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Integrating Algorithmic Processes in Informal Urban and Architectural Planning

A case study of a Maputo's neighborhood

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

Urbanization growth in developing countries is an undeniable reality and translates into concerns regarding these countries' ability to include slums, underdeveloped communities, and neighborhoods in economic, health, and climatic goals. This research focuses on the integration of algorithmic design and analysis strategies to develop a methodology to study, define, and measure key parameters that affect the design and rehabilitation of these areas. Wall and roof construction scenarios are tested for improvements, and design dimensions such as height and floor area are analyzed to establish design and comfort thresholds. An optimization process is integrated with the workflow to maximize thermal comfort, rehabilitation costs, and fairness of performance results for each building. Results show improvements in thermal comfort with several different construction scenarios from which a two-staged rehabilitation plan is defined. The first stage comprises the identification of buildings that significantly improve with rehabilitation, and the second defines the most suitable construction scenarios considering the cost of application and comfort improvement for each building. Additionally, design guidelines regarding the parameters tested for building design in the area are researched and documented, revealing the conflictive nature of different design objectives, and the architect's role in the tackled design problems.

Resumo

O crescimento da urbanização nos países em desenvolvimento é uma realidade inegável que se traduz em preocupações quanto à capacidade desses países de incluir favelas, comunidades subdesenvolvidas e bairros nas suas metas de desenvolvimento económico e sustentável. Esta pesquisa foca-se na integração de design algorítmico e estratégias de análise para desenvolver uma metodologia que estuda, define e quantifica os principais parâmetros que afetam o projeto e a reabilitação de um caso de estudo ilustrativo. Parâmetros como soluções construtivas de paredes e telhados, altura, área de piso e área de envidraçado são testados para melhorias térmicas, lumínicas, e de circulação de ar às escalas urbana e de uma casa tipo. Um processo de otimização é integrado ao fluxo de trabalho de análises para maximizar o conforto térmico, os custos de reabilitação e o balanço dos resultados de desempenho de cada edifício. Resultados mostram melhorias no conforto térmico com várias soluções construtivas a partir das quais um plano de reabilitação de duas fases é definido. A primeira fase compreende a identificação dos edifícios que melhoram significativamente com cada solução, e a segunda define as soluções mais adequadas considerando o seu custo de aplicação e melhoria do conforto em cada edifício. Adicionalmente, diretrizes de projeto relativas aos parâmetros testados são sumarizadas, revelando a natureza conflictiva entre diferentes objetivos de desempenho do edifício, e o papel do arquiteto na perspectiva de projetos futuros.

Contributions

During the development of this