\,\rho_{bd}(\Theta_i,\phi_i;\Theta_r,\phi_r)|\cos\Theta_i|\sin\Theta_i d\Theta_i d\phi_i \quad \text{(Eq. 3)}$$

where Θ is the polar angle measured from the surface normal; Φ is the azimuth angle measured about the surface normal; $L_r\ (\Theta_i,\ \Phi_i)$ is the reflected radiance; $L_e(\Theta_i,\ \Phi_i)$ is the emitted radiance (watts/steradian/square meter in SI units); $L_i\ (\Theta_i,\ \Phi_i)$ is the incident radiance; and $\rho_{bd}\ (\Theta_i,\ \Phi_{i;}\ \Theta_r,\ \Phi_r)$ is the bidirectional reflectance-transmittance distribution function (steradian-1). This equation solves the total illuminance reaching a surface, considering the emitted and reflected/ transmitted luminance. Evaluating one ray means evaluating all the other rays, since they are dependent on each other, and the process stops when (Ward & Shakespeare, 2003):

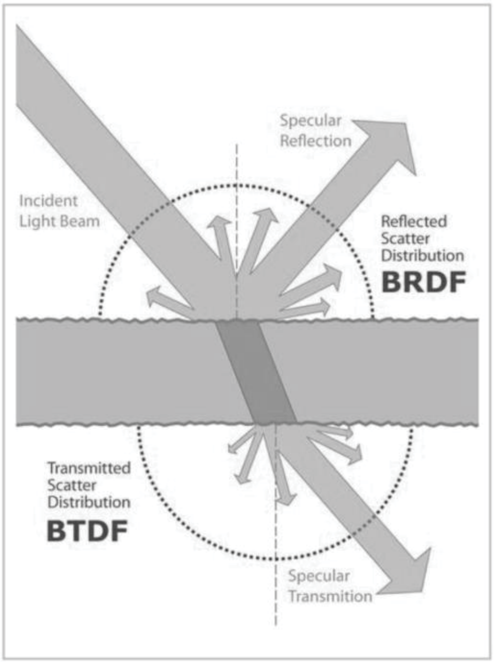
- The intersected surface is a light source;
- The ray has reflected more than a specified number of times;
- The ray “weight’, which is the product of all previous reflectances, is below a specified value.

This equation evaluates each point on a surface without the need for a tridimensional mesh, which allows the software to simulate complex scenes easier.

More recent techniques in daylight simulation have a goal to refine the light behavior in the virtual environment. Mainly when the diffuse light is reflected or transmitted by materials or when it passes through complex small geometries, like in a façade with blinds or cobogós, for instance. These techniques are based in phased-methods of calculation, and the realism achieved in reproducing the diffuse light has the BSDF[14] as main concept (Geisler-Moroder, 2019).

The BSDF adds components of transmitted scatter distribution (BTDF) and reflected scatter distribution (BRDF) to the rendering equation from any incident light beam (Figure 7).

Figure 7 - Schematic behavior of a BSDF when light reaches a surface



Source: (Wikimedia apud Geisler-Moroder, 2019)

The discretization of the sky, in 145 patches presented earlier, also has major influence in reproducing the light from the sky. Between Klem's discretization and Tregenza's, the last was focused in improving the contribution of the skylight near the horizon, by distributing 30 subdivisions in the range near the horizon, instead of 12 like proposed by Klem's discretization, mainting the same number of sky patches (145). Additionally, a variable resolution in the sky patching is also proposed by Ward (2014), based on the Shirley-Chiu-mapping method.

---

[14] BSDF - Bidirectional Scatering Distribution Function: it is an additional part of equation added to the rendering equation presented earlier.

Therefore, when BSDF are applied to the whole model, it will include a more reliable representation of the light distribution from the sky, i.e., a scene gets contribution from more sky patches, since the contribution of diffuse light increases significantly than with traditional treatment of only specular reflected and transmitted light in whole scene. Additionally, BSDF can also be applyied to the materials in the scene.

The challenge imposed and treated in recent Radiance workshops[15] is how to include BSDF in annual daylight simulations. Phase-methods are the solution for this. Between a 2-Phase method and 6-Phase method, improvements in the representation of the natural light inside buildings are being achieved according to the necessity. Phase-methods in Radiance are presented as a decision tree (**Erro! Fonte de referência não encontrada.**8) to know how many phases are necessary for a particular problem.

Briefly, the 2-Phase method consists of working with daylight coefficients to trace light back to its sources. The use of Daylight Coefficients in annual daylight simulations with Radiance-based platform, is widely viewed in the literature by using Daysim platform (Subramanian, 2017). What happens, is that when accurate spatial resolution is needed, i.e. when the façade has shading devices with small dimensions like blinds, cobogós or non-coplanar geometries, it is necessary a more refine method of calculation (Marsh, 2020).

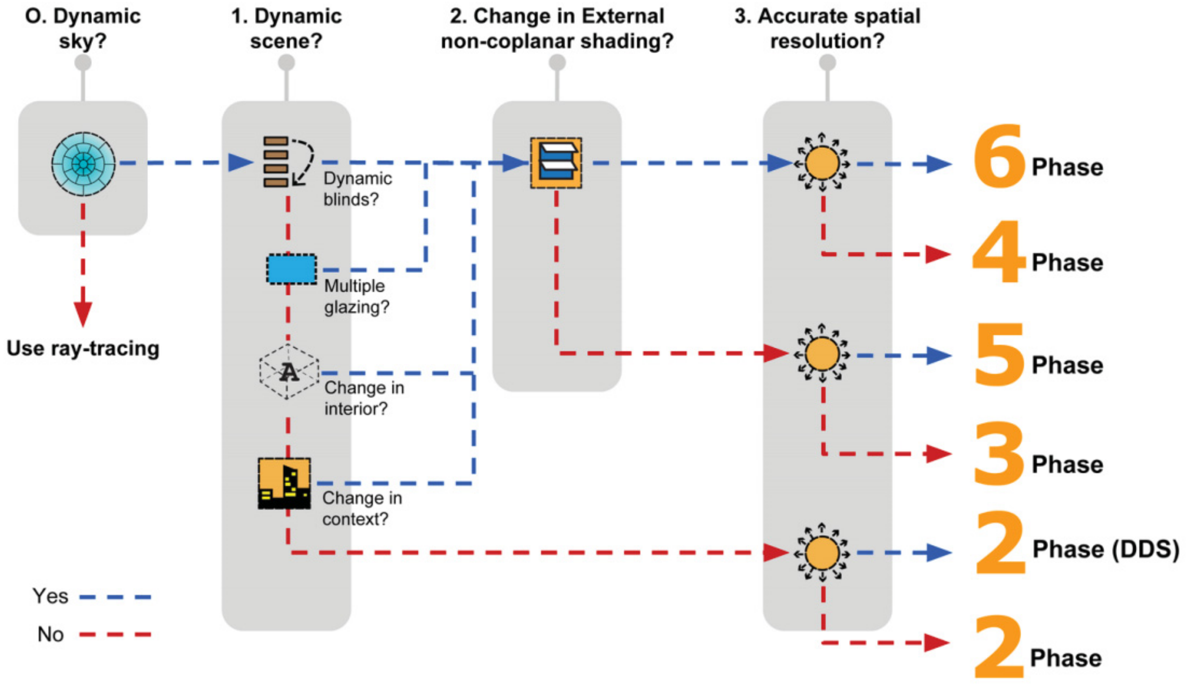
The 3-Phase method, instead of using only one component to Daylight Coefficient, it involves the calculation of illuminance based on the interior matrix component, an exterior matrix or daylight matrix, a sky matrix, and a transmittion matrix component representing the fenestrations. The 4-Phase method adds to the previous the calculation of external shading devices when not incorporated to the fenestration or when not coplanar with it, as a new

---

[15] https://www.radiance-online.org/community/workshops

component of the external matrix calculation presented. This new component is about the flux matrix entering the window (Subramanian, 2017).

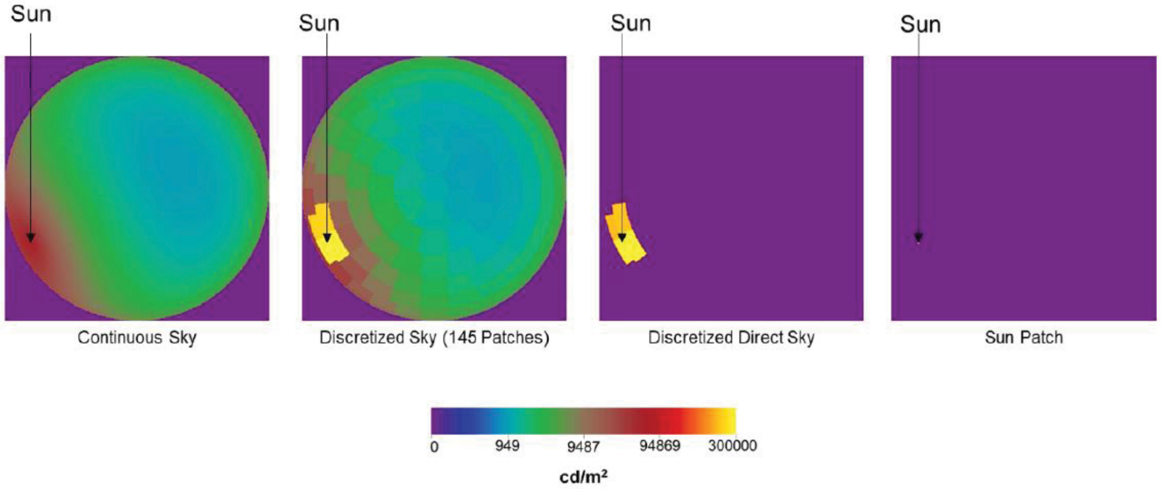
Figure 8 - A decision tree for determining the appropriate type of simulation



Source: (Subramanian, 2017)

The 2-Phase method DDS, the 5-Phase method and the 6-Phase method are used for accurate spatial resolution. The 2-Phase method DDS also works with Daylight Coefficients, but improving the direct solar contribution in a scene. This improvement is about refining the 145 patches in the sky for the sun position and therefore for direct solar radiation (Figure 9). The process is to calculate the Daylight Coefficients, extract the direct solar contribution and recalculate it from a finer discretization of the sun position.

This refinement in the direct solar rays contribution is also applied in the 5-Phase Method and 6-Phase method, based on the guidelines presented for the 3-Phase Method and 4-Phase Method. Still, the onther phase added to *both methods refers to include BSDF in the light behavior in materials and surfaces.Figure 9 - Sky and sun patches employed in 2P DDS, 5PM and 6PM. The image on the left is the standard continuous sky.*



Source: (Subramanian, 2017)

If working with anual simulation using Radiance and Daysim as the best solution, since it used the Daylight Coefficient technique, more recent techniques based on phase-methods have been incorporated to Radiance in the last few years. In fact, during the development of this thesis.

Further in this work, it is reported that the Daylight Coefficients within Daysim are applied as the technique incorporated in the script developed in this work. Although other techniques are described here, able to produce finer results, specially for complex geometries as shading devices, be aware that this work was developed with the 2-Phase method.

2.3. DAYLIGHT METRICS FOR BUILDINGS

The illuminance is the basic quantitative measurement of light distribution in interior spaces. The kind of activity developed in an ambient requires a certain range of local illuminance, and at the same time, it has to consider surrounding illuminance to avoid glare and visual discomfort. Manual or detailed tasks demand higher values of illuminance while a transition ambient can be less rigorous with it. In Brazil, ABNT published recommended values of illuminance for several types of activity (ABNT, 2013) including the limits of Unified Glare

Rating (UGR)[16] that guarantees quality in the distribution of illuminance together with the Color Reproduction Index (CRI)[17] responsible to define the quality to reproduce color in spaces. For instance, a jewelry workshop is recommended to have 1500 lux with 16 UGR_L and 90 CRI with a color temperature of at least 4000 K. For office hallway spaces the standard recommends 100 lux with 28 UGR_L and 40 CRI.

The most common metric about daylight efficiency for buildings was for a long time the Daylight Factor (DF). Although it is based on illuminance values, it does not measure it directly. The DF describes the relationship between indoor and outdoor daylight illuminances. It is a regular measurement usually used while in early stages of building design, together with some rules of thumb I will discuss further. The DF qualitatively describes a façade solution, because being a ratio it is generally stable across time. A fair assumption for a well-daylit space is that it has an average DF of 2% (Reinhart, 2014). In the academic field, DF is not a relevant metric anymore. Instead of that, climate-based analyses with annual monitoring are required. The theoretical sky, with standard conditions like overcast or clear sky, is the condition evaluated in DF analysis, while in real conditions the illuminance inside a room may vary drastically from one point to another and from one instant in time to the next.

From the illuminance concept, another daylight measurement is the Spatial Daylight Autonomy (SDA) (IES, 2012). This concept measures the required illuminance from natural daylight for a sufficient number of hours over a specific area of the building. It considers climate-based data, which produces a locally efficient solution. For instance, Reinhart (2014) adopted in a residence a recommendation that the illuminance is above 300 lux for 50 % of the yearly

---

[16] UGR_L which is the limit of UGR is equal the ration between the least and the higher illuminances in a working area. Higher values means a flexibility to allow glare, usually for space of no rigorous requirements.

[17] Higher values of CRI means that the light source is capable of reproduce trustworthy colors.

occupied hours, covering at least 55 % of the floor area. In this case, SDA should be equal to or above 55 %.

For illustration purposes, let us assume a room with an average daylight factor of 2%. For this room to be daylit by 300 Lux, the horizontal solar radiation outside must be at least equal to 15,000 lux or more. For Curitiba, it is true for 83 % of the hours with sun, therefore is plausible to assume these metrics here as well.

A third daylight metric is the Useful Daylight Illuminance (UDI), proposed by Nabil and Mardaljevic (2006; 2005). It also considers climate-based conditions and it measures a design solution with annual analysis and different sky conditions. The UDI scheme is applied by determining the occurrence of daylight illuminances that:

- Are within the range defined as useful (i.e. 100–2000 lux);
- Fall short of the useful range (i.e. less than 100 lux);
- Exceed the useful range (i.e. greater than 2000 lux).

The UDI adds to the SDA, which has no upper limit, a range where acceptable conditions are considered for human requirements. Less than 100 lux is hardly useful inside a building except for transition spaces, and more than 2000 lux are prone to overheat a space or to cause glare due to the difference of brightness. Therefore, another criterion on daylighting performance is the Annual Sun Exposure (ASE) that accounts for direct sunlight that may cause visual discomfort due to excessive brightness (glare) and increase cooling loads due to direct solar radiation[18]. ASE accounts for how much of the floor area, in percentage, receive more a specified illuminance during several hours during the year.

---

[18] For instance, in the LEED certification for buildings, the adopted measure is how much floor area will receive more than 1000 lux during 250 occupied hours per year, which must not exceed 10 % (USGBC, 2013).

The human eye can deal with a range of light signals over about 12 orders of magnitude from starlight at 0.000001 Cd/m² to over 100,000 Cd/m² on a sunlit day. Inside buildings, this range goes from 10-20 Cd/m² when reading in a dark space to thousands of Cd/m² when the sun hits a clear wall. Our eyes can adapt to only two orders of magnitude without discomfort. In adults, the transition from a bright to a dark space takes 10 minutes to adjust and about an hour for maximum sensitivity (Reinhart, 2014).

In a typical daylighting problem, it is usually required to maximize UDI, SDA, or DF, and minimize ASE.

2.4. DESIGNING WITH THE SUN

Designing with the sun means considering it since the early schematic design and mainly exploring the potentialities of natural illumination and natural heat provided by this source. The solar trajectory will strongly influence building massing and zoning.

One first way to guarantee that a building is sufficiently daylit is through the rules of thumb (Reinhart, 2014). Some of them are:

- The window-head-height-rule: the depth of a daylit space has to be between 1.5 to 2.5 times the head height of the window;
- The daylight feasibility test: the angle free of surrounding obstructions defines the number of windows; and
- The atrium rule of thumb: the width of the atrium must at least be 2.5 times the building height.

These rules of thumb concern massing studies, and despite they are not quantitatively precise, they route a well-daylit design.

Additional strategies for schematic design considering daylight may be found in (Kwork & Grondzik, 2011). For schematic design, using the daylight factor may be very helpful to understand the behavior of the natural light inside a room and allows a daylight zoning, predefinitions in top lighting, side lighting, light shelves, internal reflectances, shading devices, and electric lighting.

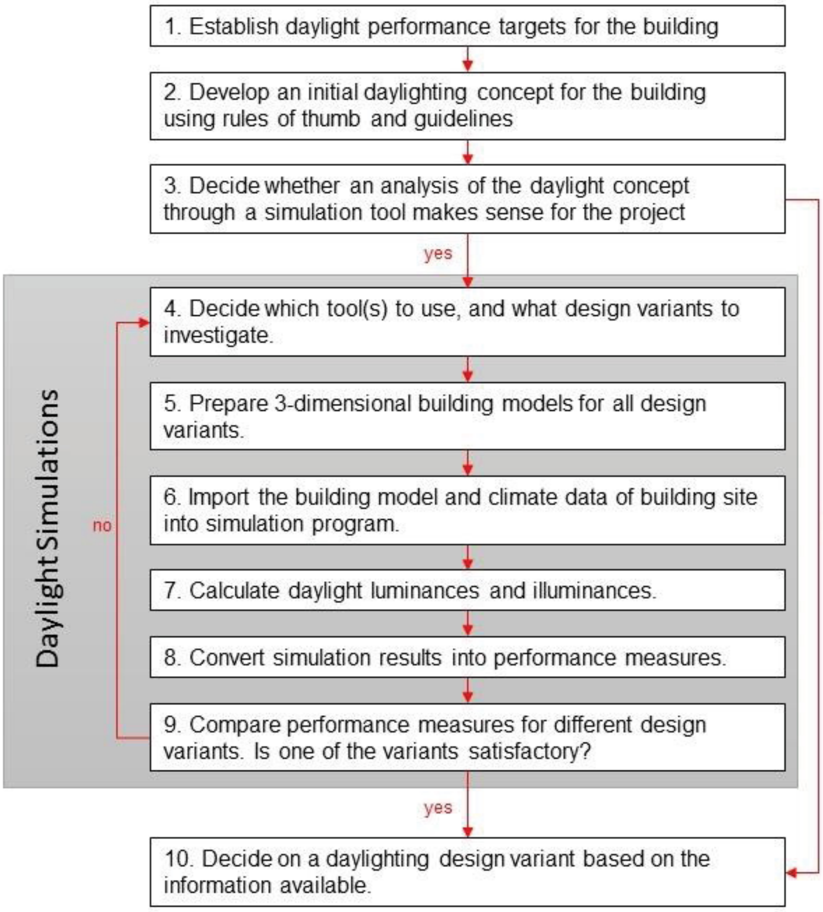
The Illuminating Engineering Society (IES) also has a publication with guidelines for daylighting design (DiLaura, et al., 2011). It is a handbook specialized in lighting design, for the design of buildings or interior spaces, presenting concepts and applications.

The concerns when designing a building are to know climatic conditions, the building usage, the site and the surrounding, the distribution of the building, shape, and the relationship with the environment, the solution about construction materials and finishes, apertures, doors, and windows, and finally the systems for electric light or HVCA (DeKay & Brown, 2014).

One conceptual approach that makes a difference when designing is to consider climate as a resource (DeKay & Brown, 2014) or metaphorically as a building material (Zumthor, 2006). Climate is the first parameter that allows buildings to reach net-zero or yet net-positive buildings. Identifying where to put the efforts to reduce loads, energy-saving or on-site energy production comes from climate analysis. For instance, shading devices are necessary to reduce internal loads coming from solar irradiance, especially in tropical climates like in Brazil. However, even here it may be helpful to reduce heating loads in colder areas like the bioclimatic zones one or two that require some solar heating as a passive strategy (ABNT, 2003).

To validate design solutions, simulation tools and methods have become more popular and necessary. Being complementary to other strategies pointed before, like scale models, site measurements when possible, or 1:1 mockups, developing these analyses together with the design schedule is an important concern when considering daylight in a design. A schematic approach to know when considering daylight studies in a design process is presented in (Figure 10).

Figure 10- Daylight simulation protocol in the design process



Source: Adapted from *(Reinhart, 2010)*

Additional to climatic data, performance targets are required to evaluate and choose one defined design solution, then the massing studies should focus on reaching the target and maybe finding more than one satisfactory solution to deeply investigate (Reinhart, 2014). After an evaluation in terms of massing, zoning, and shape of the building or ambient, the façade treatment is a step forward to define daylight and shade solutions. The use of a solar chart helps predefine the best orientation of the building and shading devices for the façade, but simulating new solutions and possibilities is helpful to improve the design or to reach a specific aesthetics with performance.

A useful tool to design windows and shading devices is also the solar chart. This tool represents the sun trajectory during the whole year in a bi-dimensional form, and through the position of the sun is possible to predict and design shading devices for a building or yet to measure the impact of the surrounding environment in a façade. Design a shading device with a solar chart is to predict the protection for the angles α, β, and Υ (Frota, 2004). The α angle measures the protection of horizontal devices, like a marquee, or horizontal louvers, or cobogós. The β angle measures the protection of vertical devices, as a vertical louver, a wall next to a window, or a prominent edge. The Υ angle limits the protection and refines the designed solution. LABEEE (LABEEE, 2018) has a useful application to design with a solar chart, the Analysis SOL-AR.

In the next section, some façade solutions will be evaluated for benchmarking future cobogó solutions.

2.5. SHADING SOLUTIONS IN BUILDING FAÇADE

For benchmarking purposes, some results presented in the literature will be presented and discussed in this topic.

Zani, Andarolo et al. (2017) shown that a $\text{UDI}_{100\text{-}2000}$ value between 74.7 % and 83.7 % was achieved with a concrete modular shading device in a south façade in Milan. The authors used parametric-design and genetic algorithms to seek an optimal solution for the specified design.

Kirimtat, Krejcar et al. (2019) demonstrated that amorphous louvers could reach a $\text{UDI}_{100\text{-}200}$ value between 41.65 % and 54.90% in a south façade in Izmir, Turkey. The authors considered illuminance efficiency against total energy consumption with air conditioning. However, the recommended, in terms of UDI, is a value above 50 % to be considered satisfactory according to Reinhart and Weismann (2012).

Yi (2019) has searched for innovative shading elements from a reference building in Barcelona by relocating it to Champaign, IL, USA. The author conditioned his choice of solution based on ASE, and SDA for quantitative measurements, and users' aesthetical preferences for qualitative measurements. The preferred solution by users was the one that allowed more daylight and sun entering the building, with ASE of 36.4 and SDA of 42.9.

Cordeiro et al. (2017) performed simulated results for a cobogó façade as a second skin for four different latitudes in Brazil (0°, -10°, -20°, -30º). The authors concluded that the cobogós applied to any façade helps to improve the distribution of useful daylight in a room, contributing for a more uniform distribution.

Cartana et al. (2017) also simulated a shading device in Brazil with Voronoi-based geometry. They simulated a west façade in Florianópolis, south of Brazil. They achieved an improvement from a UDI of 58.75% with no solar protection in the façade to a UDI of 88.14% with the shading device.

Shading devices are useful as design strategies to improve daylight performance in buildings. More uniform illuminance and less thermal loads are achieved in many examples presented earlier. Computational models associated with flexible models have allowed buildings to become more efficient with accessible tools and innovative design.

3. ADAPTIVE METHODS TO DESIGN

Computer-aided design (CAD) techniques have been providing growing contributions to the design process. From schematic and detailing phases of design to fabrication and construction of elements to management and analysis of buildings and cities, concepts like the Building Information Modelling (BIM) have been shifting the production of the built environment to more technological and informational approach and nowadays embrace the whole process of buildings design and cities development. The BIM process is much about facilitating information to flow between actors and anticipating important design solutions to build more consciously.

The faster and easier CAD tools allow us to acquire and generate information, the easier it is to perform changes in design models or to test different scenarios to choose one. The design process is becoming more and more interdisciplinary and the exchange of model information is becoming more dynamic. Software working with associative modeling has been used to support this dynamism and, at the same time, preserve shape exploration which has presented new directions for contemporary design (Oxman, 2017; Yi, 2019).

An innovative design usually has its origin in some known precedents. This knowledge is adapted until it meets new requirements with an adaptation process (Al-Kazzaz & Bridges, 2012). Two approaches to explore shapes are presented next. Both have in common the characteristic of being represented more by rules and functions than by modeling or sketching of ideas. However, one presents itself as shape manipulation (parametric modeling) usually preserving the essence of the topology, and the other as shape generator (shape grammar) based on establishing relationships between initial shapes. Both approaches are usually underlying each other when describing or adapting a design with parametric changes of shape grammars, for instance. Here some explanations about the two approaches will be presented.

A third approach exists but will not be part of this chapter. It refers to case-based design which is a deeper study of each scenario independently (Al-Kazzaz & Bridges, 2012).

3.1. DESIGN THINKING AND ADAPTIVE METHODS

The architectural design thinking has been discussed in the early works of Bryan Lawson (1980) and Peter Rowe (1987). Design thinking might be defined as a process of "creative strategies which designers utilize during the process of designing" (Visser, 2006); it also might be defined as "a process of exploration and creative strategies" in all design domains.

Oxman (2017) reports that, during the 1980s and early 1990s, the design thinking theory was based on a cognitive process with an introspective approach, which remains today as a regular practice. Then new theories evolved to a valorization of the design process itself, aiming at documenting and evaluating every decision step. With the propagation of computer-aided models in the late 1990s, the tools became supportive of design decisions and the ease of modeling and modifying a solution in a 2D or 3D environment granted later on the contemporary code-structured models that parametrically control geometries. Capabilities of simulating models, evaluating ideias, and the possibilities of fabrication within the digital process have been reformulated cognitive models of design thinking.

Besides traditional typological thinking, where elementary solutions are the basis for new designs and improvements, as in the traditional design process, the topological manipulation allowed by parametric models shifts a paradigm of design thinking (Oxman, 2017). Therefore, if conventional design processes are about sketching, analyzing, repairing, and redesigning, the parametric design processes add a relating component, or an association of elements, becoming something dependent on a chain of decisions (Woodbury, 2010). This new process configuration becomes sketching, analyzing, relating, manipulating, and redesigning with the flexibility to changes.

The digital environment became almost limitless in terms of exploration. Script languages associated with design allowed the designer to choose in a tangible world of possibilities. With the code-based models, “the designer is no longer making choices about single objects, but creating a matrix encompassing an entire population of possible designs” described as “explorative reflection” (Reas & McWilliams, 2010).

> *“Parametric design as an act of design thinking is based on the exploration and re-editing process of associative relationships in a geometrical solution space.” (Oxman, 2017)*

This statement says that re-editing a relationship in the parametric schema is an act of design and exploring the possibilities generated from this new associative model complements the act of design, giving the desired solution.

According to Oxman (2017), parametric design thinking is the intersect field between parametric models of design, computational models of digital design processes, and cognitive models of architectural knowledge.

Parametric design refers to associative relationships between geometries and functions, it is about manipulating topological structures and exploring parametric capabilities of a model. It is about exploring solutions by refinement and adaptation of a parametric schema. It is a way to evaluate predefined variations of solutions. The structure in which this schema is defined allows the geometry to have an open logic, visible through the script code or visual programming language, like in Grasshopper for Rhinoceros 3D, for instance. Therefore, a re-design demands a new set of associative rules and then the paradigm of design thinking is more focused on the structural logic of this associative model and less in the object itself (Woodbury, 2010).

> *"Understanding how to manipulate and explore associative relationships and dependencies in topological geometry are among the central concepts and principles of parametric design thinking." (Oxman, 2017)*

One traditional way to find a form or a solution in architecture is the process of form-structure-material, in which the desired form will demand a structural logic or a specific material. One possible shift in this schema, when considering parametric design, is the process of material-structure-form. For instance, the Chinese office HHDFun[19] has been working with entrepreneurship under this new paradigm. This shift is not only due to parametric design but to the digital fabrication of elements. The materialization of design becomes dependent on the new fabrication processes. For instance, the wooden structure of the Metropol Parasol in Seville designed by Jürgen Mayer and Arup in 2011 (Figure 18) is evidence of a geometric solution based on an innovative fabrication process.

A trend in the parametric design thinking is to design with patterns. Patterns may be able to generate differentiation (Oxman, 2017). The differentiation is usually due to an external stimulus like environmental conditions, restriction, or goals, and the pattern or the geometry adapts to suit these conditions. This pattern-based adaptation is also inside the domain of the parametric design thinking paradigm, which opens the possibility of design optimization since a variety of possible solutions can be tested and evaluated.

Defining and describing how a predefined shape will be able to move, duplicate, spread itself in pattern and relate itself with new shapes or other existing conditions in the ability to represent these modifications with forward-thinking. And translate shape modification to a language or

---

[19] More about their work in http://www.hhdfun.com.

an environment where these modifications can happen, relates to the shape grammar concept (Jowers, et al., 2019).

According to Oxman (2017), the process of designing with parametric thinking creating models with processes like formation, evolution, performance-based, generative models has demonstrated a holistic process of production, been innovative in design, performance, and fabrication.

Beyond the view that parametric design is only related to some media and tools to develop complex objects, contemporary theories report how parametric design has changed the design thinking and has created innovative, distinct and creative designs.

> *"Parametric design thinking is an evolutionary process of explorative design of the parametric schema." (Oxman, 2017).*

When thinking in evolutionary design, a clear distinction must outcome as Frazer (1995) notices. There are two ways of facing evolutionary design, one as a source of inspiration[20], and the other as a source of explanation. The first relies on a mind search and some physical misunderstanding may provide imaginative stimulus and visually appealing designs. The second requires that science is correct and that the analogy with scientific principles is valid. The author defends a model where nature becomes the generating force for the architectural form, therefore considering architecture as an evolving thing. The lack of intentionality when designing is one of the central characteristics of evolutionary architecture, but the outcome is

---

[20] In that sense the vision of an architectural style defended by Schumacher (Leach & Schumacher, 2012), the parametricism, may relate to the inspiration in the design process. The context in what the author discuss his ideas is not the same treated in this work, since it has to do with the cultural and communicational attributes of design and architecture, but it worth notice.

an evolved form from structured environmental modeling, unlike when we are traditionally designing with cognitive principles.

In that sense, Frazer (1995) meets the conceptual field defended by Bejan and Lorente (2008) where evolutionary design or the Constructal Design searches to evolve shape in time through physical-based description and manipulation of objects from nature or even manmade objects, imitating the design of living systems in nature. This topic will be further discussed in the next chapters.

3.2. ADAPTATION WITH PARAMETRIC DESIGN

In the past decades, the subject of parametric design has seen an increasing number of publications[21]. From the practitioners' point of view, parametric design implemented a myriad of possibilities, adding complex geometries to the contemporary architectural repertory. One trend in the contemporary architectural language is about dealing with complex geometries based on simple rules (Aranda & Lasch, 2006) or based on patterns (Boake, 2014; Woodbury, 2010). Therefore, due to its complexity of manipulation, planning parameters and rules towards a flexible model is crucial for creating complexity. One practical example in this direction is the production of the Chinese office HHD Fun.

The logic of parametric design may also shape and improve standard manufacturing constraints, assembly logic and material characteristics in the definition of simple components, and then proliferate the components into larger systems and assemblies (Khabazi, 2010). Likewise, Zani et al. (2017) worked improving a modular façade element in terms of daylighting performance, with a predefined topology. The shape was conditioned to parametric modeling to refine and

---

[21] For instance, 1138 publications do reference to parametric modeling in construction in 1997, 2274 publications in 2007, and 6536 publications in 2017 according to Science Direct web source.

search optimization for this element. Or yet, Kirimtat et al. (2019) also searched for refining a predefined topology of louvers, looking for amorphous designs.

It is possible to say that any design process is parametric on some level since it considers a bunch of limitations and conditions that will shape the final design (Gerber, 2007). Moreover, saying that a model is parametric is saying that equations rule parameters that shape the object and we can manipulate these parameters to test and generate several configurations. This manipulation is not arbitrary or not done by a software or a machine itself, but unlike, clear methods rule the algorithm which needs planning and forward view (Smith, 2007).

Models generated by algorithms tend to have an interdependency between levels of modeling. For instance, if we generate a form that respects a grid and depends on a center point, moving one of these points may change the whole model. These algorithmic levels of hierarchy and interdependency build a model that works in an associative way. Another denomination for that is associative design (Khabazi, 2010).

Parametric design is a concept workable in many available software packages, e.g. Catia, 3D MAX, 3D Maya, Grasshopper for Rhinoceros 3D, Revit with extended capabilities with Dynamo, Generative Components, Marionette, and Modelur. However, the join between Rhinoceros 3D and Grasshopper has demonstrated to be a widespread platform for visual programming of parametric models in academic works (Davis, 2013; Cunningham, et al., 2014; Elghazi, et al., 2014; Eltaweel & Su, 2017; Zani, et al., 2017; Jakica, 2018).

Many plugins developed for Grasshopper add building physics into parametric modeling. To list some, Diva performs thermal, solar, and daylighting analysis (Cunningham, et al., 2014). Ladybug performs an environmental analysis of the 3D model in the early design stages. Honeybee performs energy and daylighting analysis connecting a Grasshopper model with

Open Studio and EnergyPlus, Radiance (Youssef, et al., 2018), Daysim, and Therm. Geco connects Grasshopper with Ecotect, which some papers reported (Turrin, et al., 2011).

An approach of the plugins developed for simulation is that most of them utilize notorious physics-based engines to perform calculations and these plugins make the bridge between the engine and the parametric model. Diva for Rhino, for instance, utilizes Radiance and Daysim engines to perform these simulations. Authors have recognized these engines as seminal software for daylight simulations (Reinhart & Breton, 2009). Radiance and Daysim employ a reverse ray-tracing algorithm based on the physical behavior of light in a volumetric, three-dimensional model, which should most accurately represent reality (Ward, 1994). The validation of Radiance and Daysim appears in many studies (Reinhart, 2001; Reinhart & Breton, 2009; Reinhart & Wienold, 2011). They accurately represent occupant comfort, occupant behavior, and the distribution of natural light in a space.

For a physics-based problem, optimizing solutions is the desired goal. The parametric model responds to the imposed variables and it is possible to test the model several times to find better and better solutions. Because of that, for shape exploration, flexibility is everything that parametric models must do to free the form to work parametrically (Smith, 2007). Creating different scenarios for comparison is feasible with parametric models and for performance evaluation, it is required. To build workable and functional models is as much about inputting data, managing data, and organizing the graph as it is about modeling geometry (Davis, 2013).

3.3. Adaptation with shape grammar

The concept of shape grammar came from artistic shape explorations (Stiny & Gips, 1972) and it is completely related to translating shape possibilities into a computational environment. Iterations between shapes and repeating modification processes have as an outcome new topologies, and shape grammar is the proper theoretical approach to deal with it. Modification processes are addition, deletion, replacement, resizing, reposition, combination, and parameter adjustment (Stiny, 2006).

When we are working with shape exploration through computer-aided design, defining what are the rules, functions, and parameters changing our shape will provide flexibility to the model. Therefore, it is necessary to describe a shape and also to allow new shapes to happen. In that sense:

> *Shape grammars are generative formalisms in which dynamic changes to shape structure plays a vital role. Such changes support ambiguity and emergence, and as a result shape grammars are often used as the basis for proposed developments in supporting shape exploration in computer-aided design. (Jowers, et al., 2019)*

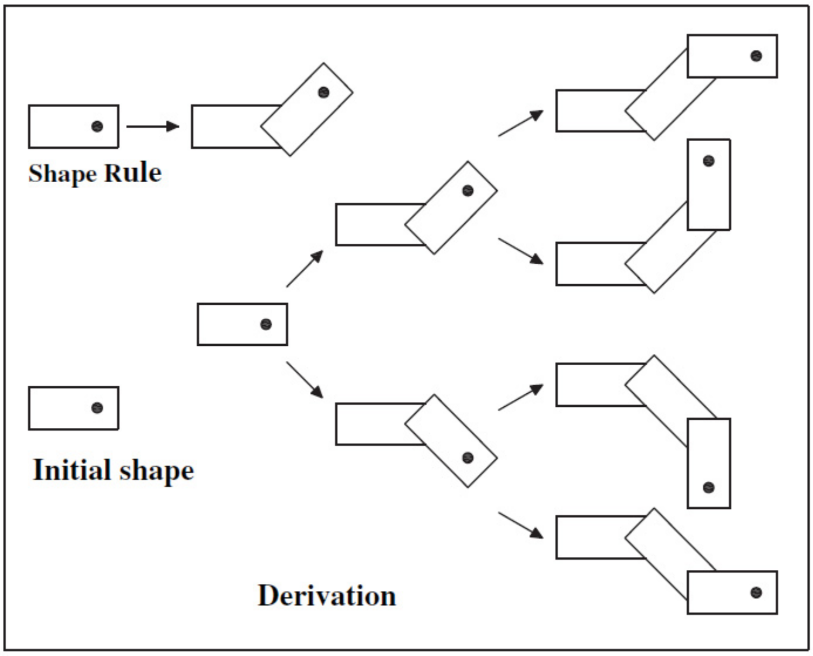
Shape grammar defines a new level of freedom, and requires a wider computational environment in terms of flexibility when compared to parametric design. In the CAD tools usually, the organization and tools to manipulate a topology tend to preserve its integrity. Therefore, according to Jowers, Earl, and Stiny (2019), shape grammars are not yet satisfactory in achieving all their potential. The hindrance is the correlation between a dynamic creative process in which new outcomes will support new embedded parts in design exploration and allow flexibility in computational models where fixed rules limit final shape exploration.

Shape grammars to achieve this level of flexibility need to allow topology changes during the design exploration (Jowers, et al., 2019). Due to the theoretical freedom proposed by the shape grammar concept, it is comparable to sketching an idea, but at the same time, assumptions must be made, to set the rules that become generative designs. That necessity leads researchers to often recognize it as limiting the use of shape grammars:

> *"However, the argument often used to justify this conclusion (that CAD systems limit the usefulness of shape grammars) recognizes that in order to specify predefined parts it is first necessary to make assumptions about the future shape explorations a designer may follow, and therefore restrict the designer's creative freedom" (Jowers, et al., 2019)*

Although these authors, who are in the frame of the creation of the concept, recently have seeing shape grammars with some dose of pessimism or frustration as presented, some works have been defining smaller cutouts to add flexibility to shape grammar systems in CAD platforms, like Al-Kazzaz and Bridges (2012). These authors also defend that shape grammars and adaptation methods are strategies to outcome new designs and shape exploration from precedent shapes (Figure 11).

Figure 11 - Example of shape exploration with a shape grammar concept



Source: (Al-Kazzaz & Bridges, 2012)

Still, some practical approaches are found in the literature. Youssef, Zhai, and Reffat (2018) apply shape grammar techniques to explore photovoltaic modules applied to build façades.

They present a conceptual exploration with building shape and photovoltaic generation potential.

The work by Vazquez (2017) modeled the construction logic of perforated masonry walls, a traditional modernist and contemporary shading and ventilation façade system in Paraguay.

Eilouti (2019) describes a complex façade composition with shape grammar rules. Although there is neither design process nor shape exploration involved, it is possible to notice that simple rules may generate these complex compositions.

4. PERFORMANCE-BASED DESIGN

Better solutions could be obtained from a comparison between scenarios. However, as demonstrated in previous chapters, associative models, which adapt their shape when required, give the flexibility to explore more scenarios without the necessity to remodel a geometric solution.

The literature demonstrates that associative models and performance simulation together may increase daylight performance in 30 to 60 % compared with standard façade solutions (Elghazi, et al., 2014)[22]. These increased performances also lead directly to an increase in the energy efficiency of buildings due to fewer hours needed for electric lighting and possibly appealing aesthetics when exploration new shapes (Yi, 2019).

Here, genetic algorithms will be discussed as the tool to evolve a shape towards optimization. Still, some artifacts from the literature will be presented and the Constructal Law is discussed as the identified law in nature for the design of natural things.

4.1. GENETIC ALGORITHMS AND OPTIMIZATION

Firstly presented by Holland (1992), yet in his original publication in 1975, the genetic algorithm[23] is a metaheuristic optimization technique based on the natural selection and evolutionary process. This process is based on genetic operators like crossover and mutation. Therefore, the crossover is the process were the characteristics of individuals will recombine among pairs of genes to generate new configurations, this process is the basis of a GA. Thereby, the progressive selection of the best-fitted individuals will drive a specie or a shape to

---

[22] In this example, the parametric façade is a dynamic folding façade and the standard façade is a static window in a wall.

[23] In his book, the term genetic plans was used in the 1975's edition and was kept in the 1992's edition as well, but years later genetic algorithm was most accepted term due to the extensively use of computers for the process.

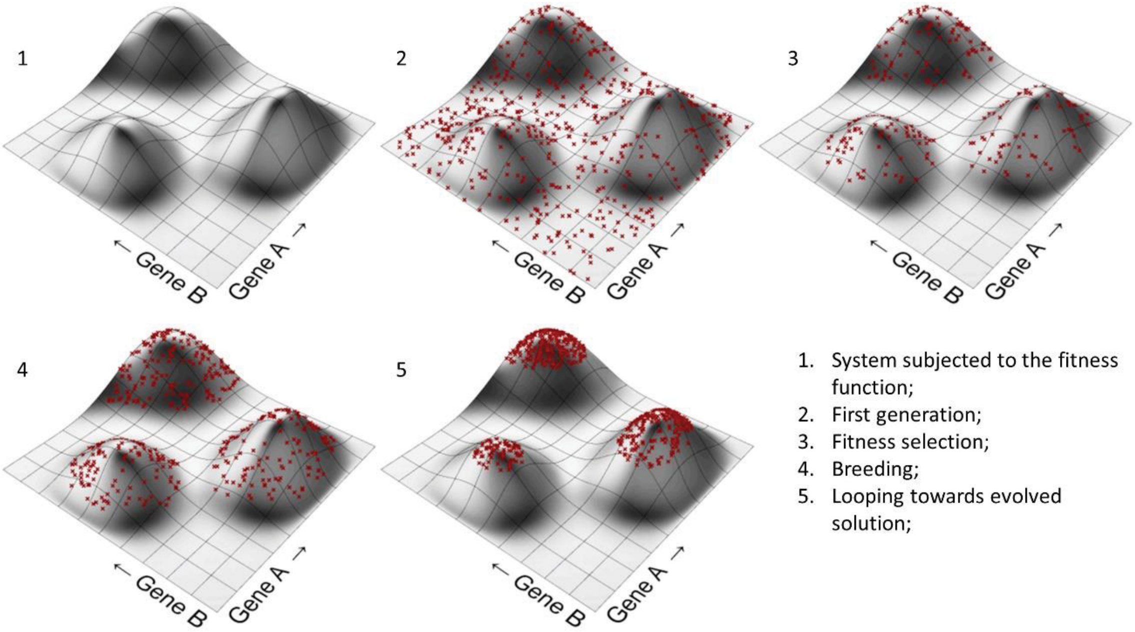
optimization. The mutation is a complementary background operator assuring that the crossover has a full range of possible configurations, avoiding the evolutionary simulation to get trapped in a local optimum, i. e. a false optimized solution. For the mutation to work properly, the number of variables has to be manageable, or the rate of mutation must be proportional to it, otherwise, the mutation will not be sufficient to avoid a local optimum during the evolutionary simulation.

Evolutionary algorithms refer to computational methods inspired by the mechanical and biological processes of evolution. They emulate natural selection as proposed by Darwin, considering the adaptation and variability of species suitable to its environment (Bronwlee, 2015). It is a field of study in evolutionary computation that seeks to resemble simplified versions of the evolutionary process with similar results of the natural evolutionary process.

> *“The logic of optimization methods can be sketched as follows: The "inner environment" of the design problem is represented by a set of given alternatives of action. The alternatives may be given in extenso: more commonly they are specified in terms of command variables that have defined domains. The "outer environment" is represented by a set of parameters, which may be known with certainty or only in terms of a probability distribution. The goals for adaptation of inner to the outer environment are defined by a utility function, usually scalar, of the command variables and environmental parameters perhaps supplemented by a number of constraints (inequalities, say, between functions of the command variables and environmental parameters). The optimization problem is to find an admissible set of values of the command variables, compatible with the constraints that maximize the utility function for the given values of the environmental parameters”. (Simon, 1996) p.116.*

Imagine you have a given population of individuals. These individuals will breed and some characteristics will come up with a new generation of individuals. These new individuals will be tested by nature and during some next generations, while some mutations may occur in their previous characteristics, some primitive characteristics will disappear for the sake of survival during a process of evolution.

Figure 12 - Genetic algorithm logics



Source: (Rutten, 2010)

In genetic algorithms (GA), like in nature, an initial population will crossover with each other and breed, generating new individuals. These new individuals will be subject to a condition to exist, this condition is represented in the GA with a fitness function. That fitness function will generate a probability of survival of the most adapted individuals. Some will be acceptable and some will not. Now, a new population represents a new generation and this cycle begins repeatedly (Figure 12). During this process, some mutations in the species will also create variety and multiplicity of possibilities until an optimized solution is found. This process, when done with predetermined and explicit conditions, is called evolutionary design (Rutten, 2010).

One characteristic of evolutionary algorithms is that they do not guarantee a solution unless the assumptions are good enough to converge (Rutten, 2010). The designer is responsible for the final product even with this machine process redesigning the initial setup. Additionally solving evolutionary models demand computational configurations or it may be time-consuming to reach the necessary number of generations.

The generic approach of these solvers allows them to deal with problems for different disciplines and provide flexibility to refine problems that are difficult to solve without it. Besides that, the solver tends to constantly select the best option, and some preliminary solutions may point in the right direction. On the other hand, if the population is not sufficient, the best solution may be never reached.

There are many kinds of methods for working with evolutionary algorithms. Some have been recently applied to problems of daylighting performance and energy saving in buildings (Kirimtat, et al., 2019). Among them, there is the multi-objective evolutionary algorithm (MOEA), the non-dominant sorting algorithm (NSGA-II) (Rizki, et al., 2018; Manzan & Clarich, 2017), the single-objective evolutionary algorithm (SOEA) (Santos, et al., 2018; Sghiouri, et al., 2018), and the Fuzzy Control System (FCS) (Katsifaraki, et al., 2017).

Three main multi-objective evolutionary optimization engines working with Rhino and Grasshopper are Galapagos (Rutten, 2010) a MOEA, the Octopus (Vierlinger, 2012), which employs the Pareto-principle for multi-objective optimization with the Strength Pareto Evolutionary Algorithm - 2 (SPEA-2) and the most recent Wallacei (Makki, et al., 2018), which employs the NSGA-II as the primary evolutionary algorithm.

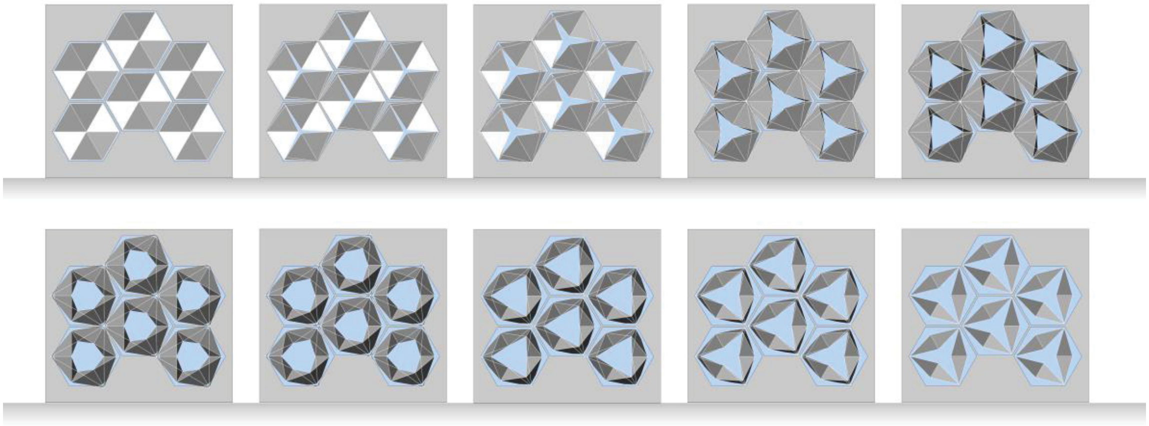
Publications report generative algorithms for several uses. In urban planning, to search for the best pathways for pedestrians in the early design stage (Suyoto, et al., 2015). In urban morphology, to observe natural ventilation and daylight requirements (Saleh & Al-Hagla, 2012). In architecture, to build the *Sagrada Familia's* tower (Davis, 2013) or to naturally illuminate the Louvre Museum in Abu Dhabi (Tourre & Miguet, 2009).

4.2. ARTIFACTS IN THE LITERATURE

As discussed in previous chapters, artifacts are all the things created by a human being. Here this concept was limited to buildings shading devices seeking optimization. The term artifact refers to the Design Science Research scientific paradigm (Dresch, et al., 2015), which conducts the researcher to improve or create an object, an artifact. Besides the artifacts, other experiences in literature are also related here.

Elghazi *et al*. (2014) present a paper aiming at finding the optimized daylighting solution for a dynamic origami-based façade for a residential building. They relate their research with LEED V4 standards for spatial daylight availability. They used Grasshopper for parametric modeling, Diva for daylighting analysis, and genetic algorithms for the optimization and after 73 solutions they reached an optimized design (Figure 13).

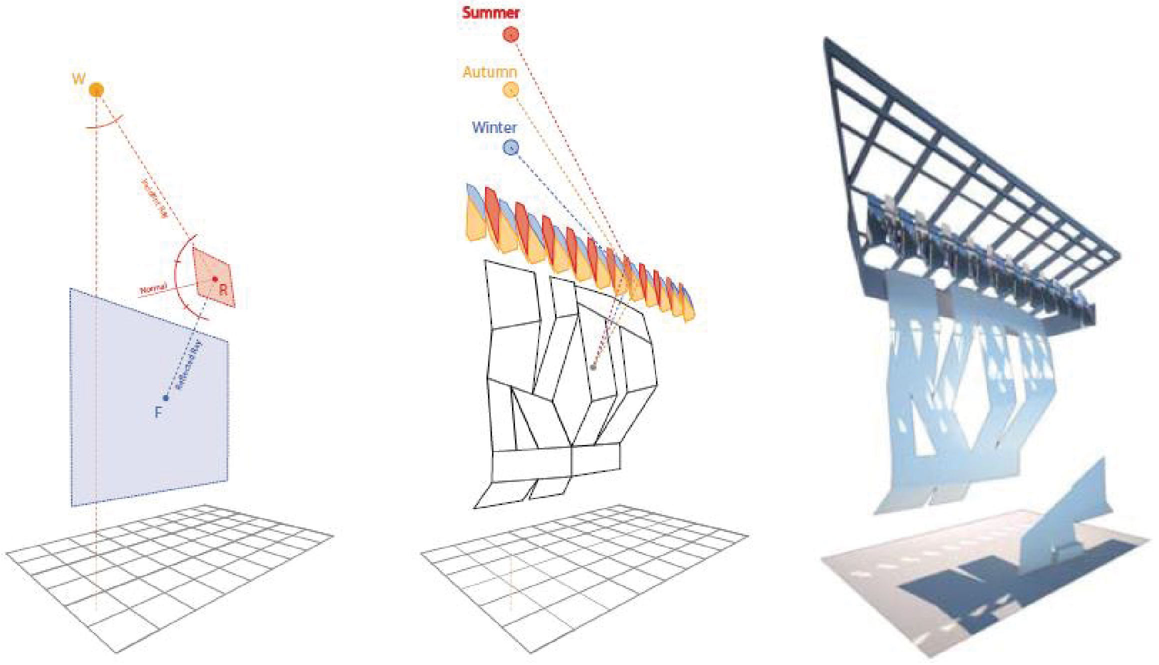
Figure 13 - Parametric configurations of the origami-based shading device



Source: (Elghazi, et al., 2014)

Cunningham et al. (2014) present the development of a parametric system using reflective properties of materials for daylighting, where panels distribute natural light in a north-oriented four-story atrium (Figure 14). The aim was to redirect light to specific points of the atrium, as the general illuminance was satisfactory. They used Diva and Grasshopper for the study. Diva generates the reflected vector of sunlight, which then may vary according to several arrangements of geometry for any specific time of the year. The parametric algorithm was able to count the number of panels, control panel angles, control the display of results, and display different options of performance.

Figure 14 - Daylight redirecting strategy



The normal of a reflective surface is derived from the incident solar vector and the focus (F) and reflector (R) points.

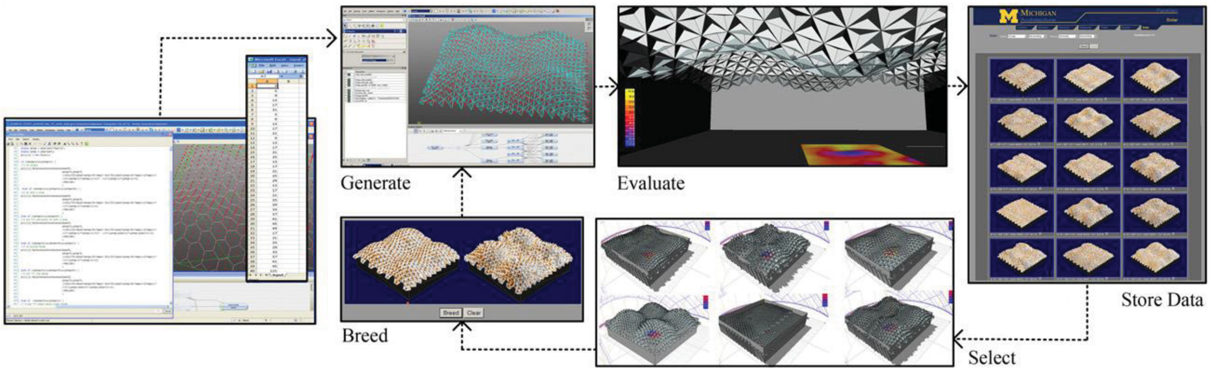
Multiple solar positions over the course of the day and year can be used to generate a series of surface normals.

Surface normals can be used to generate a faceted or curved surface that reflects light in a way that can be simulated using rendering engines.

Source: (Cunningham, et al., 2014)

In Turrin *et al.* (2010) a large span roof was parametrically integrated with structural performance, architectural requirements, daylighting, and thermal behavior. They tested the ETFE polymer and screen-printed glazed panels with varying thermal transmittance. In the same way, in the work of Turrin *et al.* (2011), authors also seek an optimal solution for a large span modular roof. The aim is to provide a broad tool that controls the geometry based on structural requirements and solar passive strategies. Their work presents the ParaGen, an interface that integrates several files to evaluate the model, and controls the geometry through a web-based server. They presented two cases, both intended to seek an optimal solution. While in one study the designer has chosen the final solution, in the second study the solution was performance-based chosen. For the second case, Figure 15 represents the whole cycle of optimization. Moreover, this cycle was firstly about defining the geometry and the parameters, then generating an initial solution with Ecotect. To develop performance-based solutions, the GA select, breed, create a new generation and reanalyze until an optimal solution is reached satisfying the initial conditions.

Figure 15 - The ParaGen cycle during the solar energy analysis



Source: (Turrin, et al., 2011)

Torres and Sakamoto (2007) subject a light-shelf façade solution to optimization regarding the illuminance values inside a room, with Radiance and a genetic algorithm.

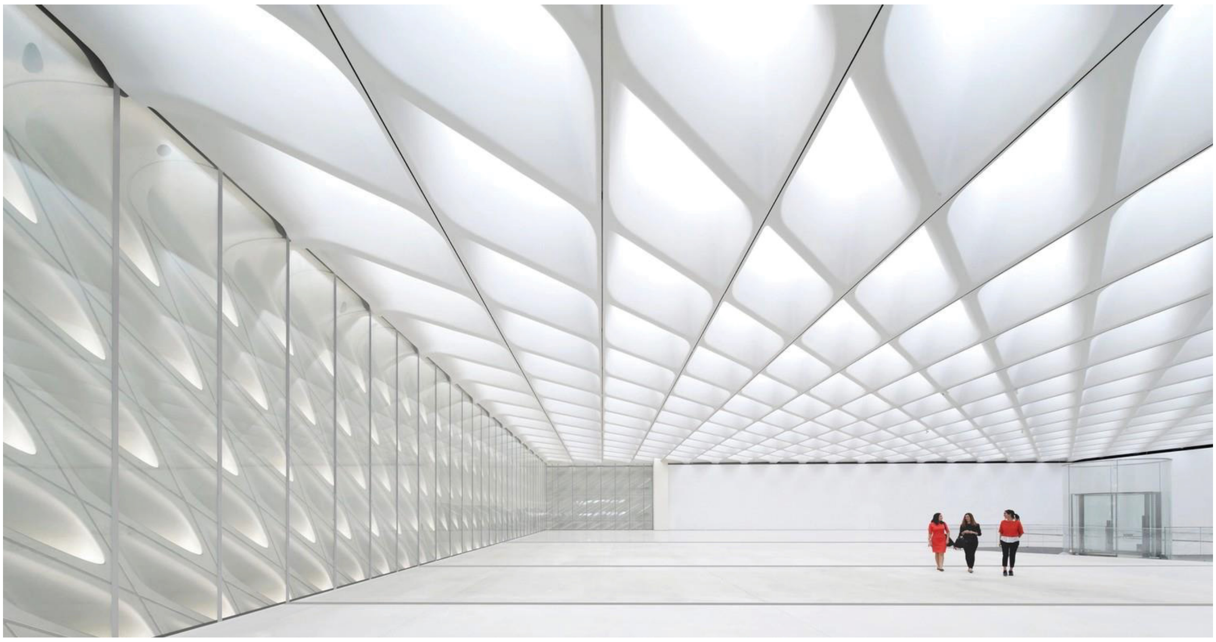
Yi (2019) optimizes an existent building façade for daylight and aesthetical requirements using parametric modeling, spatial daylight autonomy (SDA), and annual sun exposure (ASE) metrics with DIVA daylight simulation tool, and a multi-objective algorithm for optimization.

Kirimtat et al. (2019) compare multi-objective algorithms to find optimal solutions for louvers in a building façade. They were seeking for satisfactory useful daylight illuminance (UDI) while decreasing the total energy consumption (TEC) and reached a 14 % economy in TEC.

Zani et al. (2017) present an optimal solution, cited earlier, for an innovative building shading device made with concrete. The topology is manipulated until it reaches an optimal solution in terms of UDI.

The Broad Museum in Los Angeles, by the Diller Scofidio + Renfro Architecture Office (Diller, et al., 2015), works with an optimized shading façade with a parametric rhomboid pattern. This pattern covers the vertical faces as well as the roof of the building. The effect of the interior diffuse daylight may be seen in Figure 16.

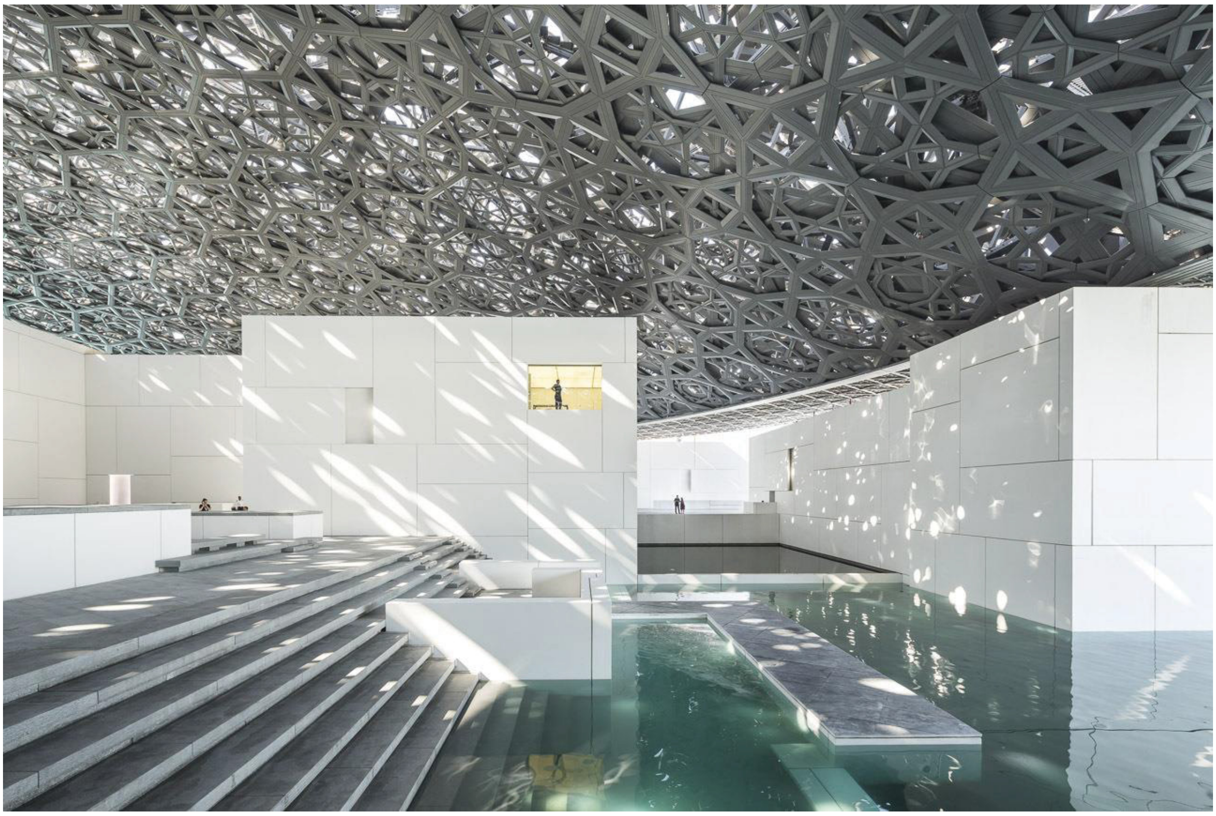
Figure 16- The interior of the Broad Museum, Los Angeles (2015)



Source: (Diller, et al., 2015)

Tourre and Miguet (2009) presented a daylight performance-based algorithm for designing openings and shading devices distribution. They applied their method to design the dome of the Louvre Museum in Abu Dhabi, from Jean Nouvel’s studio. Their method considers the openings as an intermediary light source where the emittance of these openings is an important parameter. They call their method an inverse simulation (Figure 17), which means to conceive the openings based on the requirements of the ambient light intentions. They used Solene as software for simulation.

Figure 17 – Interior daylight painting in Louvre Abu Dhabi with parametric permeable roof and Tourre and Miguet (2009) method



Source: (Boegly & Grazia, 2018)

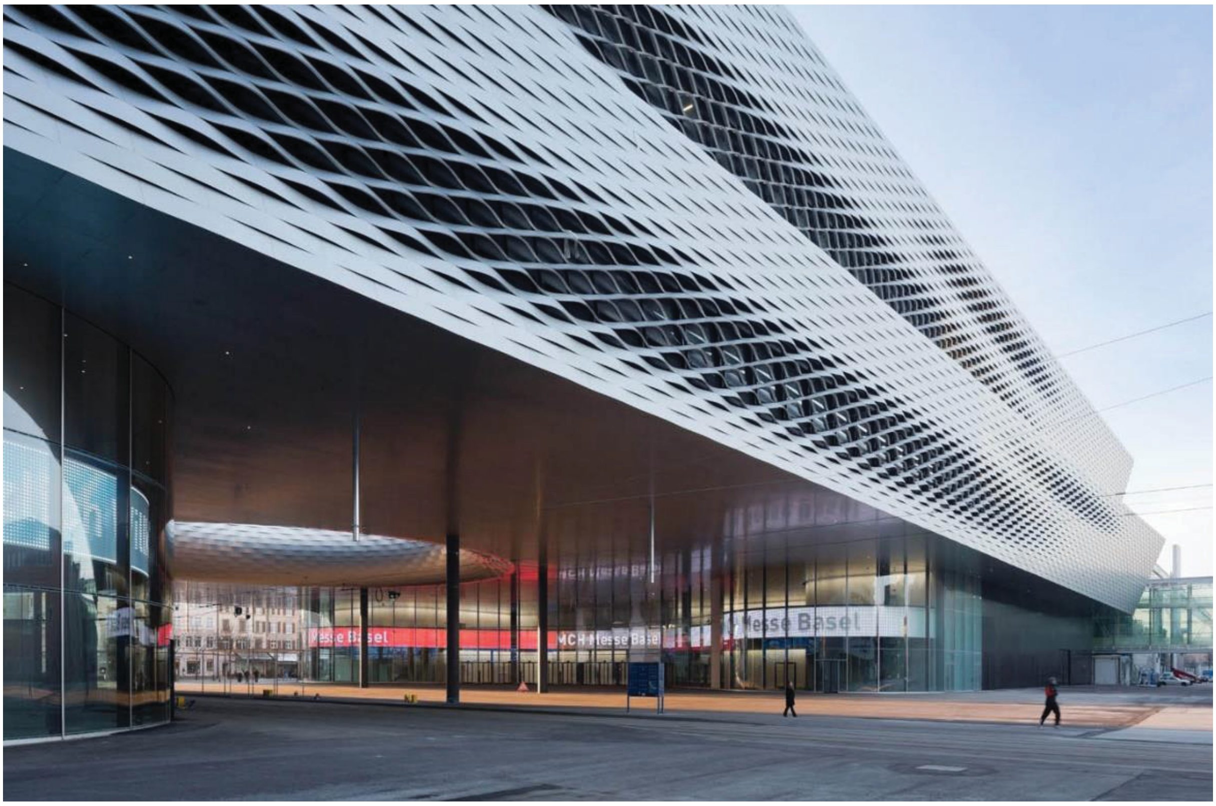
Another shading device, cited earlier, is the Metropol Parasol in Seville, Spain by Jürgen Mayer and Arup offices (Figure 18). Although it is an open public area, it provides shaded areas for the public spaces. Parametric algorithms were used for modeling the structure and detailing the wooden geometry (Oxman, 2017).

Figure 18 - View to the Metropol Parasol, Seville (2011)

Photo credits: Sérgio Fernando Tavares

In the building for the Messe Basel New Hall (Figure 19) the architecture team of Herzog and De Meuron created an aluminum pattern that bends and folds to capture indirect daylight for the interior exhibition halls and allow the view to the landscape from the inside. Parametric design thinking based on material fabrication was used to help solve the building façade (Oxman, 2017).

Figure 19 – Aluminum bent façade of the Messe Basel New Hall, 2013



Source: (Herzog & De Meuron, 2013)

Here some examples illustrated the tools and strategies to deal with similar problems of shading devices or façade elements that parametrically enhance daylighting. These publications are an important source of guidelines, standard procedures, hindrances, and evaluation of the method and their products, which are valuable when comparing to my research proposal.

Worth notice, yet, the work of Doris Kim Sung (2018; 2016) and her living façade systems based on material deformation. Her office works with performance-based façade elements as self-shading, self-structuring, self-ventilation, self-energizing architecture proposing buildings that are integrated with the climate with artistic and sustainable appealing (Figure 20).

Figure 20 - An unbuilt cooling structure for public space in Israel, 2014

Source: (Sung, 2016)

In the previous section, some works were mentioned applying evolutionary degin principles to test a geometry subject to a physical condition. In the present work, the goal is to provide a flexible code that may redesign the building envelope to find the best design for a cobogó-based façade.

4.3. CONSTRUCTAL LAW TOWARDS A GENERAL LAW FOR DESIGN IN NATURE

As presented earlier in this work, the Constructal Law (CL) states: “For a finite-size flow system to persist in time (to live), its configuration must change in time such that it provides easier and easier access to its currents (fluid, energy, species, etc.)” (Bejan & Lorente, 2008). This statement summarizes the aspects discussed previously in this work, and more specifically in this chapter. This is a general rule to predict the design of natural things[24] with the possibility to apply this same concept when designing new manmade things as well. In this sense:

> *"Constructal Theory is not modeling, even though one can build models from it. It is the conjecture that supports the idea that any occurrence of organization and design is the result of a sole natural principle." (Errera, 2018)*

Errera (2018) situates the Constructal Law in the light of the philosophy of science, discussing its validity as a law from the extreme demarcation principle of Popper's *critical rationalism*[25] to Feyerabend's *methodological anarchism*. Additionally, Constructal law has been applied to a variety of problems, like cooling systems (Bejan, 1997), airplane design (Bejan, et al., 2014), in logistics (Bejan & Lorente, 2011), or earth-heat exchangers problem (Rocha, et al., 2012). The nomenclature of law comes from the idea that it is how nature organizes things to keep them living and with a wide scientific production this law was not refuted and that it cannot be derived, or has not yet been, from any other fundamental law of nature.

As Errera (2018) presents, the Constructal theory is supported by two main hypotheses:

1. The generation and evolution of shapes, forms, structures, rhythms, i.e., design and organization in nature is a physical phenomenon - which means things react to its environment and with its internal organization, therefore design and shape of things adapt its conditions to keep existing;
2. Such a phenomenon is the outcome of a principle: the Constructal Law;

---

[24] In opposition to the Science of artificial in the Simon's work, when the Constructal Theory refers to the design of natural things, it comprises animate, inanimate and human-made realms (Errera, 2018).

[25] Popper's critical rationalism or falsicationism

If this theory was firstly a result of inductive reasoning (Bejan, 1997), where a small set of observations were the basis for a larger theory, without proving it at the moment it is stated, today more than 13.000 qualified citations refer to the constructal theory (Errera, 2018). Another author defends the status of law for the Constructal Law by saying:

> *“The Constructal Law is as general as the First and Second Laws of Thermodynamics but has a very different scope that makes it unique and complementary to those laws. While the First Law points to the conservation of energy, both the Constructal Law and the Second Law point to change, i.e. to a direction in time. Though both these laws share this common feature, they diverge as with respect to the scope. Contrarily to the Second Law, Constructal Law applies to systems out of equilibrium, i.e., systems that evolve in time. While the Second Law deals with state variables, the Constructal Law combines flows and design (size, shape, structure).” (Reis, 2011)*

Therefore, the Constructal Law complements evolutionary design through the optics of physical processes and yet validates design in the scope of the scientific field.

5. APPLICATION OF EVOLUTIONARY DESIGN

The objective of this work is to propose and evaluate a parametric schema for designing performance-based façade elements that improve daylight performance.

Firstly, a study was conducted for comparing some standard solutions for building façade. This study is a benchmarking for a shading solution in the north façade for the city of Curitiba, state of Paraná, Brazil (latitude 25°25.6668′ S). The climatic data used is an EPW file from the weather station 838420 (LABEEE, 2018). Six cases are presented for benchmarking. First a façade with two regular windows, second a fully glazed façade, then a commercial 45º horizontal louver, and commercial 60º horizontal louver, a strip window with light shelf, and a standard cobogó façade.

Then, the object of study here, the cobogó, is also evaluated for the other three façades in the same location, façades south, east, and west. Such a study shows the overall performance of this modular mass-produced building element considering daylight distribution and sunscreening.

For the sake of clarity, some assumptions and limitations were imposed to develop the work. First, the chosen façade element to optimize is the *cobogó*, a traditional architectural element that creates shade and allows natural ventilation (Figure 21). It is usually made of concrete, and it is mass-produced with cast-based fabrication. These characteristics were kept as assumptions of the study. Although many shapes are available in the construction market, the basic shape and the most spread solution is the perforated brick with an offset from its perimeter, as shown in Figure 21[26]. We begin the study with this basic topology and increase the degrees of freedom

---

[26] In this Figure, the National Library is presented as an example of Oscar Niemeyer building using the cobogó. Although the element or the façade were not designed with optimizing processes, Niemeyer confirmed the cobogó as a traditional building element of Brazilian modern architecture, and used it as an aesthetical of mass production.

to let the design evolve and explore new solutions with the evolutionary performance-based schema.

Figure 21 - Cobogó-based facade in the National Library in Brasília - DF, Brazil.

Source: From the author

The standard cobogó considered here is a 20 cm x 20 cm modular element, with 8 cm depth and 2.5 cm offset from its perimeter. The freeform modification has the intention to add flexibility to the model and allow different final objects for different façade orientations or locations. In the next section, further details will be presented about the daylighting simulation methods, the model structure and hierarchy, the genetic algorithm behavior, and the system configurations.

5.1. DAYLIGHT SIMULATION AND MODEL DESCRIPTION

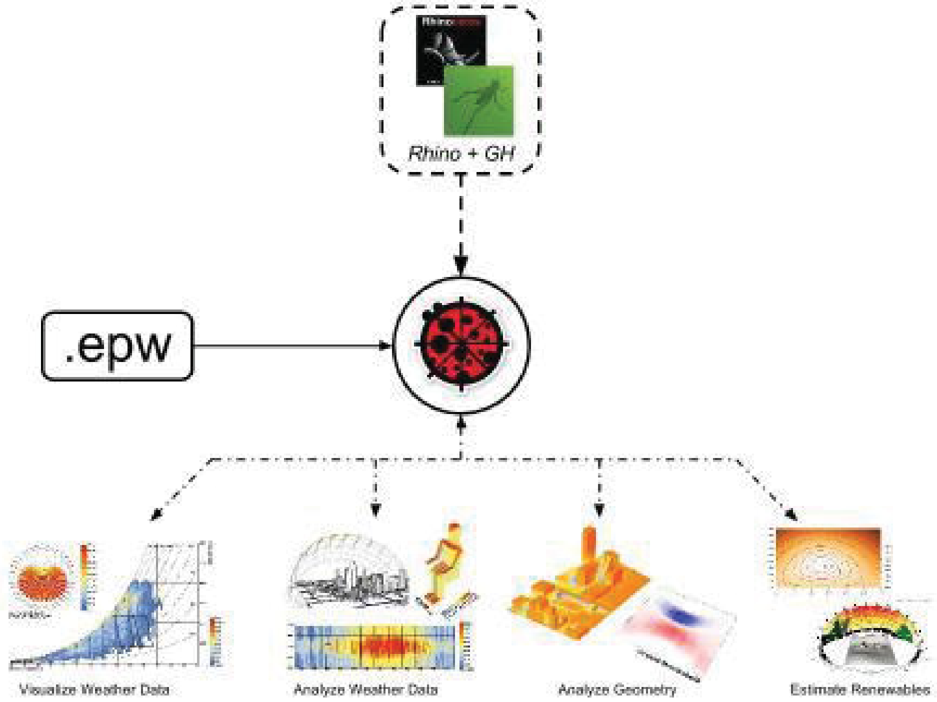
The whole process of the simulation was carried out inside Grasshopper for Rhinoceros 3D software. Rhinoceros is a 3D modeling software based on NURBS curves[27] and complex modeling tools. Grasshopper uses a visual programming language as an interface for parametric modeling with Rhinoceros 3D. Additionally, Roudsari (2020) developed a Python-based open-source plugin that links Grasshopper and Rhino 3D with Radiance, Daysim, Therm, EnergyPlus, and OpenStudio expanding the capabilities of Grasshopper visual programming environment. This plugin, called Ladybug, together with Honeybee[28] is used here in this work to connect validated simulation engines with a parametric model. The capabilities of these plugins are briefly shown in Figure 22 and Figure 23. Ladybug is platform for climate data analysis and interpreter of comfort requirements with capabilities of predicting solar radiation in external surfaces and estimating the use of solar radiation for energy generation.

---

[27] NURBS – Non Uniform Rational Basis Splines is a mathematical model used in computer graphics to represent freeform surfaces using and interpolation of curves based on points in the space, like Bézier Curves.

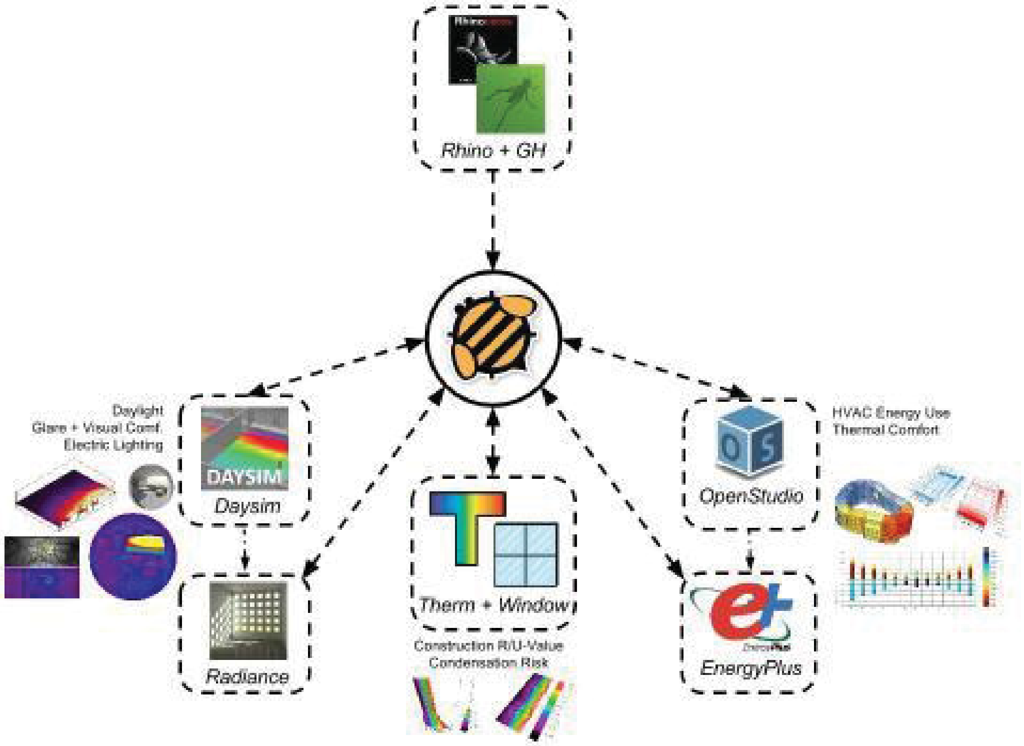
[28] Honeybee Legacy was used to build the script of this thesis. From the notes of Dr. Marsch from this thesis, and further research, I have noticed that Honeybee legacy only works integrated with Daysim. As presented in the chapter 2, Daysim performs the annual simulations and works with Daylight Coefficients technique, i.e. the 2-Phase method. More recent phase-methods (2PDDS, 3PM, 4PM, 5PM, and 6PM) were also incorporated in Honeybee, but in a parallel version, called Honeybee[+] (Roudsari, 2017).

Figure 22 - Ladybug plugin for Rhino+Grasshopper



Honeybee is a platform to perform more refined simulations, based on zone creation, considering the interior spaces of the building, performing daylight analysis, thermal behavior, and energy efficiency of buildings. The main connection of interest here is with Radiance and Daysim where daylight performance is evaluated.

Figure 23 - Honeybee plugin for Rhino+Grasshopper



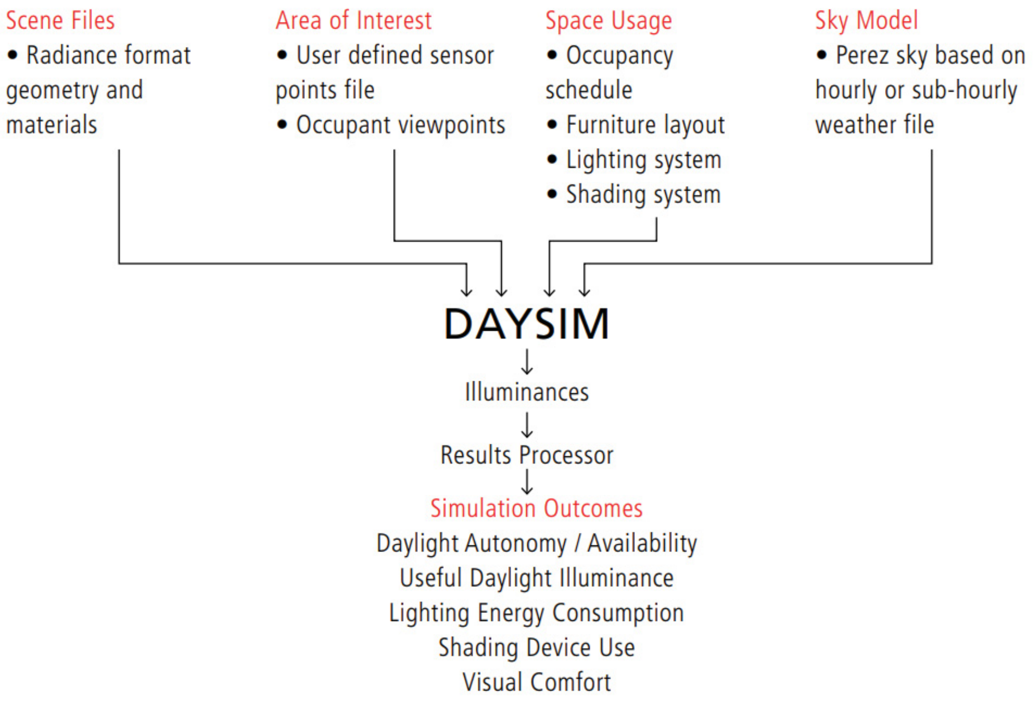
Radiance is a scientifically validated software to perform light simulation studies (Ward, 1994; Ward & Shakespeare, 2003). Radiance is a "rendering system tailored to the demands of lighting design and architecture. The simulation uses a light-backward ray-tracing method with extensions to efficiently solve the rendering equation under most conditions. This includes specular, diffuse, and directional diffuse reflection and transmission in any combination to any level in any environment, including complicated, curved geometries. The simulation blends deterministic and stochastic ray-tracing techniques to achieve the best balance between speed and accuracy in its local and global illumination methods" (Ward, 1994).

Radiance was first designed in parallel with rendering applications for architects, extending the role of illustrative images produced during design processes to light visualization techniques as a physical phenomenon to aid light design and architectural decisions.

The light-backward ray-tracing method first present by Whitted (1980) consists of the light being computed from the viewer or the photometer back to the light source. The result is the same as when computing light from the light source, but more efficient, since the software computes only the light ray that impact in the scene or the test points in the room. Radiance was previously validated as a scientific tool for light visualization (Mardaljevic, 1995; Mardaljevic, 2000a; Mardaljevic, 2001; Mardaljevic, 2004) and has been used in several papers for daylight studies and visualization (Uehara, 2018; Elghazi, et al., 2014; Mackey, 2017). Deterministic and stochastic approaches used in Radiance were presented earlier in chapter 2.

Daysim is a Radiance-based simulation tool that performs annual daylight simulations considering the Perez sky model (Perez, et al., 1993). Therefore, daylight metrics considering annual analysis, like sDA, cDA or UDI, will be performed with the aid of Daysim in this work. Additionally, Daysim has the capability of analizing comfort requirements regarding daylight problems in interior spaces (Figure 24).

Figure 24 - Daysim and its capabilities



Source: (Reinhart, 2010)

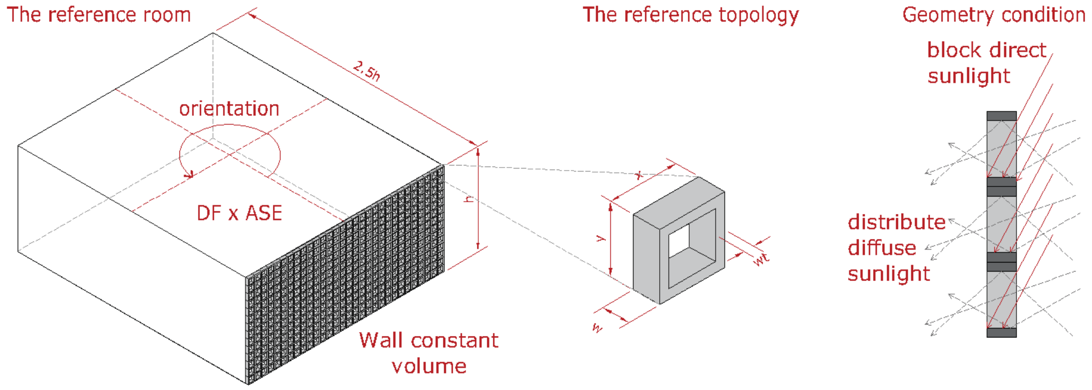
Therefore, for modeling the sky conditions and computing them for the predictions in this work, Radiance/Daysim requires annual daylighting data. Some annual data are available for public use, and even if there is a missing part for some locations, it is possible to reproduce the dynamic changes in the real sky conditions, considering a complete Test Reference Year (TRY) file with global horizontal irradiation and direct normal irradiation, using the Perez sky model, based on CIE sky types (Perez, et al., 1993).

Additionally, to spare simulation time and represent these changes, the Daylight Coefficients technique is used (Ward & Shakespeare, 2003; Ward, 2000).

In addition to the sky behavior, the surrounding environment reflectance is quantified by the albedo value that considers the overall reflectance of the surrounding buildings, trees, and the ground. Here we assume a ground floor building and its immediate surroundings with an exterior floor albedo of 0.2. Considering the surrounding floor or not, could change the results in about 1.16% according to this work pre-testing.

The room virtually built to test the shapes of cobogós has 6.0 m x 7.0 m floor dimensions and is 2.8 m high (Figure 25). The cobogó façade was fixed at the face with a 6.0 m width and a height of 2.8 m. The proportions of the room follow the rule of thumb of daylighting requirements as presented in chapter 2. Additionally, the main façade can be dynamically positioned towards any direction by the rotation of the room as presented in Figure 25.

Figure 25 - Model description



The building itself is composed of theoretical materials that were kept constant for all simulations since I seek for changing shapes to enhance daylight distribution. Its parameters are presented in Table 1.

Therefore, the cobogó has a standard reflectivity of 50 %, the same as the interior walls, the interior floor is darker with a standard reflectivity of 20 %, the same as the surrounding floor, and the ceiling is white with standard reflectivity of 80 %. Other properties like specularity and roughness are set to zero.

Table 1 - Material properties

Room Element	Radiance surface	Reflectance (R-G-B channels)	Specularity	Roughness
Cobogó	Void Plastic	0.5 - 0.5 - 0.5	0	0
Interior Walls	Void Plastic	0.5 - 0.5 - 0.5	0	0
Interior Floor	Void Plastic	0.2 - 0.2 - 0.2	0	0
Interior Ceiling	Void Plastic	0.8 - 0.8 - 0.8	0	0
Exterior Floor	Void Plastic	0.2 - 0.2 - 0.2	0	0

The quality and precision of the simulation are defined by the Radiance parameters in Table 2 to balance accuracy and computer resources. The parameters presented sets an accurate, medium to high-quality simulation according to Ward and Shakespeare (2003, p. 558) or Radiance (2020).

Table 2 - Radiance Parameters

-ab	*-ad*	*-as*	*-ar*	*-aa*
2	512	256	128	0.15

These variables are responsible for the indirect light calculations and the explanation about these variables is presented in quotations from (Ward & Shakespeare, 2003):

- The *ab* parameter sets the *ambient bounces, "This many diffuse interreflections will be calculated before the constant ambient value will replace a hemispherical sampling or/and interpolation. A setting of 0 turns the interreflections calculation off."*
- The *ad* parameter sets the *ambient divisions*, "(…) which is how many initial samples will be sent out over the divided (stratified) hemisphere. Increasing this value improves the accuracy of the calculated indirect irradiances and is necessary for a scene with a lot of brightness variation."

- The *as* parameter sets the *ambient supersamples*. “This is the number of extra rays that will be used to sample areas in the divided hemisphere that appear to have high variance. Supersampling improves accuracy significantly in scenes with large bright and dark regions by carefully sampling the shadow boundaries.”
- The *ar* parameter sets the *ambient resolution*. “This setting is akin to a universal grid resolution in a more conventional radiosity calculation. The accuracy of the indirect interpolation will start to relax at distances less than the maximum scene size divided by this number.”

Other Radiance parameters were kept constant as default[29]. The metrics used here to evaluate the performance of shape are the Useful Daylight Illuminance (UDI), that is the percentage of the room that receives illuminance ranging between 100 to 2000 Lux, the Annual Sun Exposure (ASE) which accounts for the percentage of the room that receives more than 250 hours of direct sunlight during the year, and the volume of material.

Therefore, the mesh element size is decisive when capturing the data generated by the simulation. In this study, the mesh for the test points is located 0.7 m above the ambient floor. Therefore, I conducted a sensitivity test about the mesh size influencing the results for UDI. The study is presented in Table 3.

Table 3 - Study about the mesh size influencing UDI results.

Mesh size (m)	RMSE	Solution time (min)
1	0.11	2.5
0.75	0.01	3.1
0.5	0.08	4.6
0.2	0.08	8.8
0.1	reference	10.8

---

[29] A full list of possible choices for the parameters and the range of the domains can be viewed in https://floyd.lbl.gov/radiance/refer/Notes/rpict_options.html .

Inside the room, one annual simulation computes office hours in a day from 8 a.m. to 6 p.m., including weekends, which represent 3,650 hours of illuminance. If a 0.1 m mesh size is adopted, it means that the simulation is dealing with 4,200 reading points for illuminance and direct solar rays which represents a total of 15,330,000 data collected for one annual simulation. If a 1 m mesh size is adopted, it means only 42 reading points, which represents a total 153,300 data records to be collected for one annual simulation, spending four times less compute results with RMSE of 0.11 (Table 3). As I present further, the GA was set to generate 20 individuals per generation, therefore the number of results can become enormous, possibly dealing with billions of data.

When dealing with the ASE, the mesh has a more regular behavior (Table 4), since the ASE simulation is based on the vectorial representation of solar rays.

Table 4 - Study for the mesh size influencing ASE results

Mesh size (m)	RMSE	Solution time (s)[30]
1	2,10	11
0,75	1,27	13
0,5	0,00	14
0,2	0,06	27
0,1	reference	72

Radiance uses a hybrid stochastic and determinist approach to calculate illuminance values in a scene. Both methods applied to UDI values presented a variation of 1% between simulations in the same conditions according to my pretesting simulations. The ambient air and humidity were not considered in the calculations, thus configuring no participating media.

---

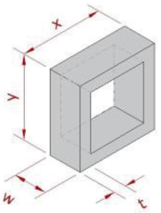
[30] Solution time is proportional to the system requirements presented further in this thesis, in section 5.5.

5.2. DESIGN ADAPTATION

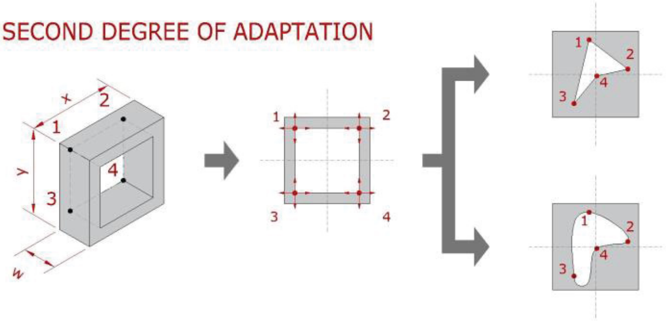
To explore shape possibilities, the initial geometry is the more common concrete element. It will allow three progressive degrees of adaptation (DA). The first is about its proportions, respecting the initial geometry integrity. The second is given the freedom to the interior shape to move in a bi-dimensional direction and assume curved shapes for new geometries. The third is adding freedom to the exterior shell to move all points in the geometry. These progressives DA are summarized in Figure 26.

Figure 26 - Degrees of adaptation in the cobogó shapes

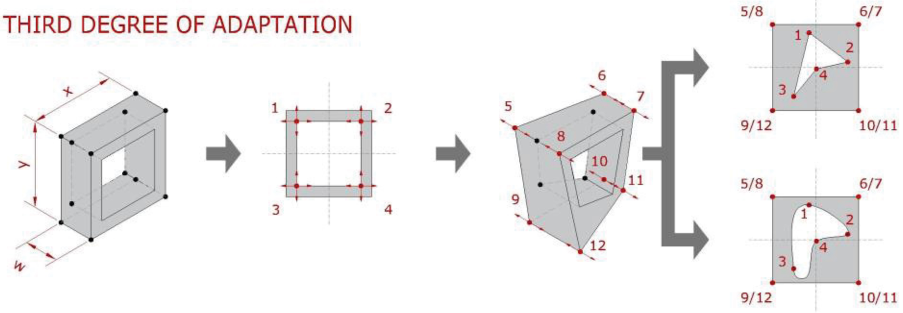
FIRST DEGREE OF ADAPTATION



SECOND DEGREE OF ADAPTATION



THIRD DEGREE OF ADAPTATION



As said before, the object to develop and to evaluate here is less the final optimized design of a *cobogó*, and more a flexible method that will allow manufacturing optimized *cobogós* for any particular surface subject to any orientation or location.

The *cobogó* is usually a grid-based pattern since it is a modular element. The construction logic is as simples as a brick stacking. Here, the assembly logics and the cobogós distribution in the studied surface comes to the logic of the grid-based surface. Therefore, the model takes a predefined shape of cobogó conceived parametrically with the visual programming language and inputs this geometry in the grid pattern assigned to the surface. Thus, the grid properties will distort the cobogó geometry to that shape of cobogó fit the grid. This logics would allow adaptation of the cobogó shape to curved surfaces or slanted walls, for instance.

When increasing the freedom to morph for the different degrees of adaptation (DA), the number of parameters increases as well. In the first DA 4 parameters rule the topology, in the second DA 12 parameters rule the topology and in the third DA 20 parameters. The description of each parameter for each one of the degrees of adaptation is shown in subsequent Tables 5 to 7.

Table 5 - Parameters for the 1st Degree of Adaptation (DA)

Parameter ID	Parameter	Units	Domain
1	Depth of the Cobogós	m	0 to 1.00
2	Vertical cobogó count	un.	7, 14, 28
3	Horizontal cobogó count	un.	15, 30, 60
4	Cobogó wall thickness	m	0.01 to 0.19

Table 6 - Parameters for the 2nd Degree of Adaptation (DA)

Parameter ID	Parameter	Units	Domain
1	Depth of the Cobogós	m	0 to 1.00
2	Vertical cobogó count	un.	7, 14, 28
3	Horizontal cobogó count	un.	15, 30, 60
4	Point 1 y-axis	cm	0 to -8.4
5	Point 1 x-axis	cm	0 to -8.4
6	Point 2 y-axis	cm	0 to -8.4
7	Point 2 x-axis	cm	0 to 8.4
8	Point 3 y-axis	cm	0 to 8.4
9	Point 3 x-axis	cm	0 to 8.4
10	Point 4 y-axis	cm	0 to 8.4
11	Point 4 x-axis	cm	0 to -8.4
12	Edge Sharpness	boolean	0 for straight lines 1 for Interpolated Curve

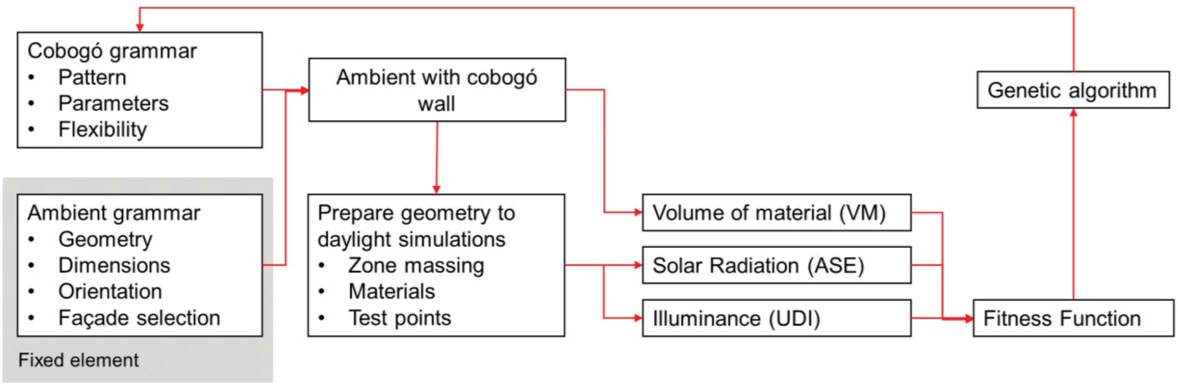
Table 7 – Parameters for the 3^{rd} Degree of Adaptation (DA)

Parameter ID	Parameter	Units	Domain
1	Depth of the Cobogós	m	0 to 1.00
2	Vertical cobogó count	un.	7, 14, 28
3	Horizontal cobogó count	un.	15, 30, 60
4	Point 1 y-axis	cm	0 to -8.4
5	Point 1 x-axis	cm	0 to -8.4
6	Point 2 y-axis	cm	0 to -8.4
7	Point 2 x-axis	cm	0 to 8.4
8	Point 3 y-axis	cm	0 to 8.4
9	Point 3 x-axis	cm	0 to 8.4
10	Point 4 y-axis	cm	0 to 8.4
11	Point 4 x-axis	cm	0 to -8.4
12	Edge Sharpness	boolean	0 for straight lines 1 for Interpolated Curve
13	Point 5 z-axis	cm	4.0 to -4.0
14	Point 6 z-axis	cm	4.0 to -4.0
15	Point 7 z-axis	cm	4.0 to -4.0
16	Point 8 z-axis	cm	4.0 to -4.0
17	Point 9 z-axis	cm	4.0 to -4.0
18	Point 10 z-axis	cm	4.0 to -4.0
19	Point 11 z-axis	cm	4.0 to -4.0
20	Point 12 z-axis	cm	4.0 to -4.0

5.3. VISUAL PROGRAMMING LANGUAGE

The code was structured in the visual programming language (VPL) and it is described in Figure 27 which is a representation of the real schema. This schema can be compared with the visual code itself in Figure 28 and also in the appendix with more details.

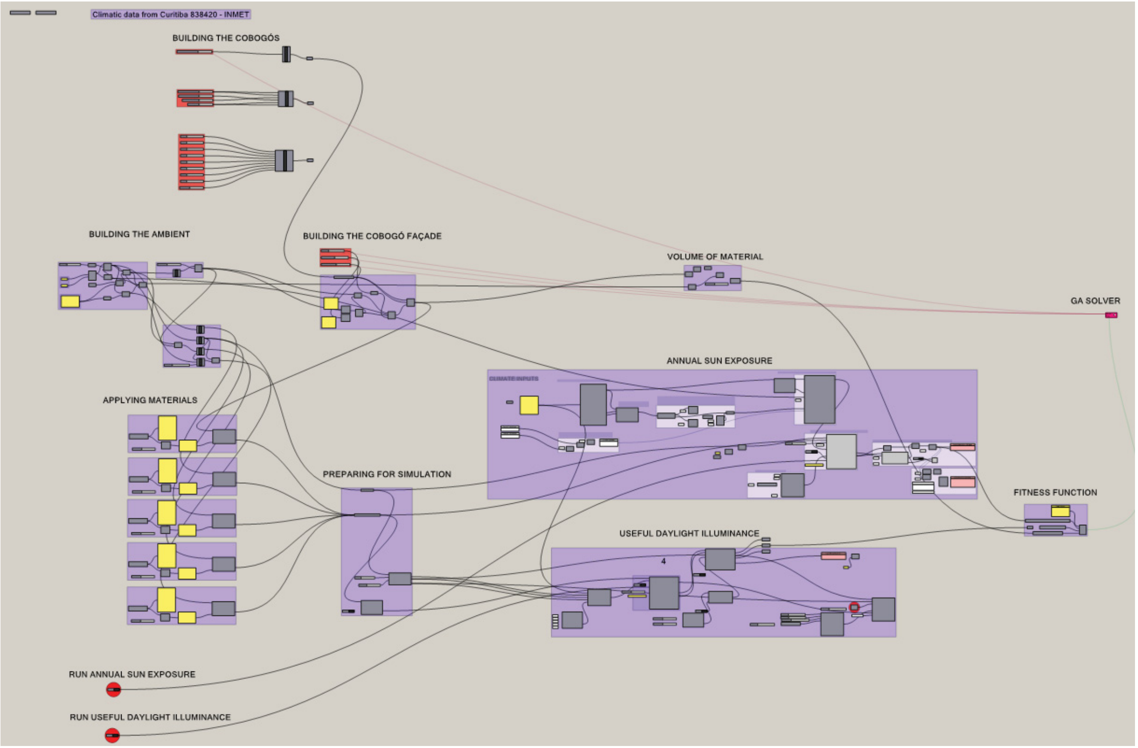
Figure 27 - VPL schema



The fixed parameter in all simulations is the room as described in section 5.1. The evolutionary models were run for an opening towards the north orientation. The ambient grammar allows the model to change proportions and dimensions, although this ability was not explored here, as same as the orientation or façade selector. These abilities were kept as fixed elements in the schema (Figure 27).

The input of the cobogó geometry occurs in the cobogó grammar function box. The pattern and all parameters that control the topology are defined according to the user preferences, which requires a pre-knowledge of modeling in Grasshopper. The codes adopted for the cobogó in this study are shown in the appendix. Each DA, presented in the previous section, has its code, therefore it is up to the user to define the façade element geometry code.

Figure 28 - VPL code



5.4. EVOLUTIONARY ALGORITHM

As reported before, in chapter 4, the genetic algorithm progressively selects the individuals who best fit a given environment. The fitting is given by the quality of adaptation to its conditions. It is quantified and the metrics used in this work are:

- The annual sun exposure (ASE), which is calculated from illuminance values and its calculation initiate when the direct illuminance is above 1000 lux, i. e., when thermal loads start more noticeably to increase with solar radiation and only direct radiation is computed in the tested surface[31]. The ASE accounts for the portion of the tested surface that is reached by direct solar radiation for 250 occupied hours of the year. In this case, I am considering a room used from 8 a.m. to 6 p.m. Therefore, it is expressed as a

---

[31] For light energy at a wavelength of 555 nanometers, a lumen is defined as 1/683 watt. This is the peak of the human visual response defined by CIE (Comission International de l"Eclairage) (Ward & Shakespeare, 2003, p. 497)

percentage. The model was adapted from Mackey (2017). ASE values are computed as an average over the mesh. Therefore, to include this value in the fitness function an average value is assumed.

- The useful daylight illuminance (UDI) is also a grid-based simulation at 0.7 m height from the interior floor. The simulation considers only office hours (8 a.m. to 6 p.m.) when the UDI is the percentage of the time during active occupancy hours that the test points receive between 100 and 2000 lux. The model was adapted from Roudsari (2015). UDI values are also computed over the mesh. Therefore, to include this value in the fitness function an average value is assumed.
- A minimum volume of material that computes the ratio between the room volume, which is constant, and the volume of material in the stacked cobogó wall, which depends on the cobogó shape. As it is a ratio, results become dimensionless. This variable can improve the efficiency of the cobogó wall in terms of embodied energy and allow a criterion for decisions among similar choices. For instance, a standard cobogó wall in the room designed for this study has an embodied energy of 370.55 kWh or 1,333.98 MJ[32]. A reduction in 10 % in the volume of material would be equivalent to enlighten the whole room with eight 9W LED lamps for 50 days during 10 hours a day[33].

The fitness function, therefore, must lead the results to find an equilibrium between enhancing the illuminance distribution with the metric of UDI, which must be high as possible, and ASE

---

[32] The material considered is the same as CMU wall, in terms of embodied energy for square meter. The data here, considers the context of Brazilian construction industry, as reported by (Tavares, 2006). Being the embodied energy for a CMU wall equals to 1 MJ/kg or 2,300 MJ/m^3 or yet 638.89 kW/m^3.

[33] The studied room has 42 m^2. To reach an illuminance above 100 Lux inside the room with LED lamps, 8 lamps of 9W would be necessary, consuming 72 Wh.

inside the room. The amount of material needed impacts the operational energy of the room and suits as a decision criterion, which is desired to be the least possible.

To represent the fitness function, a simple linear equation was developed to solve the problem. ASE can be equal to zero, as seen further in the benchmarking results, thus representing the fitness function as a ratio, for instance, could lead to infinite values for the fitness function. A linear equation communicates to the GA what to find more straightly. Positive values maximize the function, and negative values minimize it. The fitness function must answer the question, is it better to have 100 % UDI with some ASE, or minimize the ASE with the best UDI possible? And yet, how to find this equilibrium spending the least of material possible?

The premises for the fitness function were that UDI values below 50 % were unacceptable, if it happens it should be penalized. ASE values up to 10 % should be considered acceptable, values from 10 % to 20 % should be slightly penalized and values above 20 % would be unacceptable. The ratio for the volume of material results in values with two orders of magnitude below the ASE and the UDI. Therefore, the volume of material works like a selection criteria between two similar solutions, discouraging the GA to spend more material than the standard cobogó.

Therefore, the fitness function here (*FF*) is linear and dimensionless and is calculated as follows[34]:

$$FF = UDI_{100-2000} - ASE - MV \qquad \text{(Eq. 04)}$$

$$UDI_{100-2000} \begin{cases} if \ < 50\%, \dfrac{UDI}{2} \\ if \ \geq 50\%, UDI \end{cases} \qquad \text{(Eq. 05)}$$

---

[34] ASE conditions where stablished to meet Leed requirements.

$$ASE\begin{cases} if \ \leq 10\%, ASE \\ if \ \leq 20\%, ASE + 1\ \% \\ if \ > 20\%, ASE + 1000 \end{cases} \qquad (Eq.\ 06)$$

$$MV\begin{cases} if \leq 0.5, MV \\ if \ > 0.5, MV * 10 \end{cases} \qquad (Eq.\ 07)$$

The objective is to maximize the values of the fitness function (FF). The possible values for this fitness function theoretically range from -1100 to 100 plus the influence in the volume of material.

For this work, sensitivity tests regarding the genetic algorithm parameters were conducted and compared. Therefore, tuning tests were conducted to validate the schema presented as proposed by Eiben and Smit (2011). This tuning is about having a benchmarking value, which here is the standard cobogó. Then relating its chosen parameters, like operators, variations, and population management, and finally comparing results.

The more the mutation rate is increased, allowing new jumps of variables during the evolutionary simulations, the longer the solver takes to reach convergence. Conversely, the simpler and faster the model reaches a convergence, the more easily it reaches a local optimum and stops searching for new possibilities. As more variables control the topology, more individuals per generation or a bigger initial population is needed when running the genetic algorithm.

The genetic algorithm (GA) used here, which was Galapagos[35], has also two ways of starting an evolutionary simulation. The first is to freely start the simulation, and the variables are randomly chosen to define the individuals for the initial population, what I called not-biased

---

[35] Galapagos is addon on Grasshopper that allows Evolutionary simulation from genetic algorithm logics. It was developed by David Rutten (2010)

simulation. The second is to indicate a predefined solution and consider it as the base for comparison, what I call biased simulation.

In this work, since I seek to optimize a preexistent shape, the biased simulation approach was the natural way of conducting an evolutionary simulation. In opposition to that, the question of how these approaches may impact the resulting shapes or performance arose. Therefore, comparing these two approaches became an object of study in this thesis, and results are presented and discussed in the next chapter.

The output results for the evolutionary algorithm are the optimal parameters, the corresponding shape for each individual, and the biodiversity of the generations, i. e., how much of the possibilities allowed by the parameter combination are covered in that population. Therefore simulations were conducted to define initial population requirements for each degree of adaptation and further discussions are presented among results.

The evolutionary simulation needs yet to define how much of the initial individuals will continue to exist in the next generation. Here, only 5 % of the individuals are kept for the next generation, which means that the initial population or the number of individuals per generation needs to be at least 20, for one best fit to continue and crossover. Therefore, the crossover rate was set to 75 %, meaning that this best fit is responsible for generating 75 % of the next generation, being the resulting 25 % generated by mutations. The solver is the evolutionary solver.

The genetic algorithm is also designed to avoid geometry collision and to preserve the integrity of the topology. Every individual (genome) that doesn’t preserve a buildable topology is point mutated[36]. For the shape grammar theorists this property leads to a lack of innovative exploration in design shapes as pointed previously. On the other hand, it allows optimizing a solution without a massive number of simulations or individuals per generation.

5.5. SYSTEM CONFIGURATION AND MODEL PERFORMANCE

All simulations were run on a DELL XPS desktop with OS Windows 8.1 64 bit; Intel® Core™ i7-4790 CPU @ 3.6 GHz; RAM of 16 GB; Graphics Card NVIDIA GeForce GTX 745.

The software used was Rhino 6 Educational license, integrated with Grasshopper (Davison, 2018) with Radiance 5.2.0.7 (Ward, 1994; Ward & Shakespeare, 2003), Daysim 4.0, Ladybug 0.0.66 and Honeybee 0.0.63 (Roudsari, 2020) with GNU General Public License for collaborative projects. The genetic algorithm was run with Galapagos (Rutten, 2010) an addon for Grasshopper.

The code is structured in a closed loop of functions, and the evolutionary model is solved when the genetic algorithm is manually stopped or reaches 10 generations without improvement in the individuals.

Considering the whole computational time to complete one simulation, the annual daylight simulation is responsible for 85% of the total time, and the solar radiation analysis responsible for just 5 % of the total time. The remaining time is spent in generating the geometry, reading materials, and preparing the model for simulation.

The convergence criterium was either stabilization of fitness or the forms, or the maximum number of generations due to limited computational resources, namely, 25. The initial

---

[36] Point mutated means that a single parameter is reconditioned to properly construct the geometry. Sometimes it happens consecutively until the geometry can be produced. Genetic algorithms also utilizes it to create bio-diversity in generations (Rutten, 2010).

population is considered the first generation. Unfortunately, the chosen genetic simulator, Galapagos, is not able to stop the simulation and resume it thereafter, so that during several preparing tests this number of simulations was assumed to give satisfactory results in a manageable time, as seen further in the results. Simulations demanding many days to solve often lead the computer to run out of memory or the simulation crashes because of excessive hardware exposure to high temperatures, causing overheating.

6. RESULTS AND DISCUSSION

In the subsequent sections, results will be presented and discussed. In the first section, a comparison between different façade solutions is presented. In the second section, the performance of cobogós for different façade orientations is presented and discussed. In the third section, the parametric schema evaluation is demonstrated, as well as the solutions for the three degrees of adaptation for a north façade in Curitiba - PR, Brazil. Still, a discussion about shape exploration with the schema is presented.

6.1. BENCHMARKING RESULTS

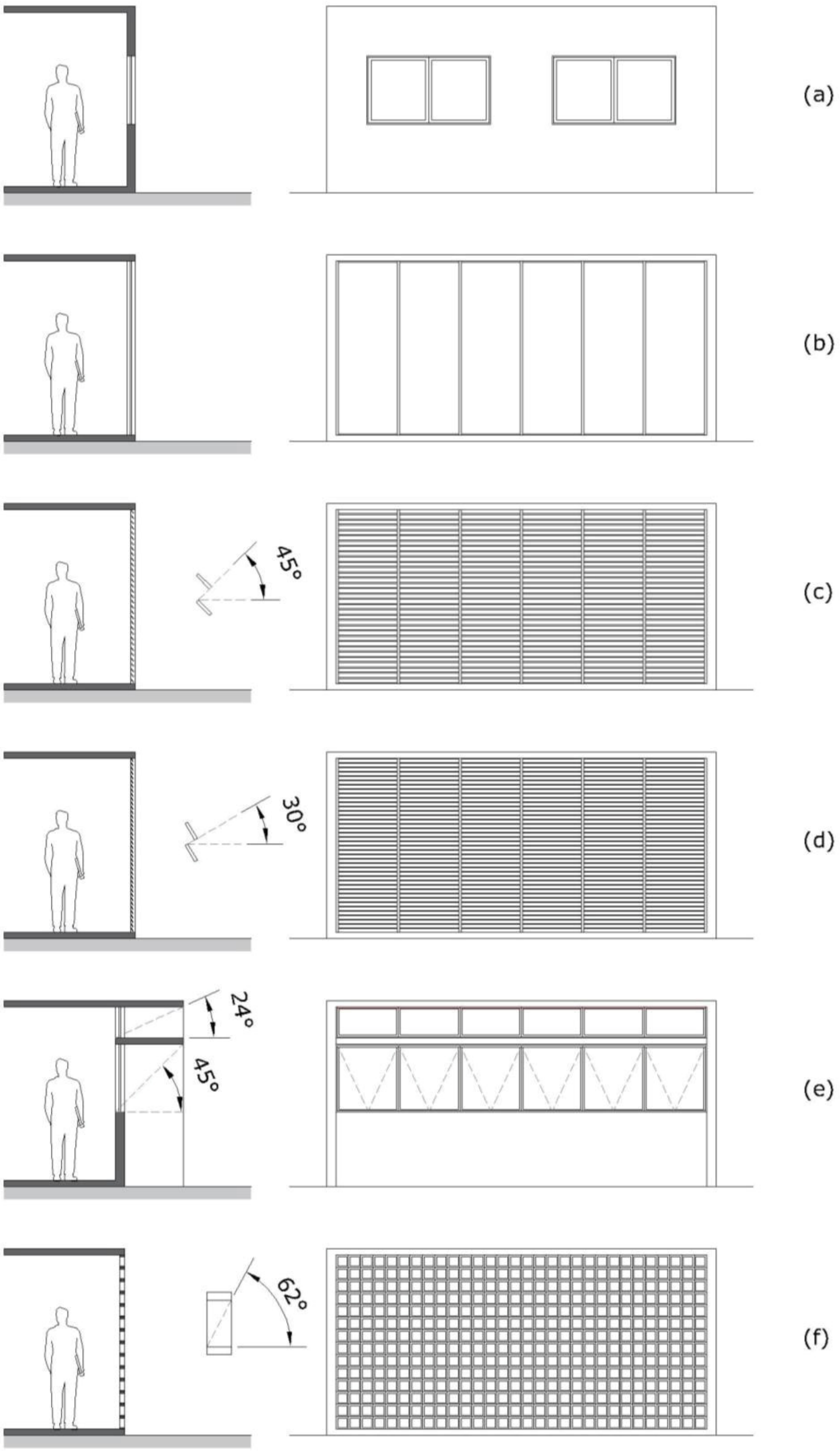
Since the work aimed at the optimization of building façade elements, here a brief comparison between different types of shading devices is presented, for a north façade in Curitiba, Paraná, Brazil. The room is the same for all simulations and has 7.0 m x 6.0 m floor dimensions with 2.8 m height.

The comparison in these simulations are about: a) a façade with two regular windows (2.0 x 1.1 m) with clear glass and no solar protection; b) a glazed façade with clear glass and no solar protection; a glazed façade with two types of commercial louver systems, c) one with 45º protection from the zenith and d) with 60º; e) a light shelf with a strip window and clear glass; and, e) a standard commercial cobogó façade (Figure 29).

Results are presented in Table 8 and they are the average of 1050 test points in the mesh for an annual analysis. Results for $UDI_{100-2000}$ is shown in Figure 30.

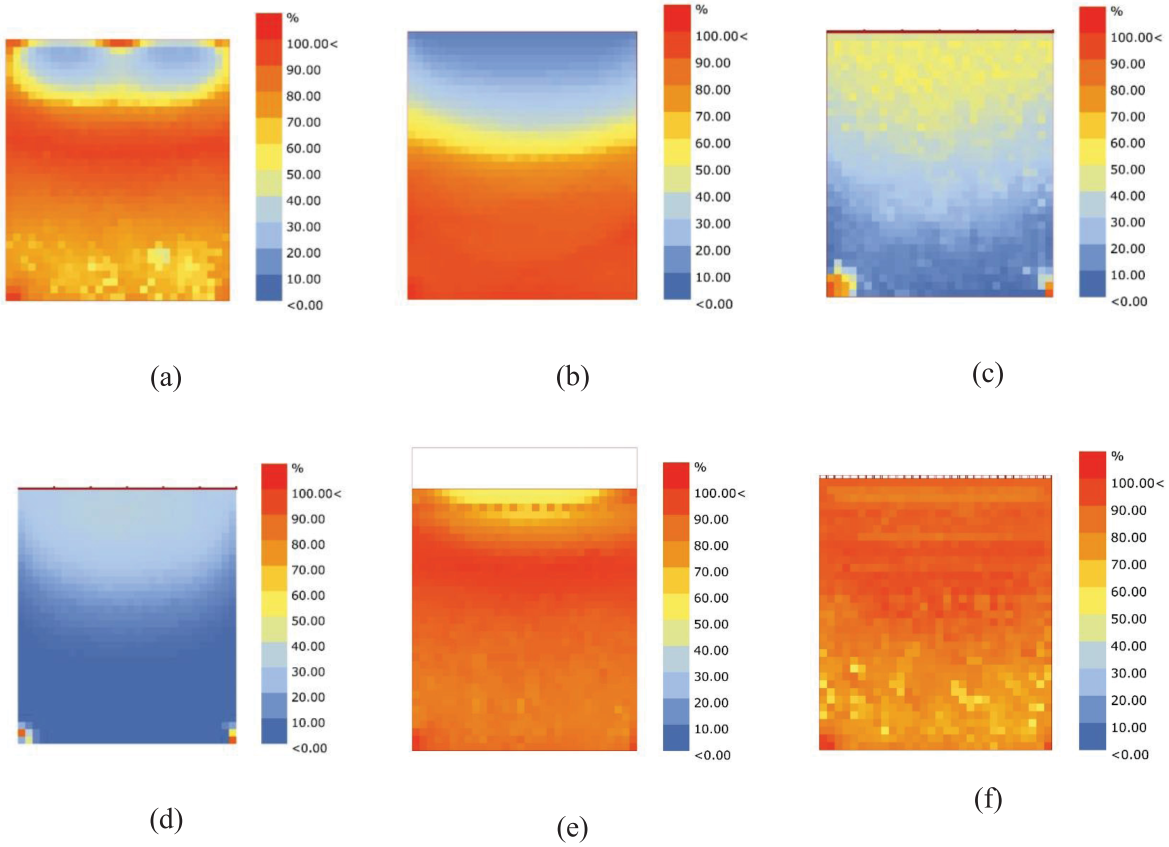
The comparison showed that the use of regular windows, solution “a”, is a satisfactory solution in terms of daylighting performance, reaching an average value of 66.4 % for $UDI_{100-2000}$, and 18.85 % for ASE (Table 8). In this case, some excessive sunlight is entering the room near the window, but the sun protection could be yet improved by using blinds, for instance, at the most uncomfortable hours. Additionally, the affordability and the cultural usage of the solution “a” makes it the most customary solution for buildings in terms of natural light utilization.

Figure 29- Benchmarking solutions



Results also have shown that the commercial louvers, at least the ones considered here, are predominantly designed as shading devices with low performance in the room illuminance. Results for UDI for both 45° and 60° angulation louvers reached average values below 30 %. Therefore, a detailed illuminance study must be carried out when choosing shading elements from the manufacturer's catalog. Otherwise, the choice of louvers could neglect all the potential of daylighting in a building.

Figure 30 - Results by mesh showing the UDI values inside the room



(a) (b) (c)

(d) (e) (f)

Legend: (a) Two regular windows; (b) Fully glazed façade; (c) Commercial 45º horizontal louver; (d) Commercial 60 º horizontal louver; (e) Designed light shelf; (f) Cobogó façade.

The designed light shelf presented best results in this benchmarking since it contributes to illuminate the back of the room due to the reflection on the shelf associated with the reflection inside the room. As it was designed with the use of a solar chart, no value of ASE was registered, but the average value of $UDI_{100\text{-}2000}$ reached more than 80 %, enhancing illumination considerably (Figure 30).

Table 8 - Comparison of lighting performance for different façade systems for a north-oriented room in Curitiba

	ASE (%)	$UDI_{<100}$ (%)	$UDI_{100\text{-}2000}$ (%)	$UDI_{>2000}$ (%)	SDA (%)
Two regular windows	18.85	16.4	66.4	17.2	58.7
Fully glazed façade	32.57	4.3	57.6	38.1	100
Glazed façade with commercial 45º horizontal louver	0	73.5	26.5	0	0.3
Glazed façade with commercial 60º horizontal louver	0	89.4	10.6	0	0.1
Glazed façade with light shelf	0	15.5	80.3	4.2	57.1
Cobogó façade	0	19.0	77.0	4.0	55.5

Also for the standard cobogó, 20 cm x 20 cm modular elements of concrete, a good illuminance distribution was achieved. Its dimensions and proportions allowed an average value of 77.0 % of $UDI_{100\text{-}2000}$ for a north façade in Curitiba.

Results of this benchmarking also shown that the SDA metric alone may be misleading since it considers illuminance above 300 lux only, with no upper limit. In the fully-glazed façade, the SDA hid overheating and possible glare in the room, since it reached 38.1 % of $UDI_{>2000}$ and 100 % of SDA at the same time, while $UDI_{100\text{-}2000}$ was just 57.6 %.

With this comparison, an optimal solution with values above the maximum of 80.3 % of $UDI_{100\text{-}2000}$ is expected when applying the evolutionary schema for the shape exploration of cobogós.

This value is expected since it is equal to the light shelf solution or at least above the 77 % presented by the standard cobogó façade.

6.2. COBOGÓ RESULTS FOR DIFFERENT FAÇADES

Also to illustrate the performance of a cobogó façade for further orientations, as it is the object of study, Table 9 shows results that were simulated on how this building element behaves in the latitude of Curitiba. Simulating the same standard cobogó shape that will be further discussed allows a comparison of the fitness function values as well as the evaluated index UDI and ASE.

Although the standard cobogó is a fixed design, the daylight performance of this element for Curitiba presented consistent results of useful illuminance even for different orientations. A whole building using this element as a shading device would have good results in terms of the illuminance of interior spaces and reduced solar exposure.

Table 9 - Cobogó façade performance for other orientations[37]

	ASE (%)	$UDI_{<100}$ (%)	$UDI_{100-2000}$ (%)	$UDI_{>2000}$ (%)	SDA (%)	Fitness function value
North Façade	0	19.0	77.0	4.0	55.5	76.4
West Façade	0	17.7	77.0	5.3	50.0	76.5
South Façade	0	21.7	78.3	0	38.9	77.8
East Façade	0	20.7	76.2	3.1	43.0	75.7

---

[37] Similar results were scope of a conference paper with different results. In that case, climatic data were from a different weather station although they were from the same city (Alves & Schmid, 2019).

This complementary comparison demonstrates that $UDI_{100-2000}$ is between 76.2 % and 78.3 % considering all the cases, while ASE is kept in 0 %, i. e, no excessive solar radiation inside the room. As a reminder, in this work, ASE considers the percentage of the floor area with direct sunlight illuminance above 1000 lux for more than 250 hours of sunlight during the year. Additionally, as the values of $UDI_{>2000}$ are below 5.5 %, which demonstrates a low percentage of excessive illuminance during the whole year, the results compared with 0 % for the ASE value in all the cases have agreed.

6.3. THE EVOLUTIONARY COBOGÓ

Here, I first analyze some performance and parameter tuning of GA applied to this specific problem of daylighting and solar exposure, and in the context of the system configurations presented earlier. The performance of the GA was determinant in defining the initial population, and predicting how the evolutionary solver interprets results for the subsequent generations through the two approaches, biased and not-biased.

Additionally, results for the three different DAs are presented and discussed. The results presented here focused on showing optimized solutions similar to the shape exploration during the process of evolutionary simulations.

6.3.1. About initial population dimensioning and GA parameters tuning

Defining the number of population input for a GA simulation has no predetermined simple rules. Each problem studied requires a certain level of detailing and accuracy to make results manageable and reliable. Here this discussion and results are the basis to the management of how to use the schema proposed in this thesis, and how the GA parameters influence the results.

Two ways of initiating an evolutionary simulation were conducted and are shown here. The first, pointed earlier at section 5.4, is about letting the GA explore new outcomes freely by manipulating the variables randomly. The second also pointed earlier, is about giving to the GA a predefined configuration to bias the results and seek for optimization and refinement of a performance-based shape.

Therefore, the number of individuals in the first generation may cause the whole evolutionary simulation to get stuck in a local optima solution when the number of individuals in the initial population is not enough and the GA does not consider a representative sort of combinations. In opposition, it may spend unnecessary computational time when the initial population is oversized, without the benefit of relevant shape exploration.

The discussion presented here considers an initial population study for an evolutionary simulation with 20 parameters. The description of each parameter was presented in Table 7. This is the most demanding configuration studied here, in terms of degrees of freedom and computational time. Thus the study considered three scenarios: an initial population (P_{in}) of 40 individuals, twice the number of parameters; 100 individuals, five times the number of parameters; and 200 individuals, ten times the number of parameters.

Results presented in Table 10 demonstrate comparisons between two different runs for the same case. For instance, the two columns show different values of biodiversity for each run of the same case, and the Root-Mean Squared Error (RMSE) measures the differences in the distribution of the population between these runs. This difference is measured considering the variables that define the shape of each individual.

When raising the number of individuals in the P_{in}, from 40 to 200, the error (RMSE) between independent simulations tends to remain constant, for both approaches, biased and not-biased. This means that if I run the simulation several times, it has a constant probability to generate the same representative initial population. In Table 10 it is possible to see that the not-biased approaches pointed out RMSE ranging between 0.37 and 0.38, and the biased approach pointed out RMSE ranging between 0.11 and 0.12. Therefore, increasing the number of individuals had no impact on the distribution of individuals. This conclusion is confirmed when the biodiversity values are compared for the first and second run. Biodiversity was quite similar between different cases for the same approach, even when increasing the P_{in}. When the not-biased initiation is considered, values between 0.824 and 0.842 reflect a percentage of the total possible solution covered by the GA, the so-called biodiversity.

Table 10 - Two ways of initiating GA simulation for a 20 parameters simulation

Type	P_{in}	Biodiv. 1st run	Biodiv. 2nd run	Improvement of the fitness function values from the benchmark	RMSE	Computation time (min.)	Factor of inefficiency
Not-biased	40	0.834	0.824	0.0%	0.38	306	116.28
	100	0.839	0.839	0.0%	0.37	932	344.84
	200	0.842	0.842	0.0%	0.37	1908	705.96
Biased	40	0.132	0.133	2.0%	0.12	285	34.2
	100	0.135	0.135	9.0%	0.11	1005	110.55
	200	0.138	0.135	8.5%	0.12	1323	158.76

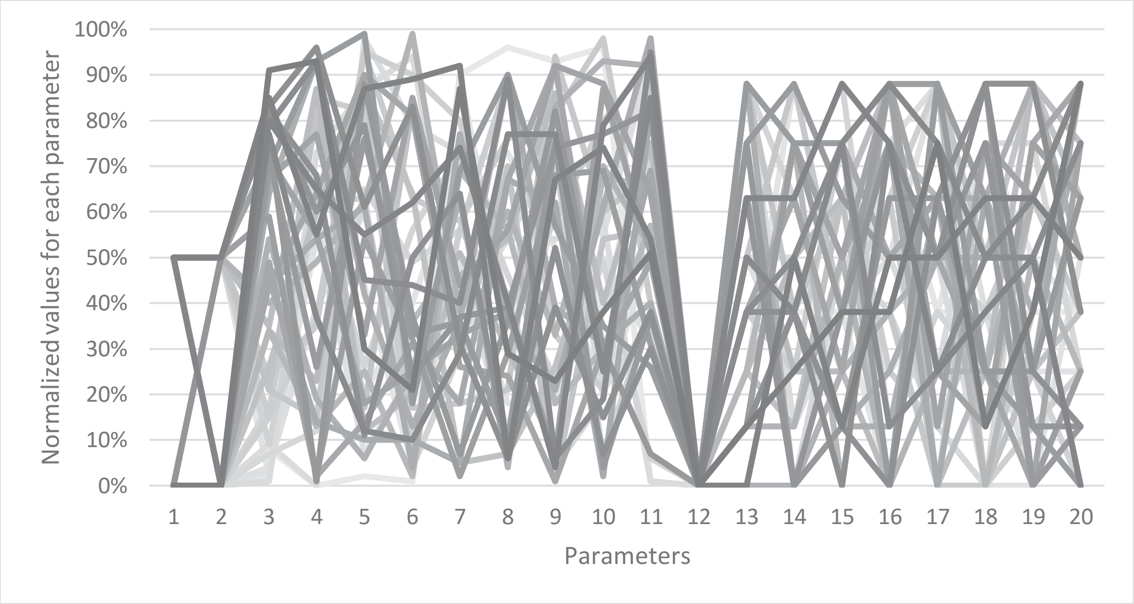
In opposition, increasing the number of individuals, caused the computational time to increase. And when considering the error of simulation (RMSE) and time spent, this comparison reflects here in what I call the factor of inefficiency, which is the product of both. This factor is better as it is close to 0. Therefore, when the not-biased simulation is run the relationship between RMSE and computational time demonstrates higher values than when the biased simulation is run. This is because the not-biased approach allows more differences between the populations to explore new outcomes. Therefore, the factor of inefficiency is proportional to the computational time since the RMSE does not vary significantly when increasing the initial population. The model seems to be relatively stable for different runs in the same conditions.

The high number of individuals at the beginning of an evolutionary simulation seemed to increase computational time but increased the possibilities of the GA to find improved solutions concerning the benchmarking yet in the initial population creation. This statement is visualized just for the biased solution that had 2% of the individuals with higher performance than the benchmarking with 40 P_{in} and 9 % when working with 100 P_{in}. A biased simulation is an approach that is possible to work with when the problem was already studied or when there is a target to optimize. In the case of this thesis, the object is preexistent and was previously evaluated.

Allowing more possible differences between different runs for the same solution (RMSE) could spare computational time. And the regularity in the factor of performance measured for the not-biased cases indicates that a huge initial population does not increase the performance if computational time is considered. Here, an initial population of 100 individuals is preferable than 200, if considering the performance of the model even when handling a problem with 20 parameters.

Figure 31 to 33 show the exploration of the parameter with not-biased initiation. The vertical axis shows each value for each parameter in a normalized form to have a comparable scale among different parameters. Each individual, or resulting shape, is a line in the graph with a specific value for each parameter. These graphs analyze how biodiversity is distributed with the parameters. The biodiversity here is represented by the percentage of the area in the graph covered with solutions, which means how much of the total possible solutions have been explored with this initial population.

Figure 31- Not-biased P_{in} of 40 individuals



Although the range of possible solutions is quite similar between the three cases, reflecting in biodiversity values that are also similar (Table 10), the number of solutions in the same region of the graph increased between these cases. In these figures, the gradation of gray colors was meant for better visualization of each line that represents an individual.

Figure 32 - Not-biased P_{in} of 100 individuals

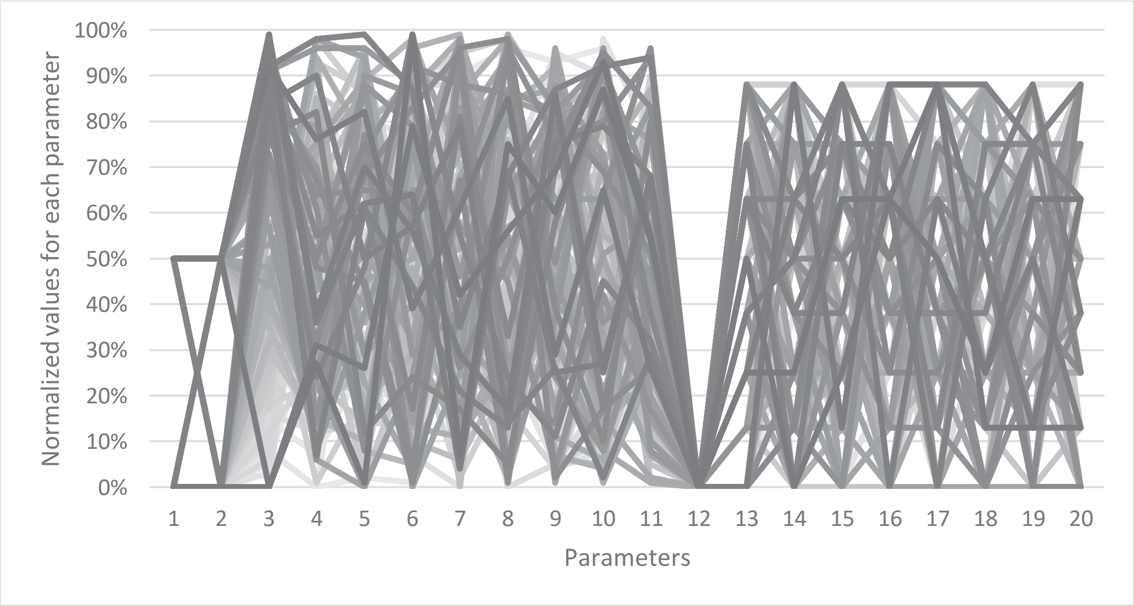
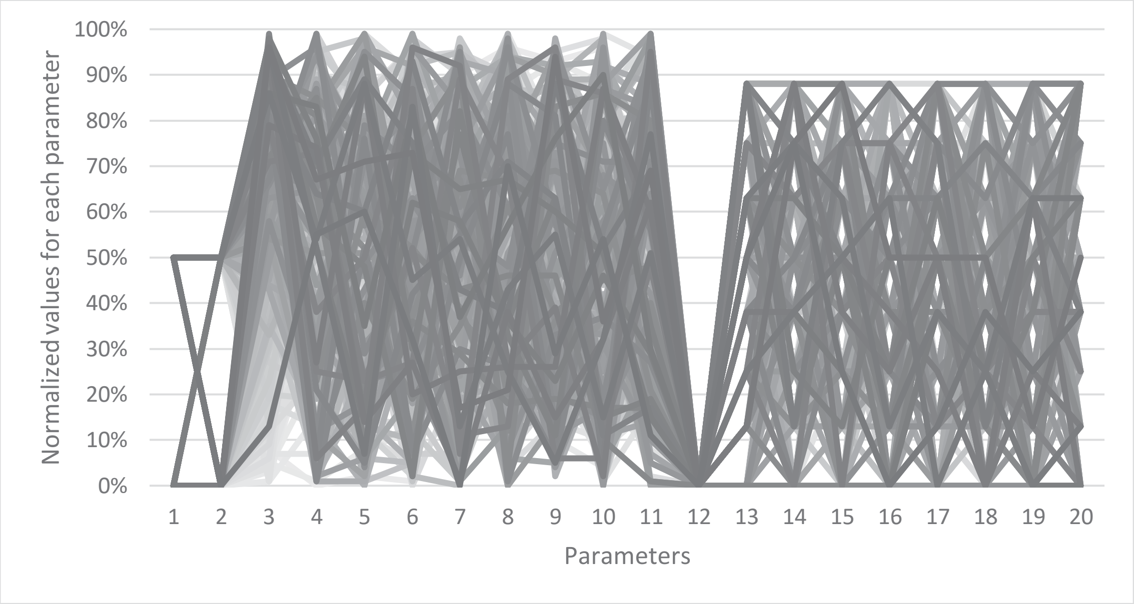


Figure 33 - Not-biased P_{in} of 200 individuals



When a biased initial population is generated (Table 10), biodiversity decreases. Establishing, thus, a predefined solution from which variables will vary, this caused biodiversity values to range between 0.132 and 0.135. However, the biased solution has found already optimized solutions, better than the one initially instantiated, which did not occur with the not-biased initial population. For a P_{in} of 100, 9 % of the total population was already improved, i. e., 9 individuals in absolute values. For a P_{in} of 200 individuals, 8.5 % of the total population was already improved, i.e., 17 individuals. Therefore, a biased simulation has the benefit of reaching optimized solutions already in the initial population. Additionally, as I am considering 5% of the initial results to be kept for the next generation, biased simulations have more potential in carrying good genes to future generations.

In Figure 34 to 36 the exploration of results is shown comparing the parameters and their values in a normalized form. Again, each line represents an individual and its respective shape generated. The difference in the color of the lines is for better visualization of each individual.

In these images, the tendency of the algorithm to find an optimized solution becomes clearer, and increasing the number of P_{in} does not necessarily contribute to the next generations, since just a percentage of the initial population will be carried out.

Moreover, if the definition of the preserved solutions is defined as 5%, which is a common value presented in other works and discussions, working with 100 P_{in} in a biased solution seems to be sufficient to carry the best genes to the next generation. Working with 40 P_{in} would already carry the best solutions forward, with the least computational time and the best factor of performance.

Figure 34 - Biased Pin of 40 individuals

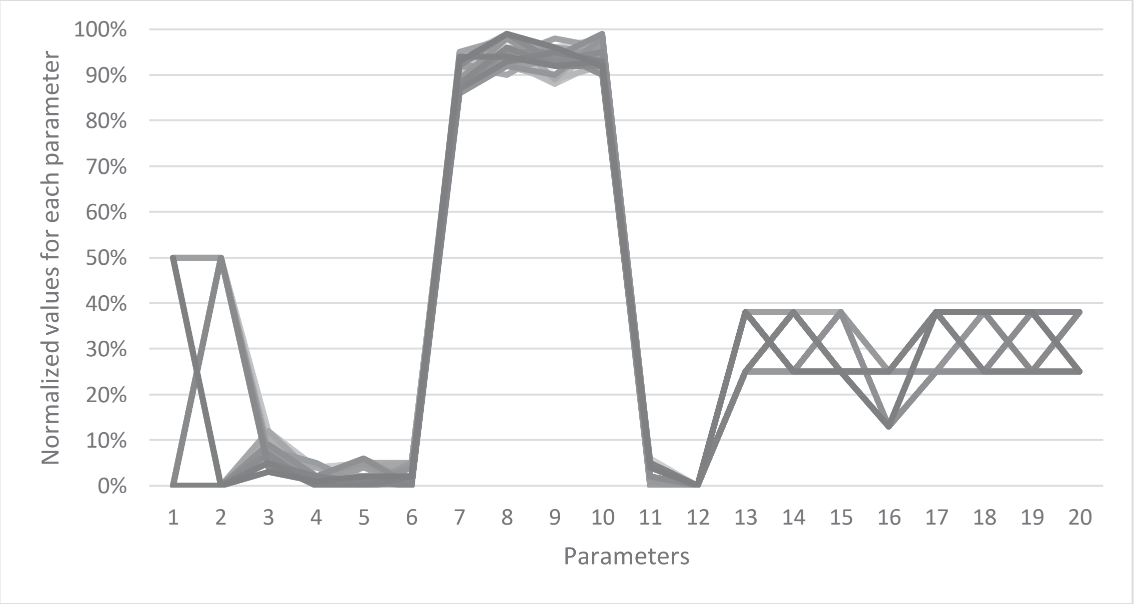


Figure 35 - Biased Pin of 100 individuals

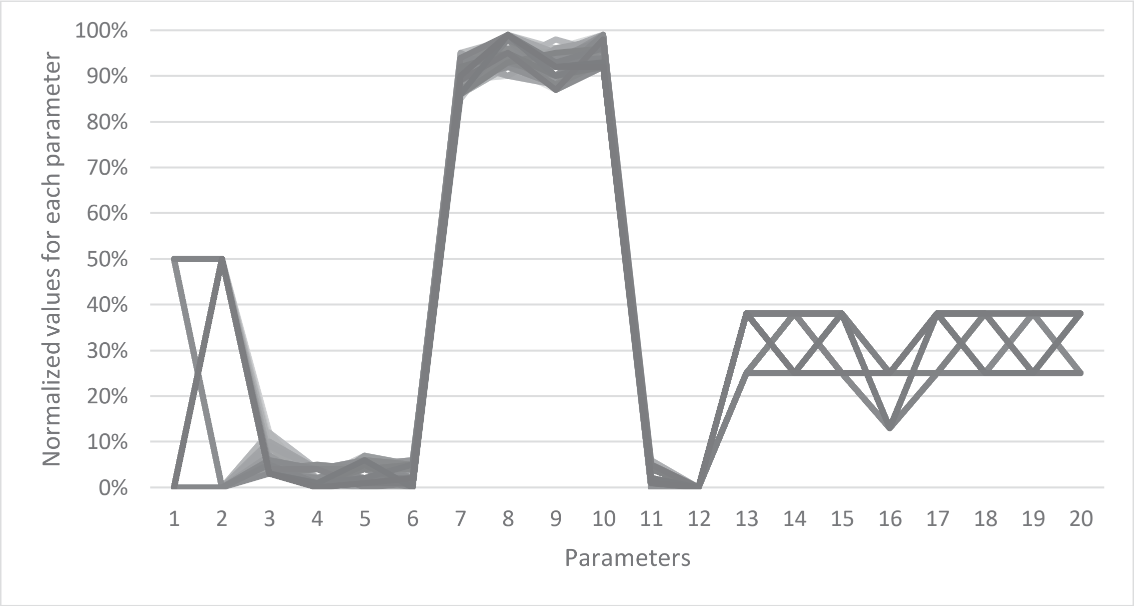
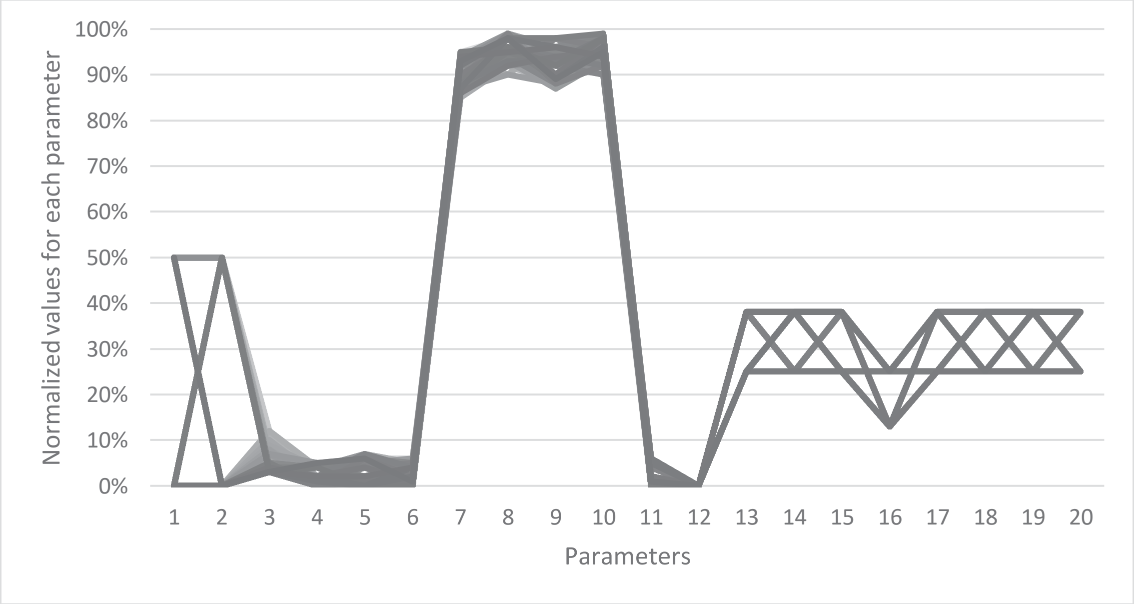


Figure 36 - Biased Pin of 200 individuals



According to results presented, starting a simulation with a predefined shape enhances the chances of achieving optimized solutions using the GA. Yet, knowing a predefined solution allows one to spare computational time and at the same time, it will probably carry the best genes to the next generations. The downside, in this case, is that the whole evolutionary simulation tends to evaluate a short spectrum in the combination of possible solutions.

Therefore, running the biased GA simulation is advisable when the overall performance of the shape is already known and the distribution of the population or the shape exploration in the individuals are not important issues, but rather the performance and refinement of a known shape.

On the other hand, starting a simulation with no predefined shape, i. e. not-biased simulation, tends to explore more possible outcomes, but without the promise of achieving real optimized solutions. The chances of reaching a local optimum are higher with this approach. This kind of simulation, that allows more freedom to new shapes to appear, also tends to be more time consuming (Table 10) even for the same number of individuals. It was perceived to happen since some random solutions result in unreal geometries. And, when this happens, the GA excludes these solutions and mutates them until a possible solution is reached. This process takes time and does not compute a solution.

6.3.2. Exploring biased and not-biased evolutionary simulations

These two approaches defined in the previous sections pointed out different conditions at the start, an evolutionary simulation with a predefined solution to be optimized, what I call biased solution, and an evolutionary simulation with no predefined solution, giving freedom to the GA to randomly choose the parameters, what I call not-biased solution. This characteristic was seen in the previous section for the 3rd DA (degree of adaptation) yet exploring the number of individuals in the initial population.

Similar characteristics are seen in Figure 37 and Figure 38 for the 2nd DA. Here, the 2nd DA has only 12 parameters as presented earlier in Table 6. These parameters are also normalized to appear on the same scale in the figures. Each line in the graph represents the final shape of an individual, and the difference in gray tones is arbitrary to facilitate the visualization.

The interesting aspect when moving forward to the other 24 generations in the evolutionary simulation is the convergence between biased and not-biased approaches. This convergence starts to be revealed at the first 12 generations for the optimized solutions as seen in the comparison between Figure 39 and Figure 40 and further in Figure 41 and Figure 42 for the final 12 generations. The optimized solutions of each approach are presented in Figure 43.

Figure 37 - 2nd DA Pin - Not-biased evolutionary simulation

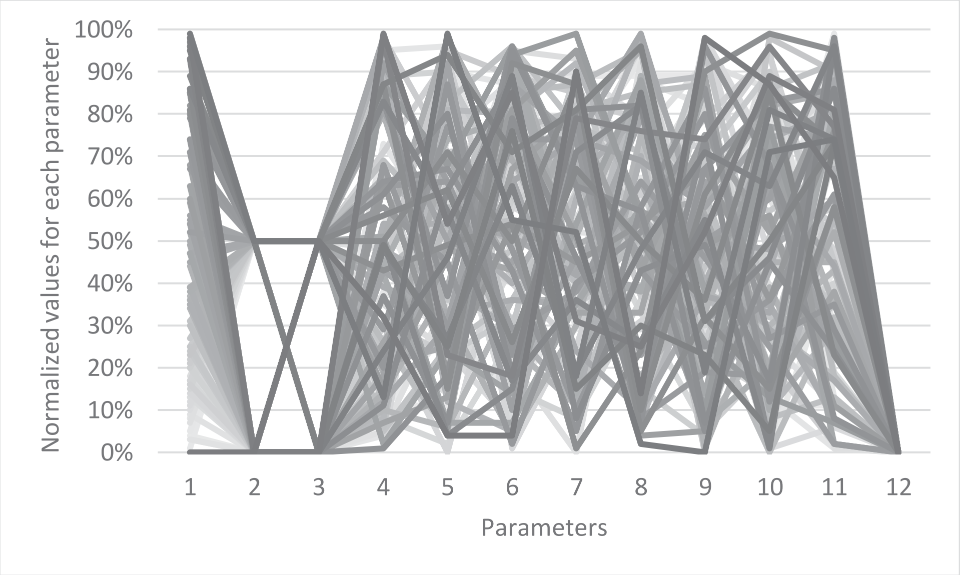
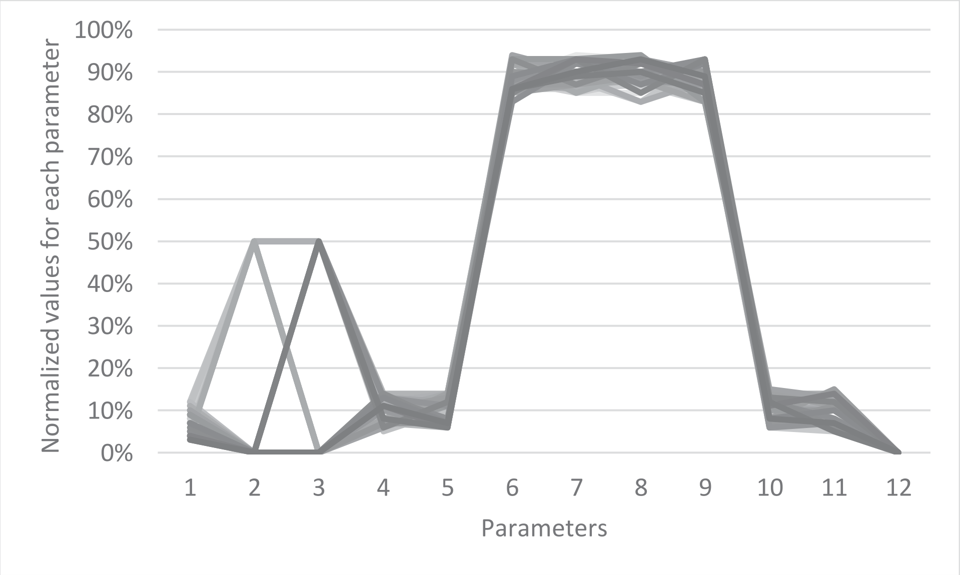


Figure 38 - 2nd DA Pin - Biased evolutionary simulation



In the initial population, a discrepancy between individuals in the two approaches is evident, being the not-biased evolutionary simulation more able to explore new shapes, and the biased simulation focused on finding small increments in the fitness function with small changes in the predefined geometry as seen also for the 3rd DA in the previous section.

Figure 39 - 2nd DA individuals for the first 12 generations with not-biased evolutionary simulation

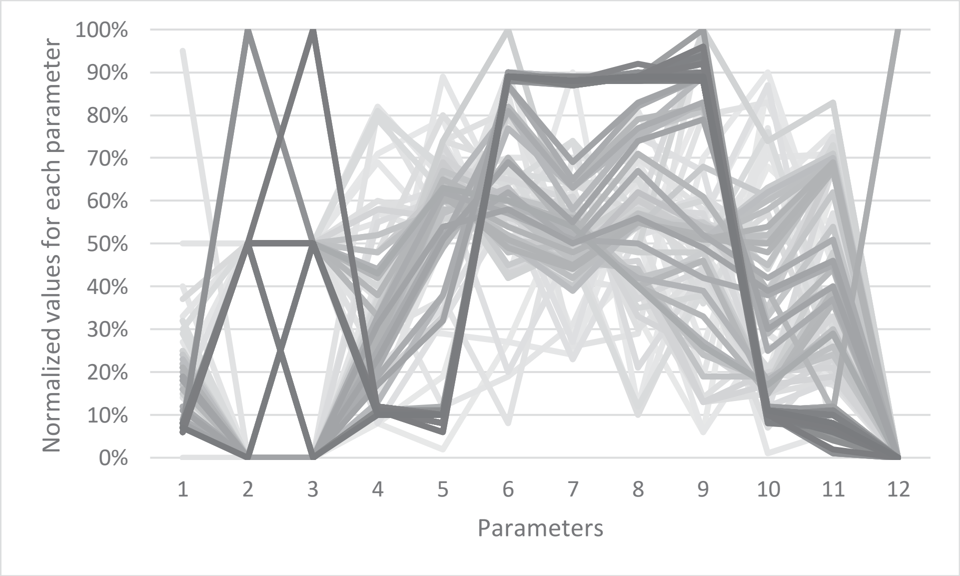
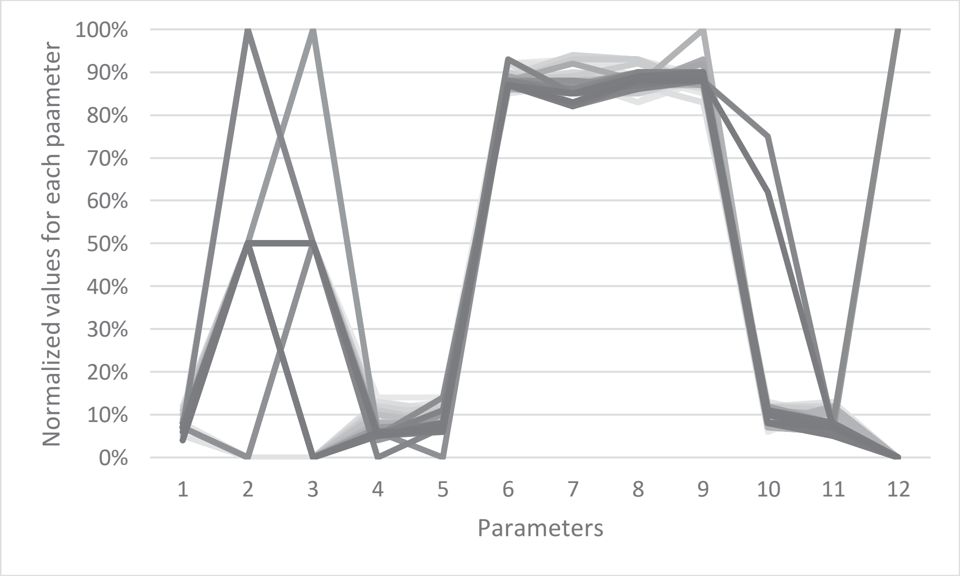


Figure 40 - 2nd DA individuals for the first 12 generations with biased evolutionary simulation



In the first 12 generations, the biased simulation starts to extend the amplitude of outputs and the not-biased does the opposite. In the last 12 generations, both approaches start to approximate their range of population distribution, which shows to be close to the standard cobogó initial solution with small increments.

Figure 41 - 2nd DA individuals for the final 12 generations with not-biased evolutionary simulation

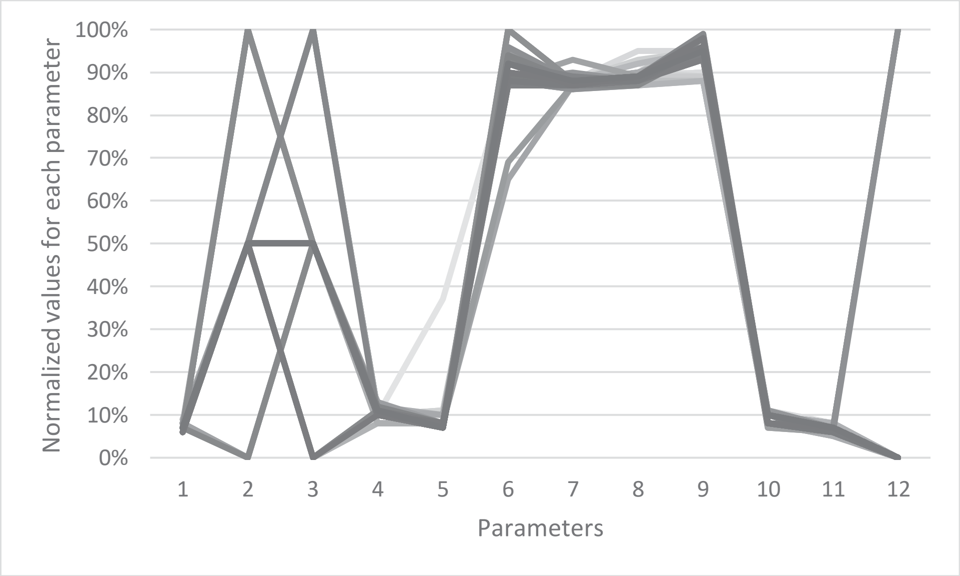


Figure 42 - 2nd DA individuals for the final 12 generations with biased evolutionary simulation

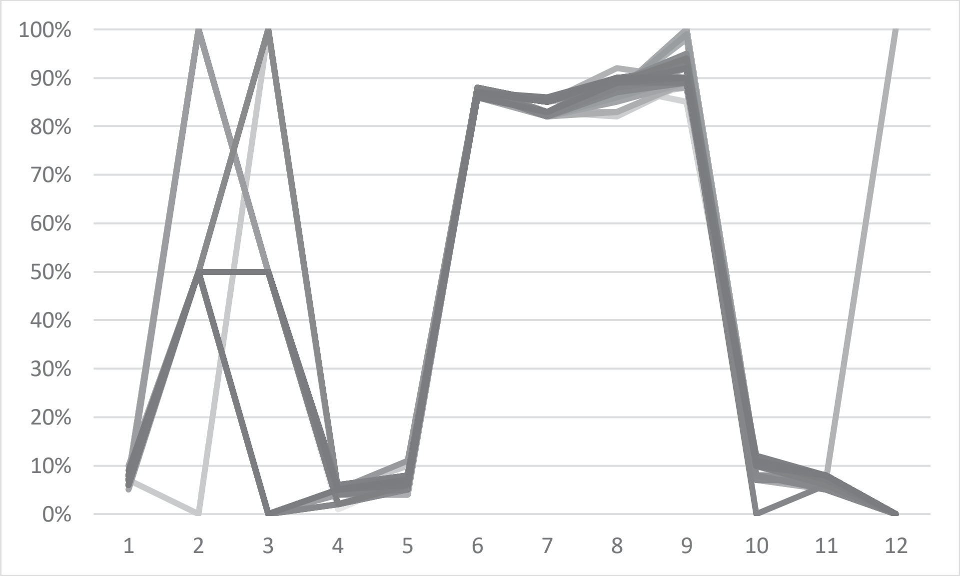
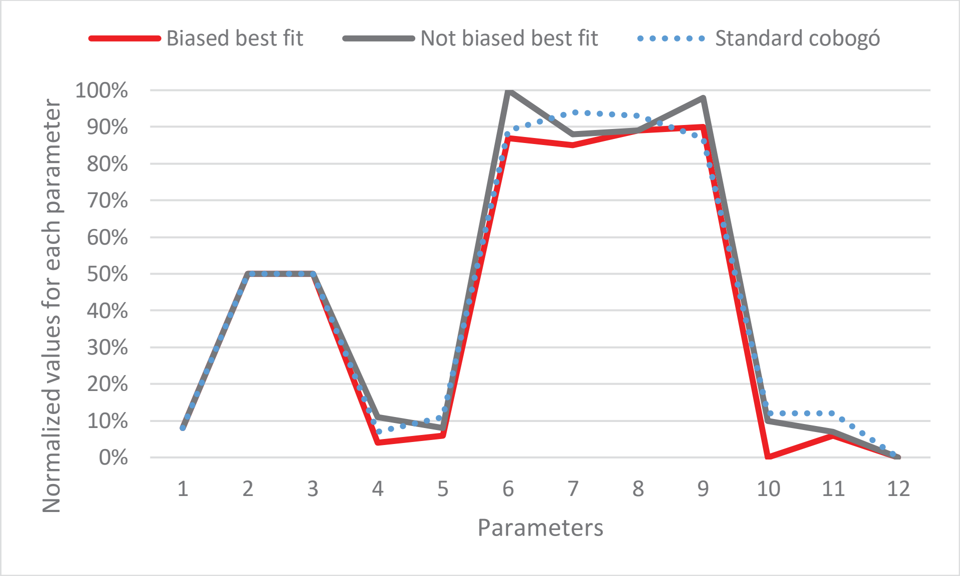


Figure 43 - Optimized solutions for the biased and not-biased simulations



This convergence was studied for the 1st and the 3rd DA as well. The differences between the results are summarized in Table 11. The metric is again the RMSE that, here, compares the biased and the not-biased approach for each DA. The RMSE presented here considers the differences between the values of the parameters for the individuals generated with biased and not-biased evolutionary simulation. Therefore, this analysis does not take into account the performance of each solution or its fitness function value, but the distribution and convergence of the population during stages of the evolutionary simulation along with the 25 generations.

For the 1st DA, the differences during the stages of the evolutionary simulation were constant throughout generations, but in the end, the optimized solutions converged as seen by the RMSE pointed out in Table 11. With just four parameters, the 1st DA obtained a better convergence than the 3rd DA.

For the 3rd DA, the differences at the final generations call attention, since they increased significantly the RMSE. There, the evolutionary simulation was starting to diverge but, similarly to the other DAs, the optimized shapes for the cobogó converged as seen in Table 11.

All the graphics for the 1st and 3rd DA related to Table 11 are presented in the Appendix.

Table 11 - RMSE between biased and not-biased approaches during the stages of the evolutionary simulation.

	RMSE for the Pin	RMSE for the 1st half	RMSE for the 2nd half	RMSE for the optimized solutions
1st DA	0,37	0,36	0,36	0,01
2nd DA	0,40	0,26	0,10	0,14
3rd DA	0,11	0,11	0,21	0,05

The data analyzed here is not conclusive in itself about the behavior of this specific problem of daylight performance and shading properties of a cobogó using the GA. In contrast, some convergence between the two approaches, biased and not-biased, was found in the optimized shapes after 25 generations. Therefore, studying a preexistent object like the standard cobogó might help point towards efficient solutions by both approaches. The benchmarking prevents the user to accept any shape from the GA as a possible good solution.

Additionally, the proximity of shapes appointed in the graphs using the GA with the standard cobogó shape also says that the standard cobogó is a kind of evolved building element considering its functions studied here. This good performance was already noticeable in the benchmarking studies and in the studies realized for different façades, as seen previously in sections 6.1 and 6.2.

6.3.3. Shape exploration within the schema

In this section, shape exploration within the GA schema is presented. Results are shown for the 1st, 2nd, and 3rd DAs. If in the previous section population distribution and convergence between individuals were explored, here a qualitative analysis allows one to interpret the shape of the previous results.

In the shape exploration within the 1st DA, it is possible to see how the shape was allowed to morph and how the best performance shape was searched for (Figure 46).

It is known that for a north façade in Curitiba, by analyzing a solar chart for its latitude, a good alpha angle to design a shading device is considering solar protection between 35° to 50° far from the zenith in the noontime. This range shades the façade especially on the hottest days close to the summer season when working with a 35° protection, or yet in the whole year, with 50° protection far from the zenith. The squared shape of the standard cobogó considered here, when applied to a north façade in Curitiba, results in a sun-shading below to 30° far from the zenith in the noon as presented in Figure 44. In contrast, the vertical walls of the concrete element help protect the room from excessive solar exposure even on the winter solstice (22th June). It happens from the sunrise until close to 8 a.m. and from 4 p.m. until the sunset on that specific day.

In comparison, Figure 45 shows the solar chart for the optimized solution in the 1st DA. The GA for the 1st DA sought a design that enhances exposure in winter both for the morning and for the afternoon hours, shading the façade in the noontime during the most of the year with an angle higher than 35° far from the zenith. Therefore, useful hours of daylighting are extended inside the room when solar radiation is mild and it is welcome to warm the room during the winter. This resulting shading profile is also found in the other DAs.

The shape exploration for this 1st DA is shown in Figure 46, from the best fit, or the optimized shape, to the worst performance shape in all the generations. From the total number of individuals simulated in the 1st DA, a total of 520 individual shapes, 50 of them achieved a fitness function value above the standard cobogó result, which represents 9.6 % of the total population.

Figure 44 - Solar chart and masking region for the standard cobogó

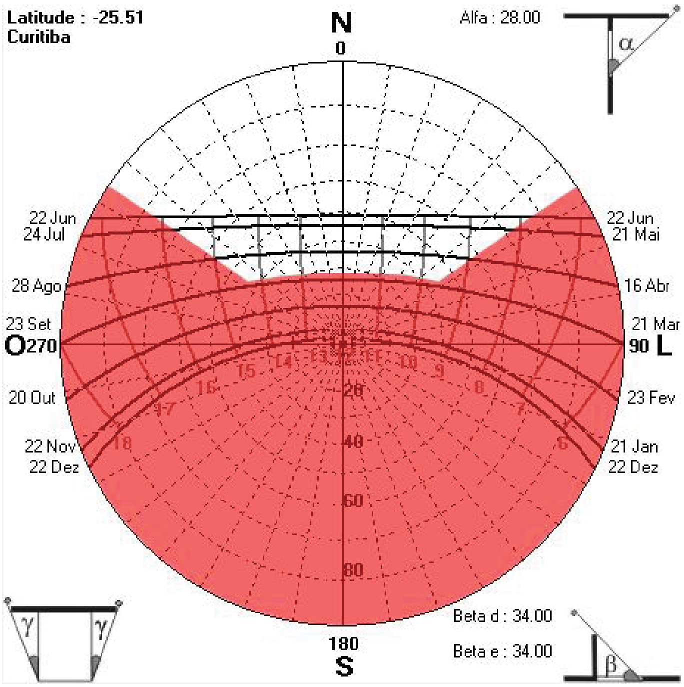


Figure 45 - Solar chart and masking region for the optimized solution in the 1st DA

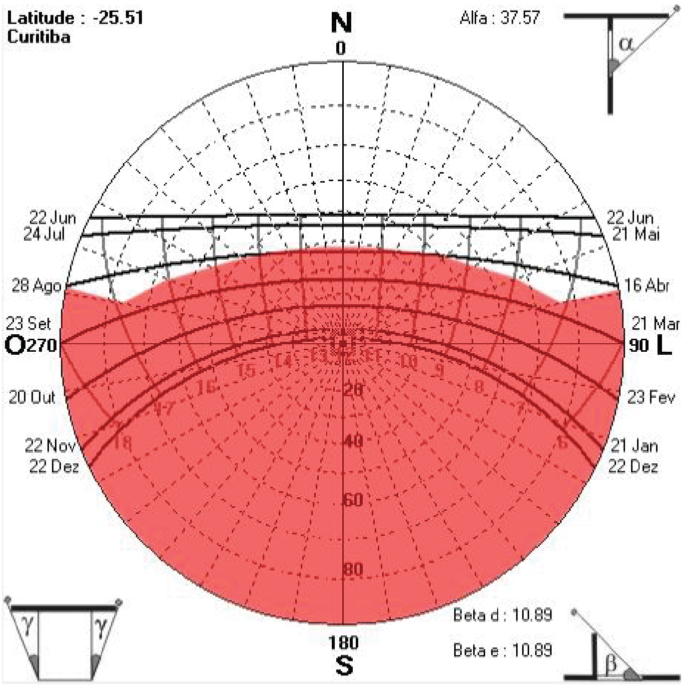
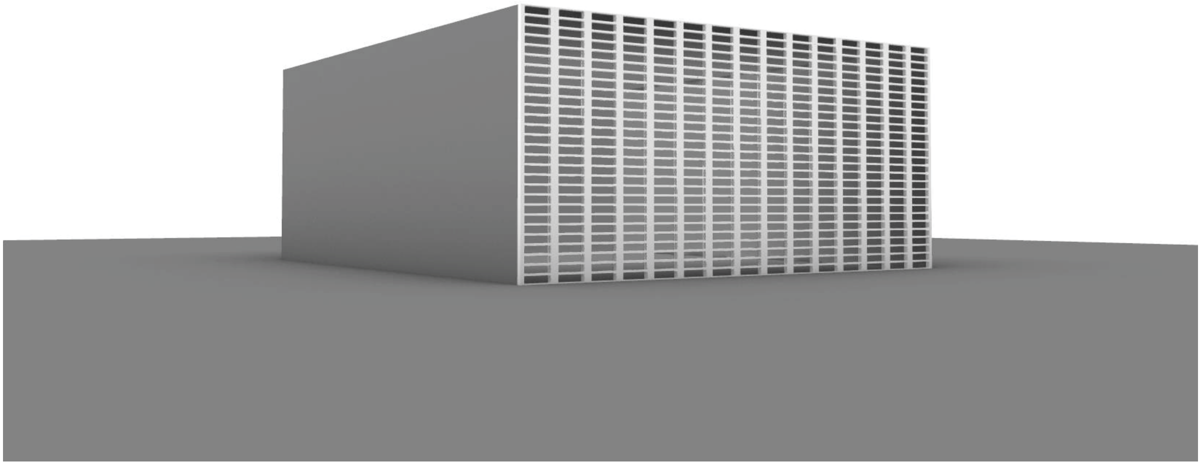


Figure 46 - Shape exploration for the 1st DA for a north façade in Curitiba



(a) Optimized solution for the 1st DA after 25 generations

(b) 100th best fit

(c) 200th best fit

(d) 300th best fit

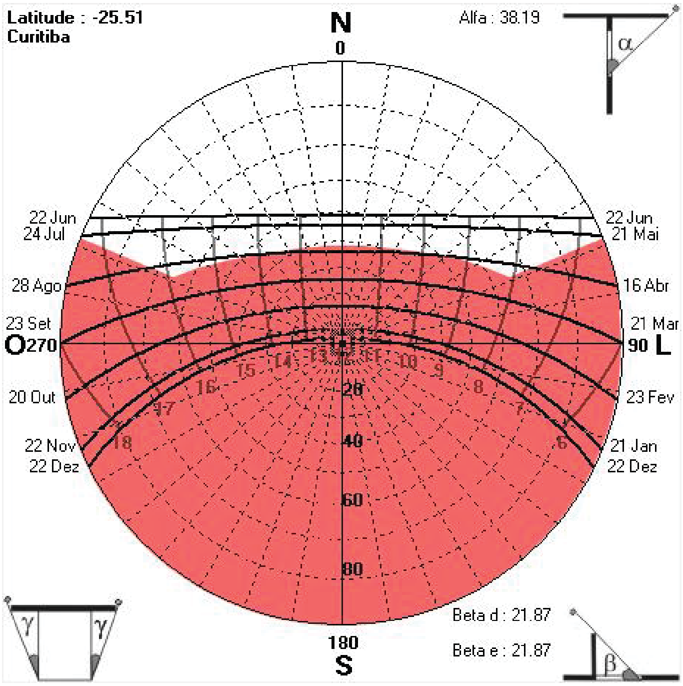
(e) 400th best fit

(f) 500th best fit

(g) Worst solution

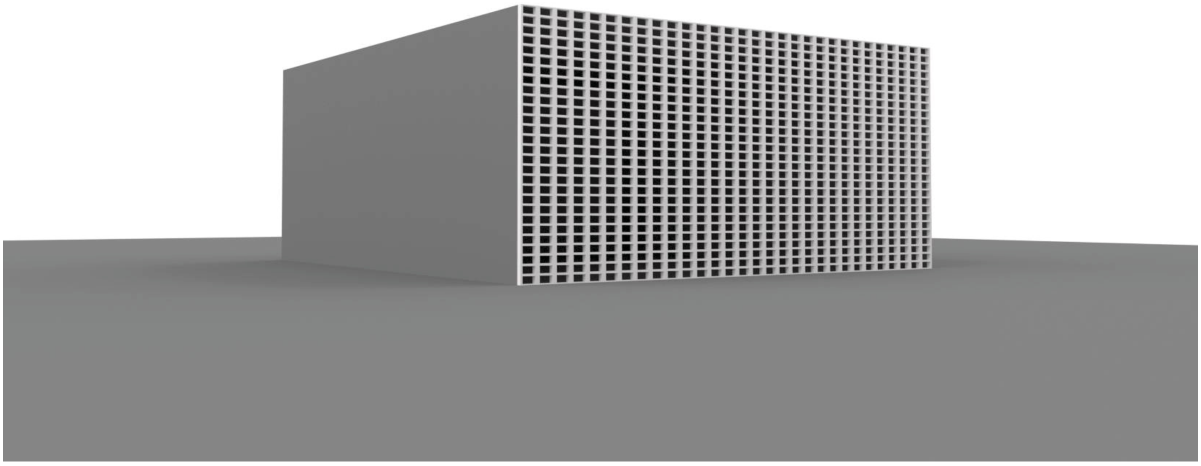
For the 2nd DA, qualitative results are shown in Figure 48. From the 580 individuals generated during the 25 generations, 270 individuals achieved a fitness function value above the standard cobogó result, representing 46 % of the total population during the 25 generations. Although the number of optimized individuals was higher compared to the 1st DA, the schema with this 2nd DA did not achieve a fitness function as high as in the 1st DA.

Figure 47 - Solar chart and masking region for the optimized solution in the 2nd DA



The solar chart in Figure 47 presents the optimized solution here, which shows more protection to solar radiation as compared with the 1st DA, especially for the mid-seasons. Therefore, an angle of 40° far from the zenith was found to be optimal and the vertical walls of the cobogó are closer to each other when compared to the 1st DA, as seen also in Figure 48.

Figure 48 - Shape exploration for the 2nd DA for a north façade in Curitiba



(a) The optimized solution for the 2nd DA after 25 generations

(b) 100th best fit

(c) 200th best fit

(d) 300th best fit

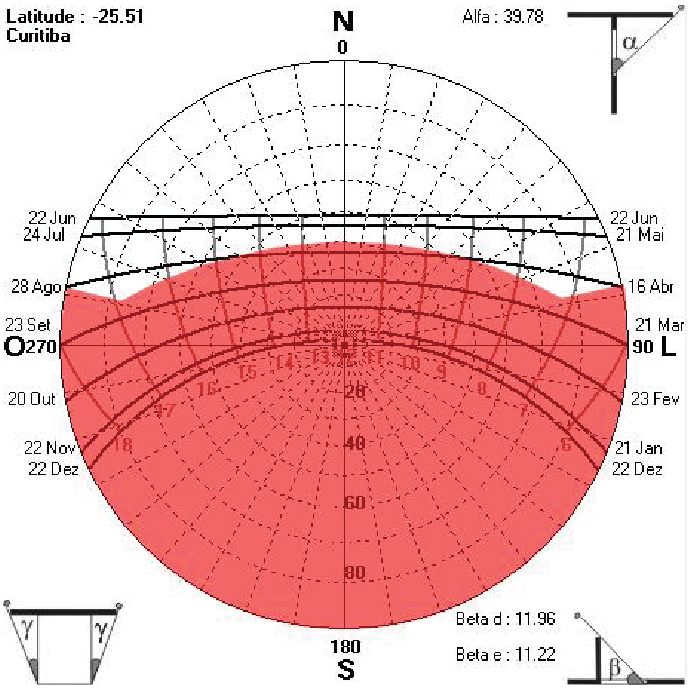
(e) 400th best fit

(f) 500th best fit

(g) Worst solution

For the 3rd DA, qualitative analysis is shown in Figure 50. From the 580 individuals generated during the 25 generations, 387 individuals achieved a fitness function value above the standard cobogó result, representing 66 % of the total population during the 25 generations.

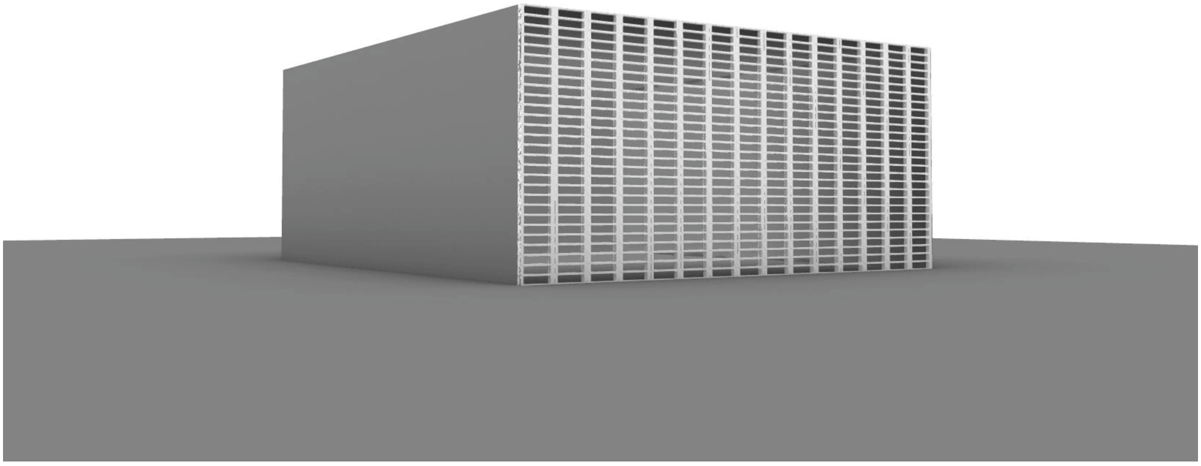
Figure 49 - Solar chart and masking region for the optimized solution in the 3rd DA



The solar chart in Figure 49 presents the optimized solution here, which shows similar protection to solar radiation compared with the 1st DA. The changes in the proportions of the cobogó where the ones that had the highest impact on the performance of the cobogó. The increments allowed by moving the nodes of the piece were tested during the evolutionary simulation but without big changes in the initial geometry.

All the shapes presented here were quite similar to the predefined standard cobogó in all the different DAs, as expected by analyzing the results shown in the previous section. Even if we consider results for not-biased simulation where the GA amplifies its search for different shapes, the optimized solutions after the 25 generations end up to converge, as seen in the previous section of the results.

Figure 50 - Shape exploration for the 3rd DA for a north façade in Curitiba



(a) Best fit

(b) 100th best fit

(c) 200th best fit

(d) 300th best fit

(e) 400th best fit

(f) 500th best fit

(g) Worst solution

The shape exploration here was conditioned to the parameters shown in Tables 5 to 7 where the range assumed to each parameter in each case is described. These limitations are necessary if it is desirable to guarantee optimized results for the final shapes, enhancing the potential to distribute the daylight inside the room and enhancing the sun shading properties of the geometry. Amplifying that ranges could end up in different formal solutions, but the optimization could not occur. Those ranges assumed previously were also the ones that represented the heuristics assumed here to find an optimized solution, the idea that I would still be working with a concrete modular mass-produced shape. Therefore the results for the shape exploration shown here demonstrated this potential. The assumption that the least volume of material was desirable, also forces the GA to refine the known geometry as well.

For using this schema in other cobogó shapes new parameters must define the shape. Therefore, testing other topologies would require the user to describe the shape grammar of the modular piece.

6.3.4. Optimized results for the evolutionary simulations

Here I present the optimized results for the three degrees of adaptation (DA) shown previously in Figure 26. As seen in Table 12, all the DAs subjected to the genetic algorithm improved the performance compared with the standard cobogó for both the fitness function and the $UDI_{100-2000}$. At the same time, they optimized the amount of material used and kept the ASE values in 0% for all the cases.

For the sake of clarity, 0% for the average value of ASE does not mean that no sunlight is achieving the interior of the building, but means the amount of sunlight is not sufficient to be accounted considering the ASE conditions.

Considering that the standard cobogó already presented good results for UDI compared to other façade solutions, as presented in section 6.1, the improvement imposed by the evolutionary algorithm could enhance the performance for the $UDI_{100\text{-}200}$ in 3.2 % at the 2nd DA-NB with the not-biased approach, in 5.5 % at the 3rd DA-B with the biased approach and up to 6.6 % at the 1st DA-B with the biased approach as well.

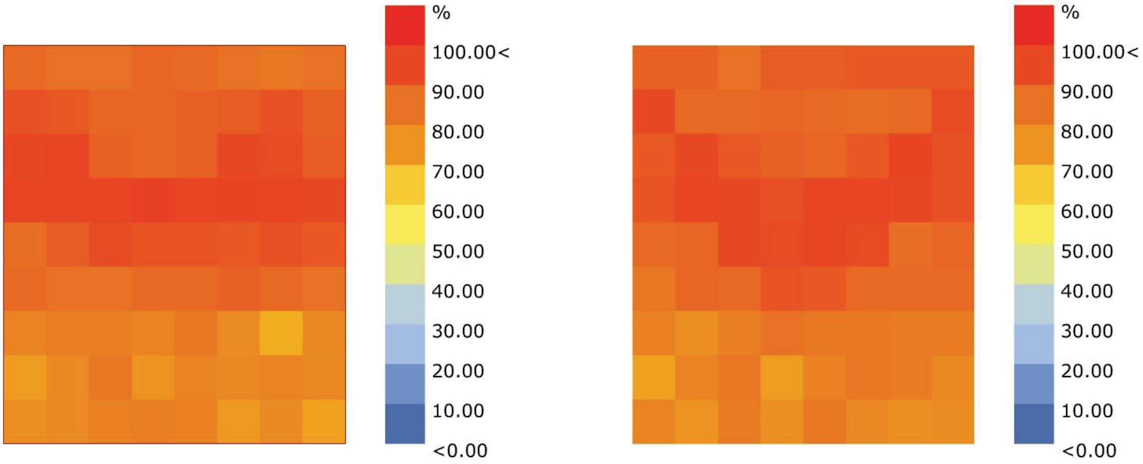
Table 12 - Comparison between evolutionary simulations for each DA

Models	Fitness function value	ASE (%)	$UDI_{<100}$ (%)	$UDI_{100\text{-}2000}$ (%)	$UDI_{>2000}$ (%)	Material volume ratio (%)
Standard Cobogó	76.4	0	19.0	77.0 (± 2%)	4.0	0.50
1st DA-NB	80.6	0	14.9	80.9 (± 2%)	4.1	0.33
1st DA-B	81.7	0	14.8	82.1 (± 2%)	3.1	0.34
2nd DA-NB	79.2	0	17.9	79.5 (± 2%)	2.5	0.35
2nd DA-B	78.6	0	15.5	79.1 (± 2%)	5.3	0.46
3rd DA-NB	78.7	0	17.0	79.1 (± 2%)	3.9	0.33
3rd DA-B	82.1	0	13.8	81.3 (± 2%)	3.7	0.32

The tendency to avoid sun exposure in the GA described here caused the cobogó to maintain UDI lower than 2000 Lux, avoiding also glare probability inside the room. This tendency is viewed in Table 12 by looking at how much the $UDI_{<100}$ values are greater than the $UDI_{>2000.}$

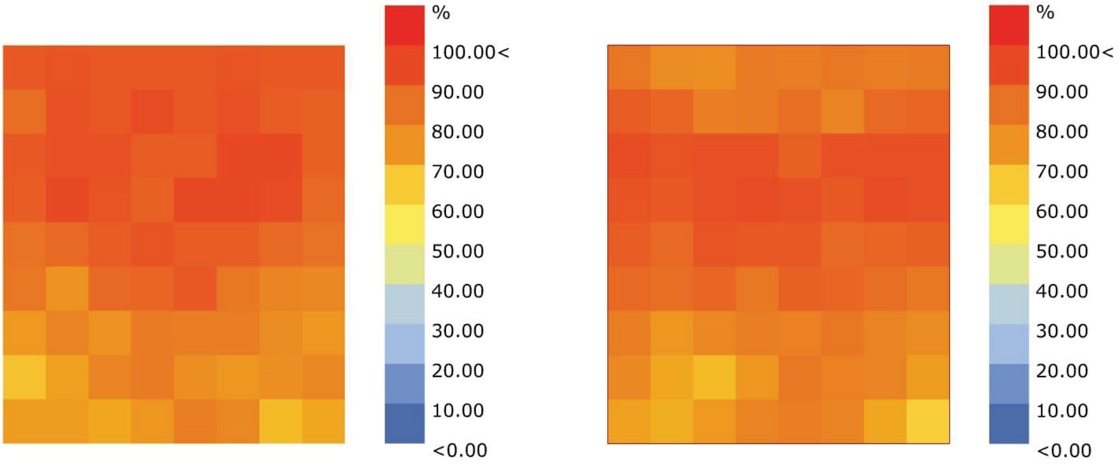
Results for the three different DAs are shown by mesh in Figure 51 for $UDI_{100\text{-}2000}$. In these images, it is possible to see similar results between the three DAs. At the same time, at the back of the room, the 1st DA-B and the 3rd DA-B reached a more homogeneous illuminance with few mesh elements below 70 % for the UDI index.

Figure 51 – Results with a mesh size of 0.75 m for UDI$_{100\text{-}2000}$ *at the three DAs*



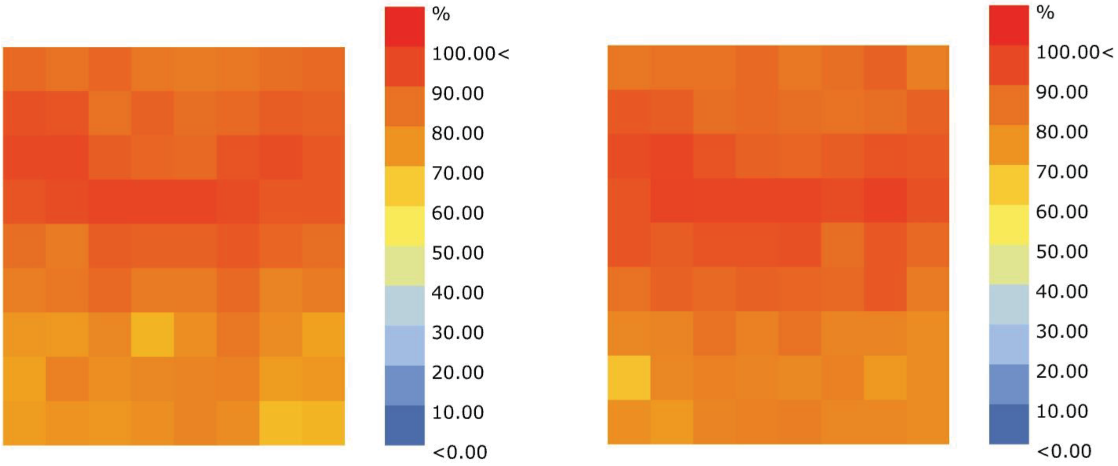
(a) 1st DA-NB

(b) 1st DA-B



(c) 2nd DA-NB

(d) 2nd DA-B



(e) 3rd DA-NB

(f) 3rd DA-B

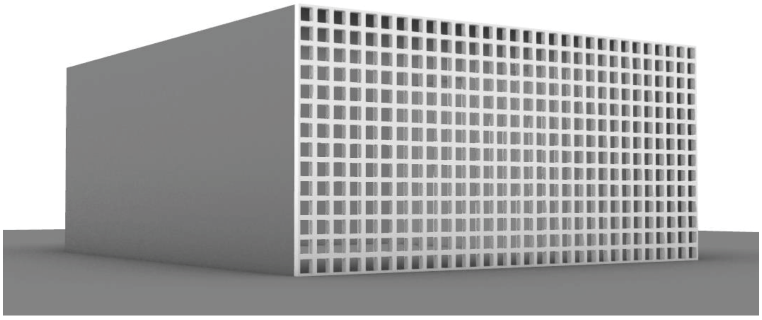
Still, close to the cobogó wall, UDI decreases because the excessive illuminance on some days causes the $UDI_{>2000}$ to increase. Therefore, the center of the room is the best-daylit area with the use of the cobogós, reaching values close to 100 % of useful daylight illuminance.

The optimized solutions considering 25 generations tended to let the cobogó shape to be horizontally slender in both best cases (Figure 52 b and d), with small adaptation in terms of geometry even with the increased freedom to morph allowed by the 3rd DA schema. Yet, increasing flexibility to morph did not necessarily increase the overall performance of the final shape, e. g. the 2nd degree of adaptation reached a fitness function above the previous simulation which was simpler in terms of parameters and possible solutions. The 1st DA demonstrated the highest mean value of UDI when considering both biased and the not-biased approach. The high performance achieved with the two models with the 1st DA was unexpected. The simpler models, with fewer parameters, were able to refine the solution with good results and with the least computational time since it has the smaller population and the least number of mutations caused by geometry collision.

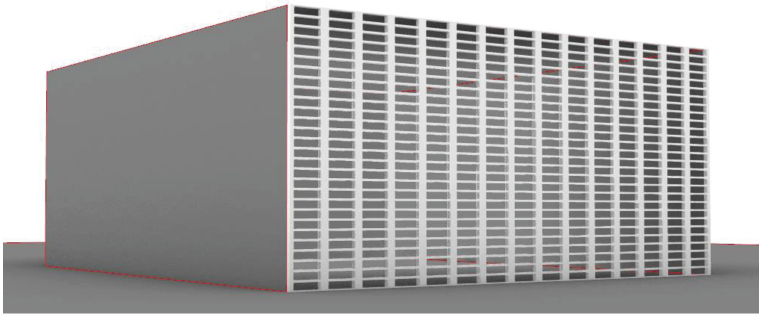
The highest value for the fitness function appeared in the 3rd DA-B, with 82.1 value, since it achieved the highest reduction of the volume of material in the cobogó wall.

About the volume of material, a reduction of 36% was achieved with the optimized solution for the 3rd DA-B. Considering all the evolutionary simulations, the reduction varied from 8 % to 36 %, with an average reduction of 29 % in the volume of material. As pointed earlier, if this economy in material and consequently the embodied energy is considered, a reduction in the volume of material in this scale would be comparable to light the whole room with LED lamps for 150 days during 10 hours. In other words, an average economy of 107 kWh was achieved with the evolutionary simulations.

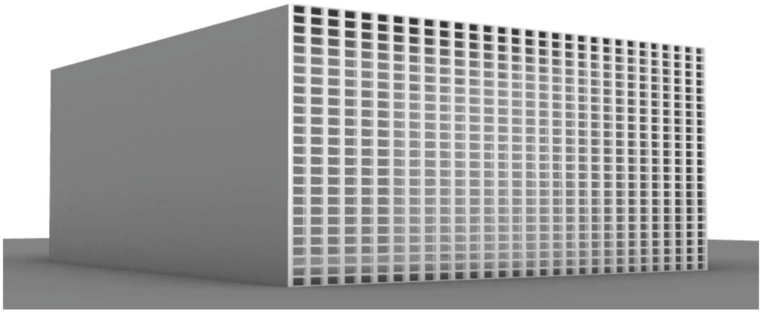
Figure 52 - Qualitative analysis for evolutionary cobogós



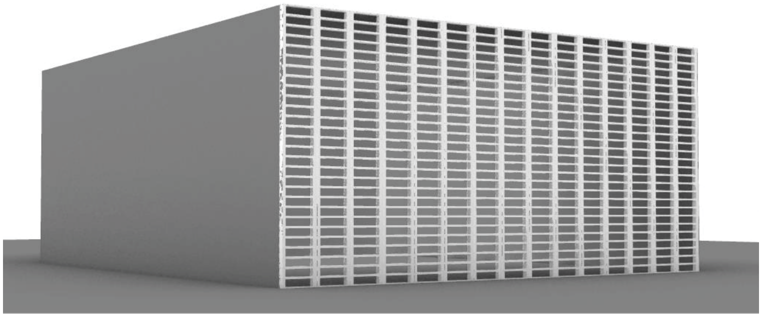
(a) Standard cobogó: Used in the initial benchmarking, it is the manufactured model, and it is the reference for comparison.



(b) Best fit for the 1st degree of adaptation (DA) after 25 generations of evolutionary simulation and 520 individuals subjected to UDI, ASE, and minimum volume of material.



(c) Best fit for the 2nd degree of adaptation (DA) after 25 generations of evolutionary simulation and 580 individuals subjected to UDI, ASE, and minimum volume of material.



(d) Best fit for the 3rd degree of adaptation (DA) after 25 generations of evolutionary simulation and 580 individuals subjected to UDI, ASE, and minimum volume of material.

It was expected that innovative cobogó shapes would appear during the simulations. However, small changes in the initial standard cobogó geometry obtained considerable improvement in terms of performance, as seen in the four solutions, presented in Table 12 and Figure 52 where the best fits are shown. It is possible to remark the similarity of the optimized shapes by looking to the best fits with the 3rd DA and the 1st DA.

Since the ASE value was kept constant in all the solutions, it is possible to evidence that the quality of the distribution of the light inside the room is being determinant to measure the performance of the schema presented here. Therefore, a margin of error of 2 % for the UDI values was assumed. To compute illuminance inside the room, Radiance uses a stochastic approach blended with a deterministic one. This blended strategy demonstrated 1 % or error in previous test simulations, and yet there is the mesh sizing assumption that carries some percentage of error and the error that came from the geometry precision of the modeling. Even with this consideration, all solutions seemed to improve the performance of the standard cobogó, and all the approaches or the degrees of adaptation could be considered similar solutions in terms of performance with each other (Table 12).

7. CONCLUSIONS

This thesis addressed the design of an architectural element as a result of a natural principle. This principle is applied to the design of things in time, and through computational simulation, this time scale is considered as an evolutionary process.

Therefore, a design method based on the evolutionary design by parameter was devised to explore the trends of a cobogó under three different criteria. These criteria searched to allow freedom to the original topology to morph when subjected to ambient conditions. These criteria were named Degrees of Adaptation (DA) and happened to manipulate proportions of the topology in the 1st DA; manipulating the 2D position of the internal points in the 2nd DA; and manipulating the 3D position of internal and external points in the 3rd DA, as seen in Figure 26.

The evolutionary design was based on a genetic algorithm and it was carried out numerically. It was conditioned to find the optimized shape considering maximum Useful Daylight Illuminance (UDI), and minimum Annual Sun Exposure (ASE) and volume of material.

Results showed that the traditional cobogó, developed by vernacular and traditional methods of design reached levels of performance above other façade solutions. Besides, when the cobogó is subjected to different orientations, it demonstrated consistency in daylight performance. Nevertheless, this thesis pointed out the design trends that cobogó would further evolve, and may have anticipated years of empirical, trial-and-error, design evolution, by showing how it evolves, and how it can be adapted to other use conditions. The findings of this thesis may be extended and adapted to not only the design of cobogós but to other architectural elements with the due assumptions.

7.1. ABOUT THE METHOD APPLICATION

The results demonstrated that modeling and allowing flexibility with a parametric schema allows for simulating several cases. This technique is adequate when performance-based solutions are required. It has shown the benefits of exploring more possibilities, benefits of understanding the logic behind topologies, and incrementing a new level of abstraction to design thinking. This contribution, if extended to other scales like the building scale, the neighborhood scale, or the city scale may also expand possibilities in the design of things, and could give amplitude to the decision making processes.

The application of evolutionary design in the context of this work has shown that improving the performance of building elements is promising, but specific conditions to find satisfactory results are also required. The use of genetic algorithms needs to be carefully conducted. It is a process where the designer still handles results, as it is very sensitive to the model parameters and the choice of the correct population and individuals. The more parameters the model is conditioned to, the bigger is the required population, be it for the initial population or during generations. If parameters are not properly dimensioned or sufficiently tested, local optima undergo results to false optimization and the variability allowed by the parametric model becomes underused.

The cumulative error is something to be aware of when dealing with computational simulations. In the context of this work, sources of errors were studied, but in fact, it may come from several decisions made during the process. Considering or not considering the albedo in the simulations showed an error of 1.16%, while the same simulation ran twice showed an error of more 1 % due to the stochastic approach for indirect lighting calculations which has to have its parameters balanced to work with accuracy and speed. The precision of geometry representation and material properties could generate errors as well. The mesh element size or the number of testing points also may introduce errors in the whole simulation. Additionally, rounding of results and the use of averages to input values in the fitness function for the evolutionary simulation were also sources of computational error. The literature pointed out an average error of 20 % when dealing with daylight problems, as seen previously in this work. If some error was computed and described here, the overall precision of the model was not the focus of this work although I looked for validated platforms to perform the simulations.

If the overall method seemed adequate to deal with the problem addressed here, some limitations in working with standard calculation methods in Radiance and Daysim must be pointed out. As the techniques and results from this work were gradually being refined, it became apparent that the number of rays generated from each test point inside the room (i.e. the level of ambient sampling) seemed to be not enough to capture the intended small differences in the geometry of the cobogó. When small geometries are responsible to let the sunlight enter the room, like in blinds, louvers, or the 20 cm x 20 cm cobogós in this work, only a few number of rays can manage to reach the external light source, i. e., the sun or the sky. And as the test points becomes far from the cobogó facade less light rays will be able to reach the exterior light sources.

Therefore, two possible solutions were identified: to either increase the number of rays from each test point; or to greatly increase the number of test points. Still, these solutions are not able to capture small differences in the daylight distribution with small differences in the cobogó geometry, since computational time increase significantly and the accurary of a daylight simulation to work properly is not achieved.

Accurate and fast results with daylight simulation are mandatory to perform evolutionary simulations, since the number of generations and individuals demand quite computational time.

However, Radiance/Daysim seemed to present limitations when work with small geometries in the façade, which can hide real improvements achieved with different cobogó shapes.

Alternatively, the use of BSDF[38] should be explored to determine if they can help the light rays to be scattered in the simulated environment, and reproduce a more realistic light distribution. However, for annual daylight simulations Daysim is the responsible software and the one that was used in this work. Daysim does not support BSDF, at least until the publication of this work. Including BSDF in annual simulations has been subject of conference presentations and workshops like presented by Geisler Moroder (2019) where multi-phased methods are presented.

These multi-phase methods tends to create a better representation of the light distribution withtout the need of high resolution simulation parameters. By calculate daylight contributions separately, multi-phase methods can manage a more accurate representation of both direct and indirect or transmitted light with dynamic skies.

Additionally, another suggestion is about dealing with BSDF assigned with a larger planar aperture, like scaling the geometry in order to have enough light rays crossing the aperture of the cobogó and capturing differences in the daylight performance between small changes in the shape configuration during the evolutionary simulation.

In this thesis, the 2 phase method was used, based on Daylight Coefficients simulations, thus BSDF was not considered. Thus, in order to consider BSDF, the 5 or the 6 six-phase method have to be considered since they work with accurate spatial resolutions for direct solar contribution at the same time they use BSDF to represent scattered light. The particulariry about

---

[38] BSDF - Bidirectional Scatering Distribution Function: it is an additional part of equation added to the rendering equation presented earlier.

dynamic blinds is the high accurate spatial resolution, which ressembles to our problem with the cobogó elements. Therefore, it is advisable to consider a phase-method in Radiance in order to consider the scattered light with BSDF. Like so, some studies could yet be conducted in these directions in order to refine result precision in finding daylight performance improvement in small geometries like in this work, specially when evolutionary simulation is considered:

> *"Often, the primary objective of daylighting simulations is to parametrically and iteratively evaluate only a certain aspect of the scene. This is especially the case if multiple daylighting simulations are performed to evaluate the performance of various types of glazing or shading systems while keeping everything else in the scene constant. In such instances, the Daylight Coefficient method, which involves tracing rays from inside the room to the sky in a single step, becomes prohibitively expensive. The Three-Phase Method (...) is more suited for such simulations". (Subramanian, 2017)*

About the example brought along by this thesis, I conclude that the process of using evolutionary simulation for a performance-based problem has shown considerable improvements. Here, a predefined solution was already known: the standard cobogó. Therefore, with a shape to have as a reference, the evolutionary simulation with the use of GA becomes more reliable, since a benchmarking analysis could be performed.

7.2. ABOUT THE SHAPE EXPLORATION

The simplicity of the shape chosen here allowed me to study several degrees of adaptation, increasing the complexity of the parameters manipulating the geometry and allowing more freedom to the shape to morph. A few numbers of parameters could be preferable when optimizing a known shape. Here, the simpler version with only 4 parameters, manipulating the proportions of the cobogó geometry reached similar results as the most complex evolutionary simulation with 20 parameters. Increasing the number of parameters increases simulation time as well, and at least for a small shape like the cobogó here, small changes in the geometry did not have major impacts on the performance.

In all simulations, the equation for the fitness function input in the GA caused the shapes to protect the room from excessive sun exposure during the year. In contrast, I demonstrate that the values of annual sun exposure (ASE) equal to 0 % are not the same as no solar radiation reaching the room. In the solar charts presented in section 6.3.3, it is possible to see that the optimized shapes allowed direct sun during the winter season. This balance could improve the performance of useful daylight illuminance (UDI) without compromising the visual comfort inside the studied room. In this context, the use of the schema presented here could enhance the illuminance inside the room by about 6.6 %, considering that the standard cobogó is already a good solution compared to other standard façade assemblies.

As ASE was kept constant at 0 %, and UDI was maximized, the control of the volume of material in the equation refined the solutions to optimize the amount of construction material. This condition performed as a decision criterion between similar results for UDI. This condition was also responsible for avoiding the GA to find more innovative solutions like a big tab at some edge, or something like a big marquee. If the main objective, hypothetically speaking, is to find innovative designs, this kind of restrictions could be removed or yet smoothed.

Shape grammar theorists called attention to the fact that CAD software has its limitations of shape manipulation to preserve the integrity of the geometry, and therefore, keep it readable for tridimensional visualization. In the final shapes of cobogó for the city of Curitiba, the design appeal, that was previously desired to happen, did not match the expectations. Firstly, because a simple shape was the basis of all simulations, and this simple shape presented already good results for illuminance distribution and sun exposure, as shown in the benchmarking results for several façade solutions in section 6.1. Second, because the more parameters manipulate the shape, the higher is the initial population required, as well as the number of individuals per generation. Thus, exploring shapes with a great number of parameters becomes time-consuming. I conclude that a huge number of parameters are desirable when expected results in terms of shape and aesthetics were already met and only the optimization is desired. Here, with the resources available for this research, 20 parameters were considered a huge number, since the 25 generations took approximately 4 days to solve in a simpler mesh resolution and 9 days with a more refined mesh. In opposition, a simple evolutionary model as the 1st DA with 4 parameters took 2 days to solve in a simples mesh resolution and 4 days to solve if element size was doubled. Still, the simpler evolutionary simulation was one that presented more options of shape exploration and good quantitative results for the performance of the cobogó.

Although I presented here limited conditions as to when applying evolutionary design, this concept can be applied to improve any initial topology, design, or shape. As pointed earlier, evolutionary design is not just about optimization towards a single shape, but it may induce new outcomes.

7.3. FURTHER DISCUSSIONS

The level of abstraction, geometry creation, and forward-thinking when dealing with performance-based models requires knowledge of descriptive and analytical geometry that extends what is traditionally taught in architecture schools. To consciously create the flexibility needed to generate innovative but not arbitrary shapes, traditional contents of math and science need to be incorporated into the design process. Therefore, if parametric modeling, performance-based design, and evolutionary design are possible strategies for building design with ease of shape creation, modification, and manipulation, reliable outcomes must embrace more interdisciplinary solutions for the conception processes.

The visual programming language, parametric modeling, and genetic algorithms bring math and analytical geometry together with architectural design by looking to topologies as sequences of functions hierarchically organized. In a traditional way of design, this interdependency is already part of the process, as Gerber (2007) pointed. But the visualization of this "meta-design" with the addition of flexibility and shape exploration must be yet explored in the current design process.

Against that, CAD software and other applications that aid the design process are progressively easier to use and more able to reach satisfactory regular solutions. If some authors pointed out that parametric design will overcome the traditional process of design, it requires a higher level of development. Will it facilitate the flux of regular building production, or it will become the method for special projects only?

In architecture theory, several architects rely, in their speech, on other properties of design conception, the materiality of architecture, and spatial perception. Sometimes their speech also seems to deny the importance and the amplitude allowed with new technologies and approaches to design that is, for instance, physics-based or conditioned to objective aspects of buildings (Pallasmaa, 2006; Zumthor, 2006) because for them the connection with the built space is achieved with sensibility and subjectivity. The study developed here, and the literature presented was a rich discussion in terms of architectural theory as well. A discussion that needs yet to be broader.

The artistic dimension of architecture has presented things that are not every time strictly functional, but questions the purpose of the built environment, sometimes playing with our spatial perception, like in the *Parc de la Villette* in Paris, by Bernard Tschumi which designed the public space in opposition to the landscape and the environmental constraints. This dimension of architecture is fundamentally important to human perception and our lives as humankind. It is art, and it questions us and helps us see all aspects of human life. On the other hand, they are not the main purpose of most of the buildings where people live, work, educate themselves, and care for their health. Therefore, by knowing that the building industry is responsible for major environmental impacts, balancing these approaches must be required to build our regular architectural production with quality.

There is an image associated with parametric modeling in architecture that is defended by some architects as a new style in architecture: parametricism (Leach & Schumacher, 2012). Which besides encouraging new methods and technologies to rethink how builds might be, this kind of approach produces an innovative aesthetics for architecture, redefining the ambiance of some cities and buildings. Still, these iconic productions lead to innovations in the construction industry in a broader way, e. g., when thinking about the 4D industry and more technological methods to materialize buildings and artifacts. When I think that parametric modeling can optimize these aesthetical and conceptual appealing approaches for the design of things, through evolutionary simulation, shapes start to balance their generative potential between aesthetics and performance. Here, this work has shown how this typical Brazilian building element, the cobogó, is evolved enough as a shape to be largely produced and have satisfactory performance in its functions of shading device and small light shelves in building façades. It is worth notice that what I call standard cobogó in this thesis is pretty different from the patented original shape (Vieira, et al., 2013). Therefore, this standard shape is already an evolved version of the originally designed shape, evolved from empirical remarks throughout the years.

In this sense, is the Constructal Law applicable to architectural production? Does an evolutionary principle exist when the subject is the design of buildings? Maybe, if we consider a properly time-scale it would be possible to identify a tendency in architectural design evolution. And it is worth notice that the Constructal Law, as well as the other theories of evolutionary design, does not foresee an optimal final design, but instead an evolutionary principle that keeps adapting the system to remain alive under certain environmental conditions. It carries the thought that new conditions appear, that the environment may change and that the restrictions of a structure may find new ways to keep responding to these stimuli. Is this not true when thinking about architecture and all its movements along with history? These are just additional thoughts that arise during the development of this work. Ideas that could be taken to further works.

Also as further works, the application of this method into the production of cobogós is conditioned to the possibility to calibrate real materials, surrounding conditions to the applicable façade, and specific room geometries. Here, even if I preserved the mass production characteristic of the *cobogós*, the schema developed demonstrates the possibility to adapt the production of these components as to be suitable for different locations and orientations.

Studies with phase-method in Radiance are also desirable, in order to improve accuracy in the script, as pointed out earlier.

The contribution of this work is about the conceiving of a schema that allows us to evaluate different façade solutions, focused on sizing and defining conditions to find the best suitable cobogós. With this schema, cobogó production could be performance-based designed at any location and orientation with proper climatic data. The idea was to preserve the main characteristics of this element: mass-produced and made of concrete.

The script developed here, could yet be used to teach architecture students about light distribution and shading devices when trying to manage an equilibrium between these properties of the cobogós.

Another contribution of this work is to introduce the concept of the Constructal Law into architectural design, and the discussion among other evolutionary theories of design. This theoretical approach is worth further investigation.

REFERENCES

ABNT, 1992. *NBR 5413: Iluminância de interiores,* Rio de Janeiro: s.n.

ABNT, 2003. *NBR 15220: Desempenho térmico de edificações ,* Rio de Janeiro: s.n.

ABNT, 2005. *NBR 15215: Iluminação natural,* Rio de Janeiro: s.n.

ABNT, 2013. *NBR ISO/CIE 8995: Iluminação de ambientes de trabalho,* Rio de Janeiro: s.n.

Addis, B., 2006. The Crystal Palace and its place in structural history. *International Journal of Space Structures ,* March, 21(1), pp. 1-20.

Al-Kazzaz, D. A. & Bridges, A. H., 2012. A framework for adaptation in shape grammars. *Design Studies,* Volume 33, pp. 342-356.

Alves, A. B. M. & Schmid, A. L., 2019. *Constructal design to enhance daylight through façade building elements.* Porto Alegre, s.n.

Aranda, B. & Lasch, C., 2006. *Tooling.* New York: Princeton Architectural Press.

Barrios Hernandez, C. R., 2006. Thinking parametric design: Introducing parametric Gaudi. *Design Studies,* May.27(3).

Bejan, A., 1996. Street network theory of organization in nature. *Journal of Advanced Transportation*, Volume 30, pp. 85-107.

Bejan, A., 1997. Constructal-theory network of conducting paths for cooling a heat generating body. *International Journal of Heat and Mass Transfer*, Volume 40, pp. 799-810.

Bejan, A., Charles, J. D. & Lorente, S., 2014. The evolution of airplanes. *Journal of Applied Physics*, Volume 116.

Bejan, A. & Lorente, S., 2008. *Design with Constructal Theory.* New Jersey: Wiley and Sons.

Bejan, A. & Lorente, S., 2011. The constructal law origin of the logistics S curve.. *Journal of Applied Physics*.

Berson, D. M., 2003. Strange vision: Ganglion cells as circadian photoreceptors. *TRENDS in Neurosciences,* 26(6), pp. 314-320.

Boake, T. M., 2014. *Diagrid structures: Systems, connections, details.* Basel: Birkhauser.

Bodart, M. & Deneyer, A., 2006. A guide for the building of daylight scale models. *Proceedings of PLEA 2006,* September 6-8.

Boegly, L. & Grazia, S., 2018. *A engenharia por trás da impressionante cúpula geométrica do Louvre Abu Dhabi.* [Online] Available at: https://www.archdaily.com.br/br/886490/a-engenharia-por-tras-da-impressionante-cupula-geometrica-do-louvre-abu-dhabi
[Acesso em 13 01 2020].

Bronwlee, J., 2015. *Clever Algorithms: Nature-Inspired Programming Recipes.* [Online] Available at: http://www.cleveralgorithms.com/nature-inspired/evolution.html
[Acesso em 27 11 2019].

Caldas, L. & Santos, L., 2016. Painting with light: An interactive evolutionary system for daylighting design. *Building and Environment*, Volume 109, pp. 154-174.

Cannon-Brookes, W. A., 1997. Simple scale models for daylighting design: Analysis of sources of error in illuminance prediction. *Lighting Reserach and Technology,* 29(3), pp. 135-142.

Cartana, R. P., Pereira, F. O. R. & Mayer, A., 2017. *Estudo piloto para análise de elementos de controle solar com formas complexas.* Balneário Camboriu, ANTAC, pp. 1684-1693.

Corbusier, L., 2004. *Por uma arquitetura.* 6th ed. São Paulo: Perspectiva.

Cordeiro, A. C. A., Lukiantchuki, M. A., Roriz, V. F. & Caram, R. M., 2017. *O uso de simulação compuational para a análise de desempenho lumínico em uma sala de escritório, utilizando os cobogós como uma segunda pele.* Balneário Camboriu, ANTAC, pp. 1730-1739.

Cunningham, P., Zaferiou, P. & Lagios, K., 2014. A case study in reflective daylighting. *Perkins+Will Research Journal,* 06(01), pp. 29-53.

Darula, S. & Kittler, R., 2002. *CIE general sky standard defining luminance distributions.* Montreal, Canada, s.n.

Davis, D., 2013. *Modelled on software engineering: Flexible parametric models in the practice of architecture.* Melbourne: RMIT University (PhD Thesis).

Davison, S., 2018. *Grasshopper: Algorithmic modeling for Rhino.* [Online] Available at: http://www.grasshopper3d.com/ [Acesso em 08 03 2018].

DEFuller; AMcneil, 2017. *Radiance: A validated lighting simulation tool.* [Online] Available at: https://www.radiance-online.org/about [Acesso em 2020].

DeKay, M. & Brown, G. Z., 2014. *Sun, wind and light: Architectural design strategies.* 3rd edition ed. New Jersey: John Wiley & Sons.

DiLaura, D. L., Houser, K. W., Mistrick, R. G. & Steffy, G. R., 2011. *The lighting Handnook: Reference and Application.* New York: Illuminating Engineering Society.

Diller, E., Scofidio, R. & Renfro, C., 2015. *The Broad.* [Online] Available at: https://dsrny.com [Acesso em 31 07 2018].

Dresch, A., Antunes Júnior, J. A. V. & Lacerda, D. P., 2015. *Design Science Research: A method for science and technology advacement.* Basel: Springer.

Eiben, A. & Smit, S., 2011. Parameter tuning for configuring and analyzing evolutionary algorithms. *Swarm and Evolutionary Computation*, Volume 1, pp. 19-31.

Eilouti, B., 2019. Shape grammars as a reverse engineering method for the morphogenesis of architectural fac¸ade design. *Frontiers of Architectural Research*, Volume 8, pp. 191-200.

Ekici, B., Cubukcuoglu, C., Turrina, M. & Sariyildiza, I. S., 2019. Performative computational architecture using swarm and evolutionary optimisation: A review. *Building and Environment*, Volume 147, pp. 356-371.

Elghazi, Y., Wagdy, A., Mohamed, S. & Hassan, A., 2014. Daylighting driven design: Optimizing kaleidocycle facade for hot arid climate. *Fifth German-Austrian IBPSA Conference,* pp. 314-321.

Eltaweel, A. & Su, Y., 2017. Parametric design and daylighting: A literature review. *Renewable and Sustainable Energy Reviews 73,* pp. 1086-1103.

EnergyPlus, 2020. *Weather Data.* [Online] Available at: https://energyplus.net/weather [Acesso em 19 03 2020].

Errera, M. R., 2018. Constructal Law in light of philosophy of science. *Proceedings of the Romanian Academy*, Volume Series A, Special Issue, pp. 111-116.

Fonseca, R. W., Fernandes, F. F. & Pereira, F. R., 2017. *Zonemanto bioclimático referente à iluminação natural para o território brasileiro.* Balneário Camboriu, s.n., pp. 1889-1898.

Frazer, J., 1995. *An evolutionary architecture.* London: Architectural Association.

Frota, A. B., 2004. *Geometria da Insolaçao.* São Paulo: Geros.

G1, 2013. *Livro registra história do cobogó, ícone da arquitetura pernambucana.* [Online]
Available at: http://g1.globo.com/pernambuco/noticia/2013/09/livro-registra-historia-do-cobogo-icone-da-arquitetura-pernambucana.html
[Acesso em 09 03 2018].

Gan, V. J. L. et al., 2019. Parametric modelling and evolutionary optimization for cost-optimal and low-carbon design of high-rise reinforced concrete buildings. *Advanced Engineering Informatics*, Volume 42.

Gan, V. J. L. et al., 2019. Simulation-based evolutionary optimization for energy-efficient layout plan design of high-rise residential buildings. *Journal of Cleaner Production*, Volume 231, pp. 1375-1388.

Geisler-Moroder, D., 2019. *BSDF generation and use in annual, matrix-based daylight simulations with Radiance.* [Online] Available at: https://www.radiance-online.org/community/workshops/2019-new-york-ny/presentations/day1/20190821_BSDF_and_Matrix_Tutorial_final.pdf
[Acesso em 2020].

Geisler-Moroder, D., 2019. *Radiance Online.* [Online] Available at: https://www.radiance-online.org/community/workshops/2019-new-york-ny/presentations/day1/20190821_BSDF_and_Matrix_Tutorial_final.pdf
[Acesso em 2020].

Gerber, D., 2007. *Parametric practices: Models for design.* Cambridge: Harvard University.

Herzog, J. & De Meuron, P., 2013. *Messe Basel New Hall.* [Online] Available at: www.herzogdemeuron.com
[Acesso em 31 07 2018].

Holland, J. H., 1992. *Adaptation in Natural and Artificial Systems.* Cambridge: The MIT Press.

Hopkinson, R. G., Petherbridge, P. & Longmore, J., 1966. *Daylighting.* London: William Heinneman Ltda.

IES, 2012. *Approved method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE),* New York: s.n.

Jakica, N., 2018. State-of-the-art review of solar design tools and methods for assessing daylighting and solar potential for building-integrated photovoltaics. *Renewable and Sustainable Energy Reviews*, Volume 81, pp. 1296-1328.

Jowers, I., Earl, C. & Stiny, G., 2019. Shapes, structures and shape grammar implementation. *Computer-Aided Design*, Volume 111, pp. 80-92.

Katsifaraki, A., Bueno, B. & Kuhn, T. E., 2017. A daylight optimized simulation-based shading controller for venetian blinds. *Building and Environment*, Volume 126, pp. 207-220.

Khabazi, Z., 2010. *Generative algorithms using Grasshopper.* Published online: www.morphogenesism.com.

Kirimtat, A., Krejcar, O., Ekici, B. & Tasgetiren, M. F., 2019. Multi-objective energy and daylight optimization of amorphous shading devices in buildings. *Solar Energy*, Volume 185, pp. 100-111.

Kittler, R., 1967. *Standardisation of the outdoor conditions for the calculation of the Daylight Factor with clear skies.* Bouwcentrum Rotterdam, s.n., pp. 273-286.

Kwork, A. G. & Grondzik, W. T., 2011. *The green studio handbook: Environmental strategies for schematic design.* New York: Routledge.

LABEEE, 2018. *Laboratório de Eficiência Energética em Edificações.* [Online] Available at: http://www.labeee.ufsc.br/
[Acesso em 02 10 2018].

Lawson, B., 1980. *How designers think.* s.l.:Architectural Press.

Leach, N. & Schumacher, P., 2012. On Parametricism: A Dialogue Between Neil Leach and Patrik Schumacher.. *Time + Architecture*, Volume 5, pp. 1-8.

Lorente, S. et al., 2012. The constructal-law physics of why swimmers must spread their fingers and toes. *Journal of Theoretical Biology*, Volume 308, pp. 141-146.

Los Angeles County Museum of Art, 2013. *The Presence of the Past: Peter Zumthor Reconsiders LACMA.* [Online] Available at: http://pacificstandardtimepresents.org/exhibitions/the-presence-of-the-past-peter-zumthor-reconsiders-lacma/
[Acesso em 14 April 2020].

Mackey, C., 2017. Calculate ASE for LEED. *HydraShare*, 7 December.

Makki, M., Showkatbakhsh, M. & Song, Y., 2018. *Wallacei.* [Online] Available at: https://www.food4rhino.com/app/wallacei-0#downloads_list
[Acesso em 17 03 2020].

Manzan, M. & Clarich, A., 2017. FAST energy and daylight optimization of an office with fixed and movable shading devices. *Building and Environment*, Volume 113, pp. 175-184.

Mardaljevic, J., 1995. Validation of a lighting simulation program under real sky conditions. *Lighting Research and Technology*, 27(4), pp. 181-188.

Mardaljevic, J., 2000a. *Daylight simulation: validation, sky models and daylight coefficients.* Leiceister: Loughborough University.

Mardaljevic, J., 2000b. *Beyond Daylight Factors: Daylight Coefficient,* Leicester: s.n.

Mardaljevic, J., 2001. The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques. *Lighting Research and Technology*, 33(2), pp. 117-134.

Mardaljevic, J., 2002. Quantification of parallax error in sky simulator domes for clear sky conditions. *Lighting Research and Technology,* 34(4), pp. 313-332.

Mardaljevic, J., 2004. Verification of program accuracy for illuminance modelling: Assumptions, methodology and an examination of conflicting findings. *Lighting Research and Technology*, 36(3), pp. 217-239.

Marsch, A., 2018. *CIE Sky Generator.* [Online] Available at: https://drajmarsh.bitbucket.io/cie-sky.html [Accessed 05 11 2020].

Marsh, A., 2020. *The effect of Radiance parameters.* Perth: s.n.

Matsuura, K., 1987. Luminance distributions of various reference skies. *CIE Technical Report of TC 3-09.*

Membrini, J., Samberger, S. & Labelle, G., 2014. Parametric scripting for early design performance simulation. *Energy and Buildings*, Volume 68, pp. 786-798.

Merin, G., 2013. *AD Classics: The Cristal Palace - Joseph Paxton.* [Online] Available at: https://www.archdaily.com/397949/ad-classic-the-crystal-palace-joseph-

paxton
[Acesso em 03 01 2019].

Mitchell, W. J., 2008. *A lógica da arquitetua: Projeto, computação e cognição.* Campinas: Editora da Unicamp.

Mook, W., 2018. *How many lumens does the sun produce?.* [Online] Available at: https://www.quora.com/How-many-lumens-does-the-sun-produce [Acesso em 18 02 2020].

Moon, P. & Spencer, 1942. Illumination from a non-uniform sky. *Illumination Engineering*, Volume 37, pp. 707-726.

Nabil, A. & Mardaljevic, J., 2005. Useful Daylight Illuminance: A New Paradigm to Access Daylight in Buildings.. *Lighting Research & Technology*, Volume 37, pp. 41-59.

Nabil, A. & Mardaljevic, J., 2006. Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, Volume 38, pp. 905-913.

Oxman, R., 2017. Thinking difference: Theories and models of parametric design thinking. *Design Studies,* Volume 52, pp. 4-39.

Pallasmaa, J., 2006. A geometria do sentimento: um olhar sobre a fenomenologia da arquitetura. Em: *Uma nova agenda para a arquitetura: Antologia teórica 1965-1995*. São Paulo: Cosac Naify.

Perez, R. et al., 1990. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy*, 44(5), pp. 271-289.

Perez, R., Seals, R. & Michalsky, J., 1993. All-weather model for sky luminance: Preliminary configuration and validation.. *Solar Energy*, 50(3), pp. 235-245.

Qingsong, M. & Fukuda, H., 2016. Parametric office building for daylight and energy analisys in the early design stages. *Procedia - Social and Behavioral Sciences,* Volume 216, pp. 818-828.

Radiance, 2020. *Setting Rendering Options.* [Online] Available at: https://floyd.lbl.gov/radiance/refer/Notes/rpict_options.html [Acesso em 06 11 2020].

Reas, C. & McWilliams, C., 2010. *Form+Code in design, art and architecture..* s.l.:Priceton Architectural Press.

Reinhart, C., 2001. *Daylight availability and manual lighting control in office buildings: Simulation studies and analysis of measurements..* Karlsruhe: University of Karlsruhe (PhD Thesis).

Reinhart, C., 2014. *Daylighting Handbook I.* s.l.:www.DaylightingHandbook.com.

Reinhart, C. & Breton, P. F., 2009. *Experimental validation of 3DS MAX® Design 2009 and DAYSIM 3.0.* Glasgow, The 11th International IBPSA Conference.

Reinhart, C. F., 2010. *Tutorial on the use of Daysim simulations for sustainable design.* Cambridge: Harvard Design School.

Reinhart, C. F. & Weismann, D. A., 2012. The daylit area: Correlating architectural student assessments with current and emerging daylight availability metrics. *Building and Environment*, Volume 50, pp. 155-164.

Reinhart, C. & Wienold, J., 2011. The daylighting dashboard: A simulation-based design analysis for daylit spaces. *Building and Environment,* Volume 46, pp. 386-396.

Reis, A. H., 2011. Design in nature, and the laws of physics Comment on “The constructal law and the evolution of design in nature” by Adrian Bejan and Sylvie Lorente. *Physics of Life Reviews*, Volume 8, pp. 255-256.

Rizki, M. et al., 2018. Optimisation of daylight admission based on modifications of light shelf design parameters. *Journal of Building Engineering*, Volume 18, pp. 195-209.

Rocha, L. A. O., Lorente, S., Bejan, A. & Anderson, R., 2012. Constructal design of underground heat sources or sinks for the annual cycle. *International Journal of Heat and Mass Transfer*, Volume 55, pp. 7832-7837.

Roudasari, M., 2015. Honeybee Annual Daylight Simulation Example. *HydraShare*, 9 November.

Roudsari, M. S., 2017. *Honeybee[+} 0.0.3 Release notes for Grasshopper and Dynamo.* [Online]
Available at: https://www.grasshopper3d.com/forum/topics/honeybee-0-0-3-release-notes-for-grasshopper-and-dynamo?groupUrl=ladybug&
[Acesso em 21 11 2020].

Roudsari, M. S., 2020. *Ladybug Tools.* [Online]
Available at: https://www.food4rhino.com/app/ladybug-tools
[Acesso em 08 01 2020].

Rowe, G. P., 1987. *Design thinking.* Cambridge: The MIT Press.

Rutten, D., 2010. *Evolutionary Principles applied to Problem Solving.* [Online] Available at: http://www.grasshopper3d.com/profiles/blogs/evolutionary-principles [Acesso em 07 03 2018].

Saleh, M. M. & Al-Hagla, K. S., 2012. Parametric urban comfort envelope: An approach toward a responsive sustainable urban morphology. *International Journal of Architectural and Environmental Engineering,* 6(11), pp. 930-937.

Santos, L., Leitão, A. & Caldas, L., 2018. A comparison of two light-redirecting fenestration systems using a modified modeling technique for Radiance 3-phase method simulations. *Solar Energy*, pp. 47-63.

Schmid, A., 2004. Simulação da luz natural: combinação dos algoritmos de raytracing e radiosidade e aplicações na arquitetura. *Ambiente Construído*, Volume 4, pp. 51-59.

Schmid, A. L. & Uehara, L. K. S., 2017. Lighting performance of multifunctional PV windows: A numeric simulation to explain illuminance distribution and glarecontrol in offices. *Energy and Buildings*, Volume 154, pp. 590-605.

Sghiouri, H., Mezrhab, A., Karkri, M. & Naji, H., 2018. Journal of Building Engineering. *Shading devices optimization to enhance thermal comfort and energy performance of a residential building in Morocco*, Volume 18, pp. 292-302.

Simon, H., 1996. *The sciences of the artificial.* 3rd edition ed. Cambridge: The MIT Press.

Smith, R., 2007. *Technical notes from experiences and studies in using parametric and BIM architectural software.* [Online] Available at: http://www.vbtllc.com/images/VBTTechnicalNotes.pdf [Acesso em 11 March 2018].

Stiny, G., 2006. *Shape: Talking about seeing and doing.* Cambridge: MIT Press.

Stiny, G. & Gips, J., 1972. Shape Grammars and the Generative Specification of Painting and Sculpture. *Information Processing* , Volume 71, pp. 1460-1465..

Subramanian, S., 2017. *Daylight simulations with Radiance using Matrix-based Methods.* s.l.:Lawrence Berkeley National Laboratory.

Sung, D., 2016. A New Look at Building Facades as Infrastructure. *Engineering*, Volume 2, pp. 63-68.

Sung, D., 2018. [Online]
Available at: https://www.dosu-arch.com/
[Acesso em 17 03 2020].

Suyoto, W., Indraprastha, A. & Purbo, H. W., 2015. Parametric Approach as a Tool for Decision-making in Planning and Design Process. Case Study: Office Tower in Kebayoran Lama. *Procedia - Social and Behavioral Sciences,* Volume 184, pp. 328-337.

Tavares, S. F., 2006. *Metodologia de análise do Ciclo de Vida Energético de edificações residenciais brasileiras.* s.l.:(Thesis) Universidade Federal de Santa Catarina.

Tietz, J., 2008. *História da arquitectura contemporânea.* s.l.:H. F. Ullmann.

Torres, S. L. & Sakamoto, Y., 2007. Facade design Optimization for daylight with a simple genetic algorithm. *Proceedings: Building Simulation,* pp. 1162-1167.

Tourre, V. & Miguet, A., 2009. *A light-based parametric model, Proceedings of Caad.* Montreal, Canada, Proceedings of Caad Futures International Conference, pp. 786-799.

Tregenza, P., 1983. The Monte Carlo method in lighting calculations. *Lighting Research and Technology* , 15(4), pp. 163-170.

Turrin, M., Van Dem Ham, E., Kilian, A. & Sariyilds, S., 2010. *Integrated design of a large span roof: A parametric investigation on structural morphology, thermal comfort and daylight.* Nottingham, s.n.

Turrin, M., Von Boelow, P. & Stouffs, R., 2011. Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms. *Advanced Engineering Informatics,* Volume 25, pp. 656-675.

Uehara, L., 2018. *Potencial da janela fotovoltaica para edifícios de escritório com múltiplos pavimentos: Avaliação da iluminação natural em termos de iluminância e ofuscamento,* Curitiba: s.n.

USGBC, 2013. *LEED Reference Guide for building design and construction,* Washington DC: s.n.

Vazquez, E., 2017. *A grammar of perforated masonry walls: A formal analysis of brick walls used for shading and ventilation in Paraguay.* Concépcion, Chile, s.n.

Vieira, A., Borba, C. & Rodrigues, J., 2013. *Cobogó of Pernambuco.* Recife: J. Rodrigues.

Vierlinger, R., 2012. *Octopus.* [Online] Available at: https://www.food4rhino.com/app/octopus [Acesso em 17 03 2020].

Visser, W., 2006. *The Cognitive Artifacts of Designing.* New Jersey: Lawrence Erlbaum.

Ward, G., 1994. *The Radiance lighting simulation and rendering system.* Orlando, The 21st Annual Conference on Computer.

Ward, G., 2000. *Mardaljevic J. Beyond daylight factors: an example study using daylight coefficients,* York: s.n.

Ward, G., 2001. The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques. *Lighting Res. Technol.*, 33(2), pp. 117-136.

Ward, G., 2014. *Reducing Anisotropic BSDF Measurement to Common Practice.* s.l.:s.n.

Ward, G. & Shakespeare, R., 2003. *Rendering with Radiance: The art and science of lighting visualization.* Davis, CA: Space & Light.

Whitted, T., 1980. An improved illumination model for shaded display. *Communications of the ACM*, Volume 23.

Woodbury, R., 2010. *Elements of parametric design.* Abingdon-on-Thames: Routledge.

Yi, Y. K., 2019. Building facade multi-objective optimization for daylight and aesthetical perception. *Building and Environment*, Volume 156, pp. 178-190.

Youssef, A. M. A., Zhai, Z. & Reffat, R. M., 2018. Generating proper building envelopes for photovoltaics integration with shape grammar theory. *Energy and Buildings*, Issue 158, pp. 326-341.

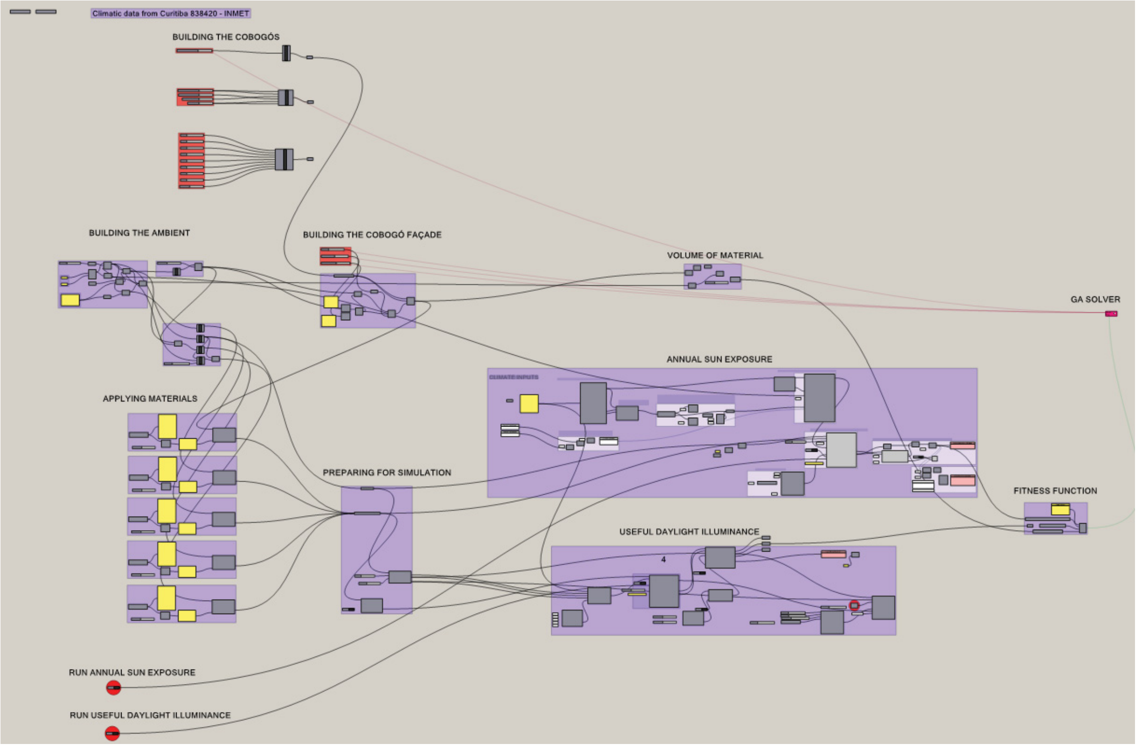
Zani, A. et al., 2017. Computational design and parametric optimization approach with genetic algorithms of an innovative concrete shading device system. *Procedia Engineering*, Volume 180, pp. 1473-1483.

Zumthor, P., 2006. *Atmospheres: Architectural Environments, Surrounding Objects.* Basel: Birkhäuser.

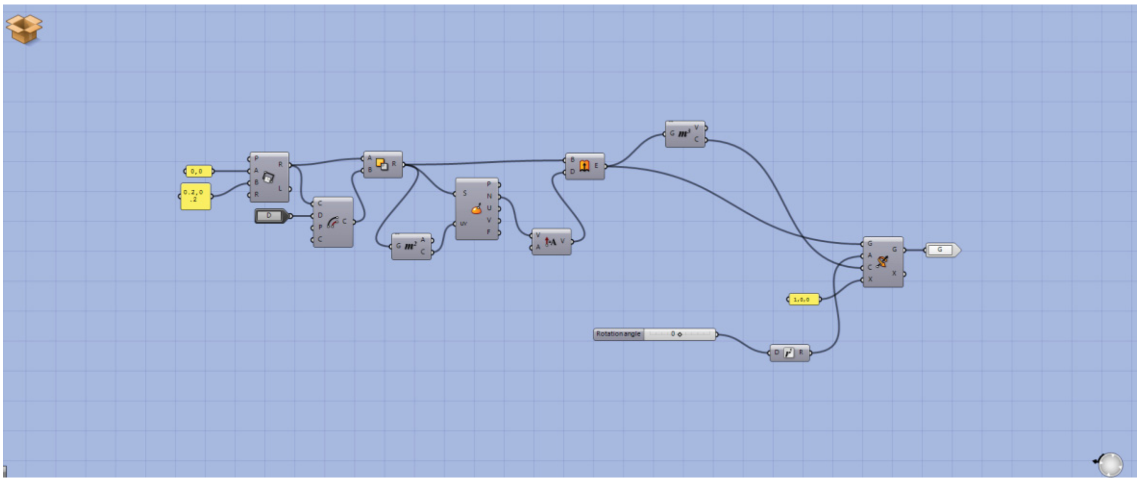
APPENDIX

A. Visual Programming language screenshots

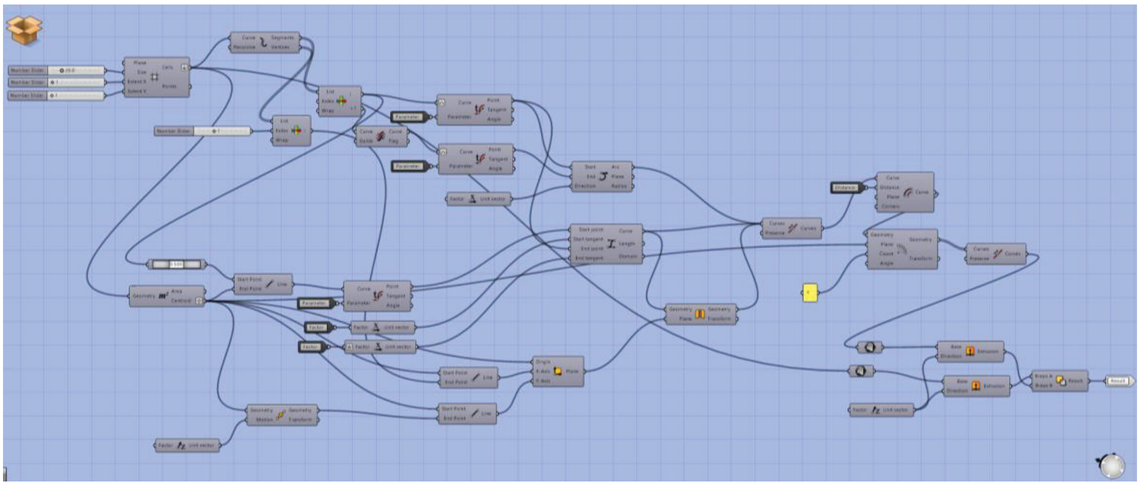
A. Figure 1 - Complete VPL schema



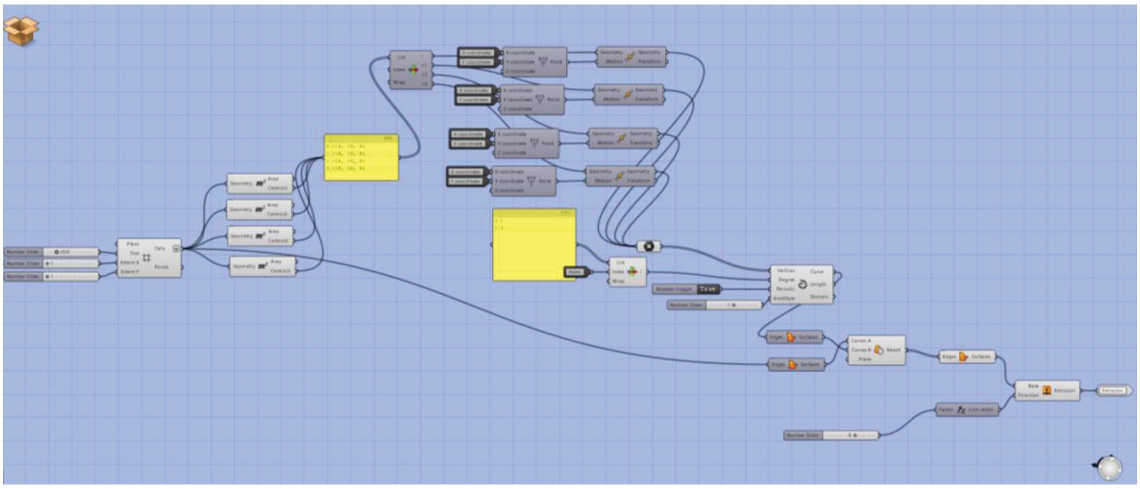
A. Figure 2 - 1st DA Cobogó schema



A. Figure 3 - 2nd DA cobogó schema



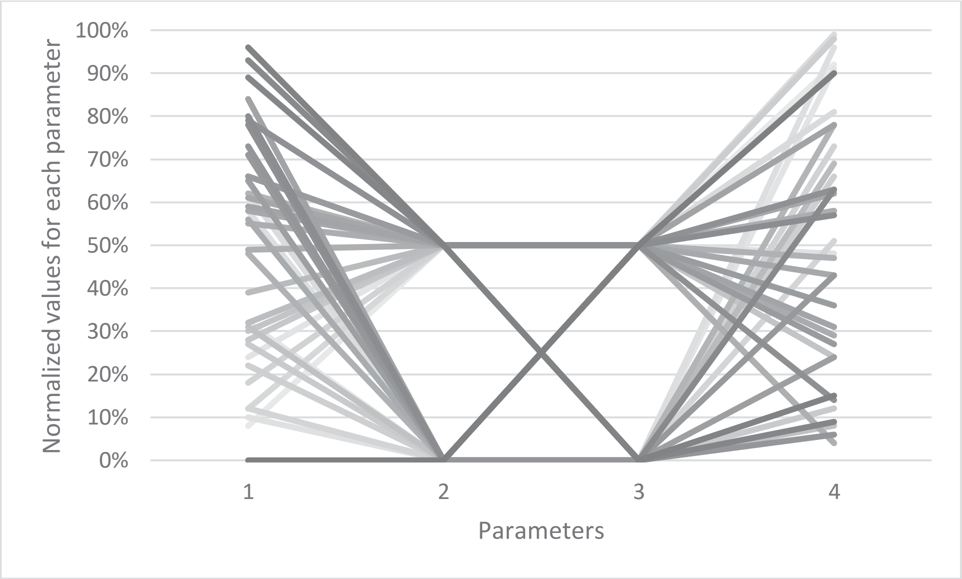
A. Figure 4 - 3rd DA cobogó schema



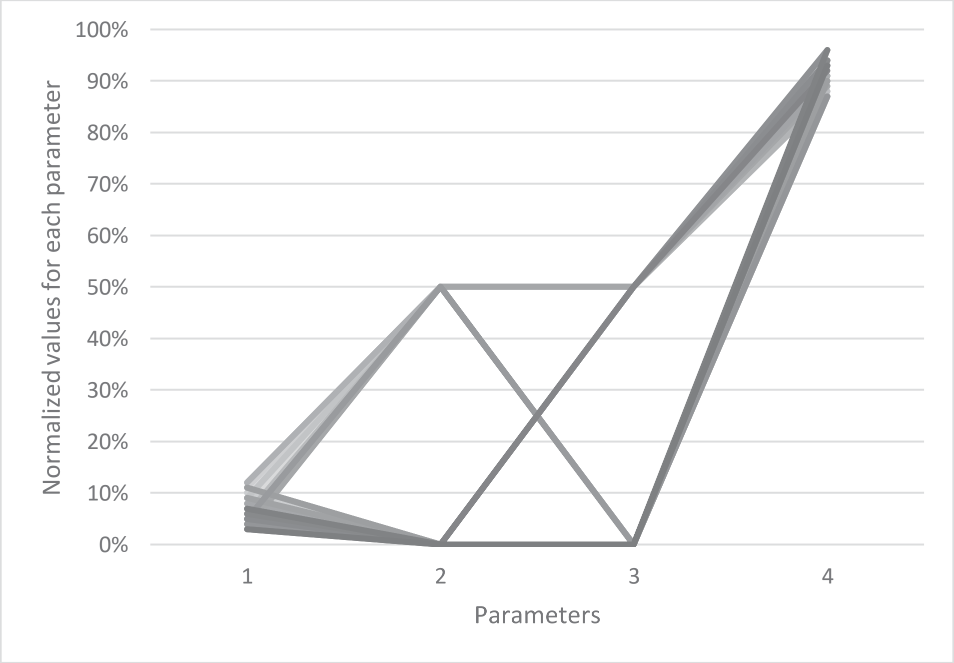
B. Distribution of the population considering biased and the not-biased evolutionary simulations.

B1. 1st Degree of adaptation

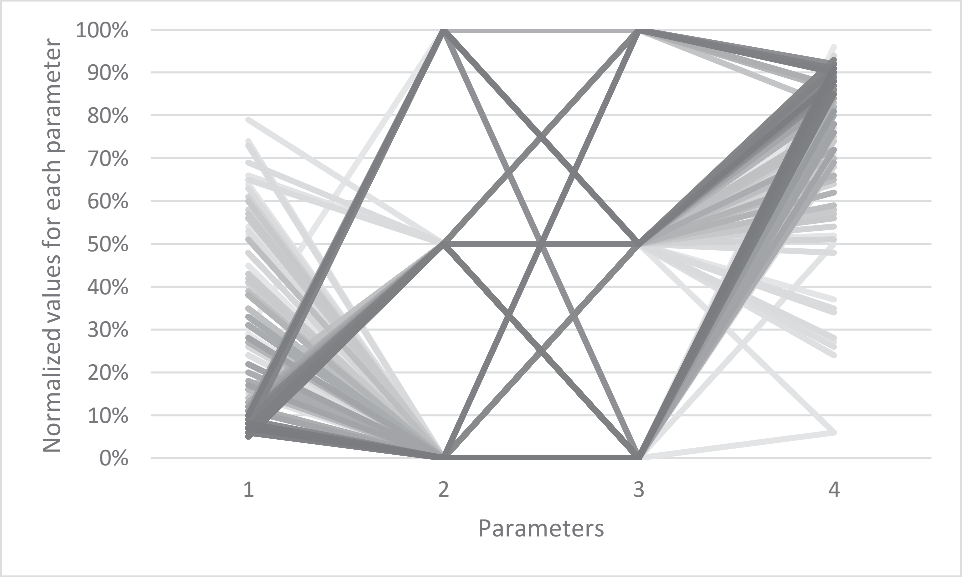
A. Figure 5 - 1st DA Pin - not based evolutionary simulation



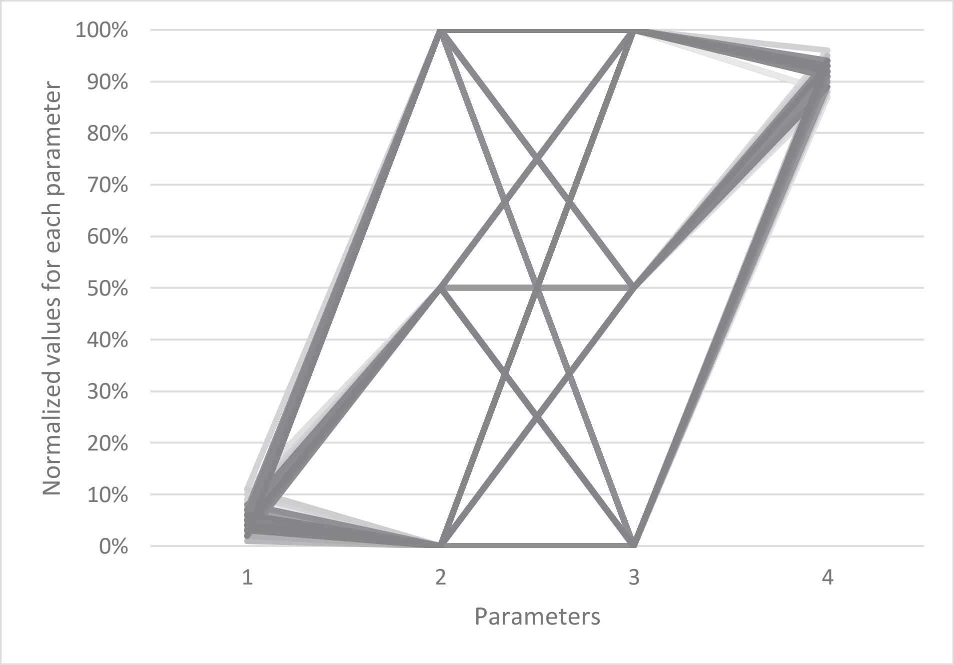
A. Figure 6 - 1st DA Pin - biased evolutionary simulation



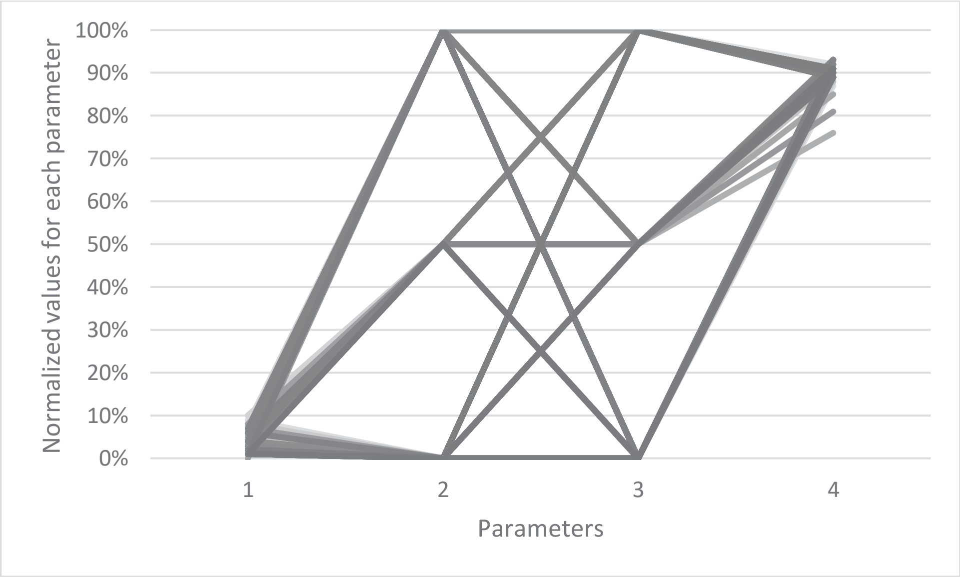
A. Figure 7 - 1st DA individuals for the first 12 generations - not-biased evolutionary simulation



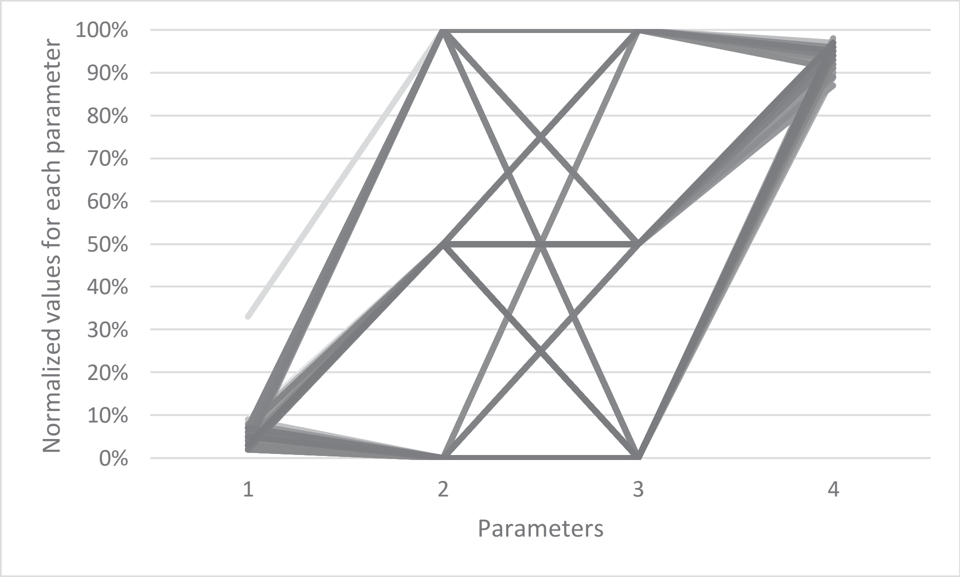
A. Figure 8 - 1st DA individuals for the first 12 generations - biased evolutionary simulation



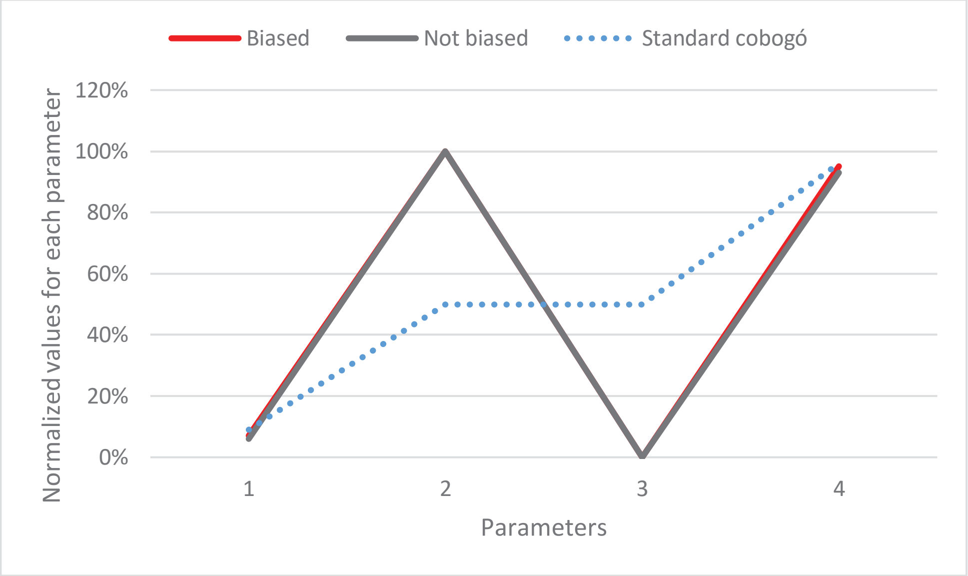
A. Figure 9 - 1st DA individuals for the last 12 generations - not-biased evolutionary simulation



A. Figure 10 - 1st DA individuals for the last 12 generations - biased evolutionary simulation

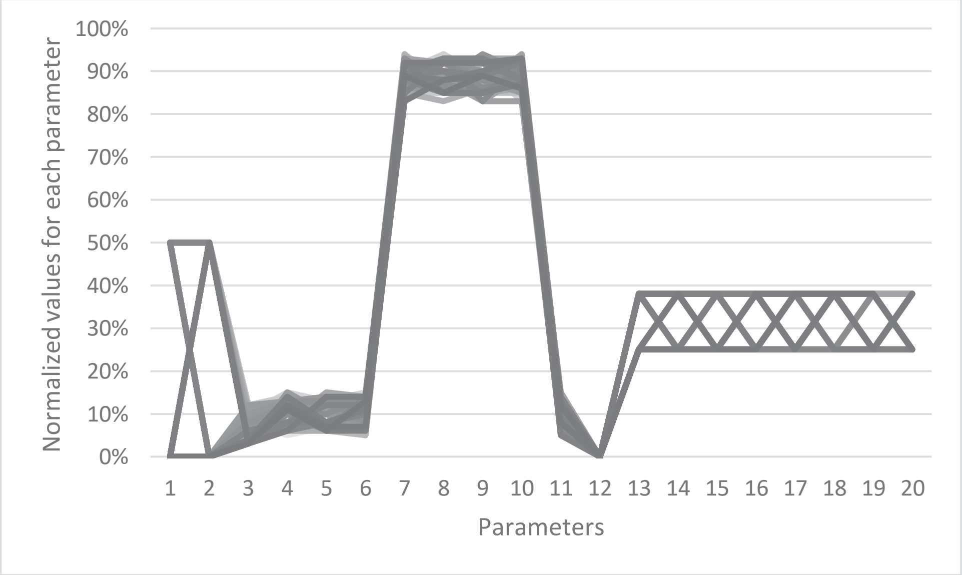


A. Figure 11 - Optimized solutions for both approaches in the 1st DA

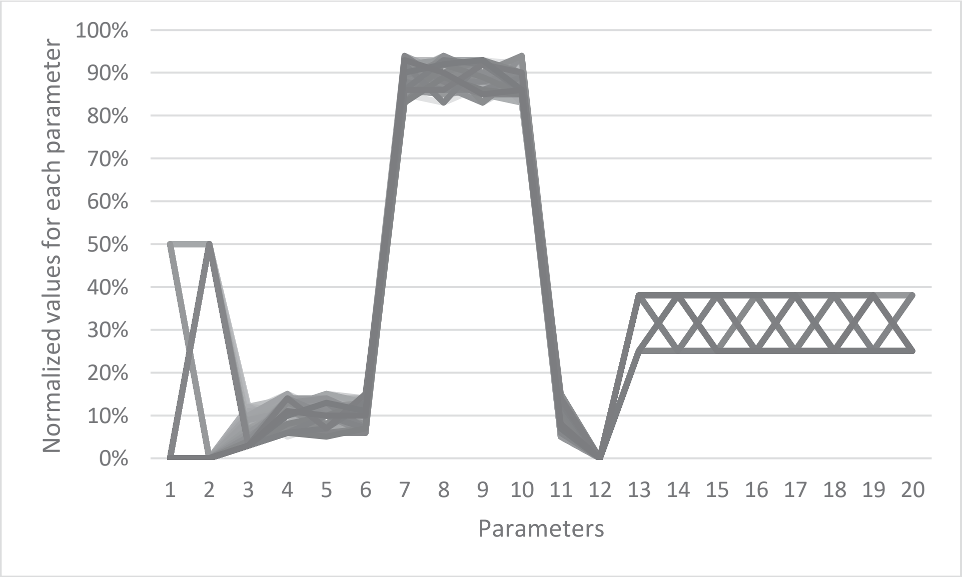


B2. 3rd Degree of Adaptation

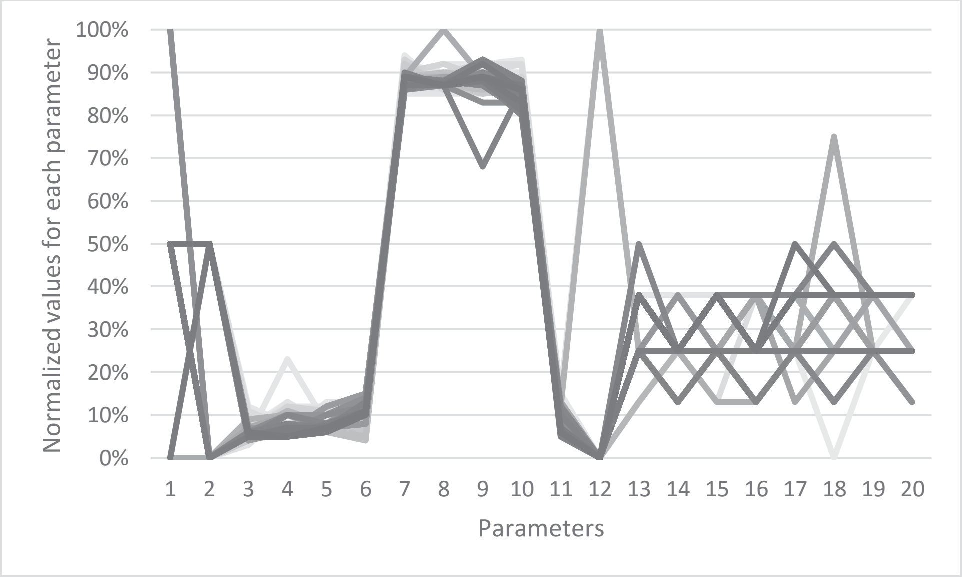
A. Figure 12 - 3rd DA Pin – not-biased evolutionary simulation



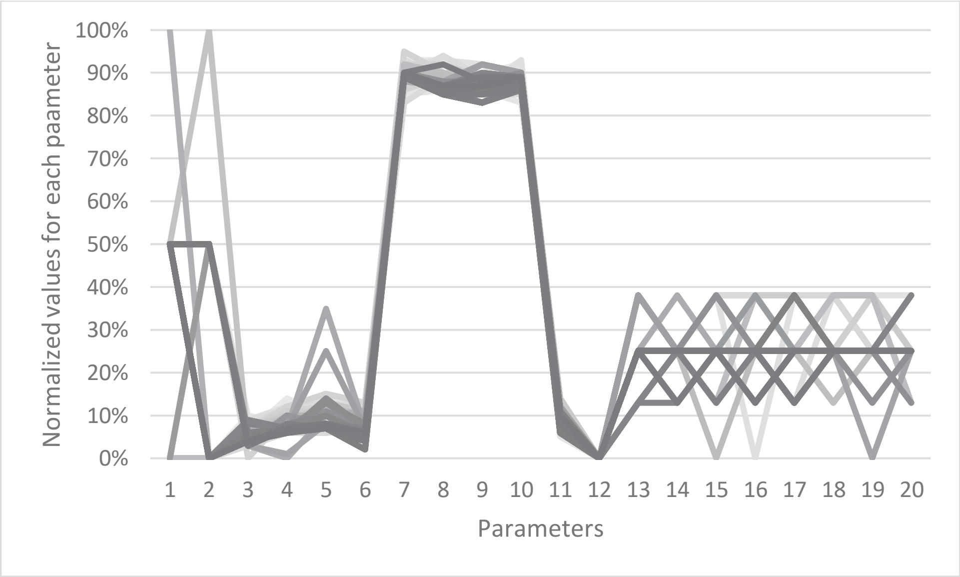
A. Figure 13- 3rd Pin - biased evolutionary simulation



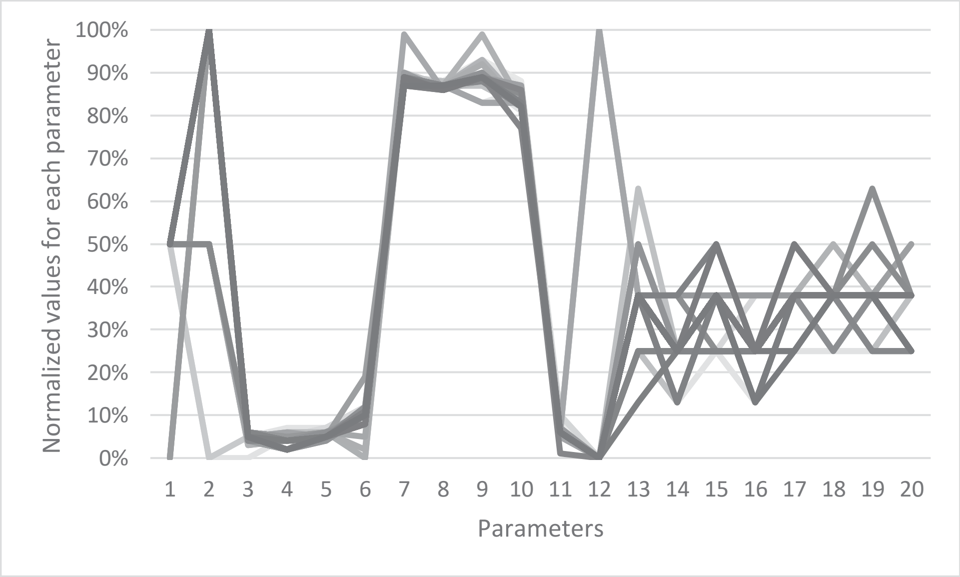
A. Figure 14 - 3rd DA individuals for the first 12 generations - not-biased evolutionary simulation



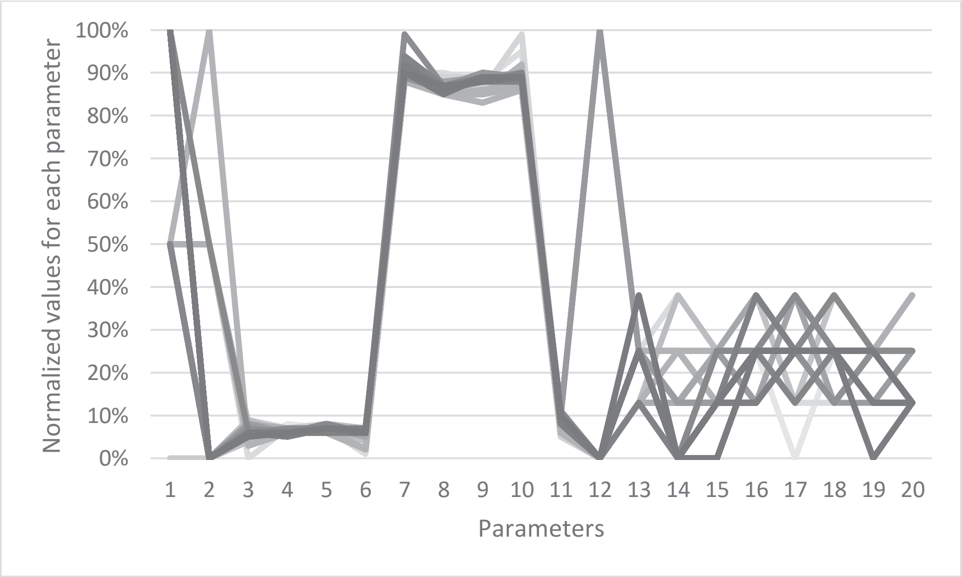
A. Figure 15 - 3rd DA individuals for the first 12 generations - biased evolutionary simulation



A. Figure 16 - 3d DA individuals for the final 12 generations - not-biased evolutionary simulation



A. Figure 17 - 3rd DA individuals for the final 12 generations - Biased evolutionary simulation



A. Figure 18 - Optimized solution for both approaches in the 3^{rd} DA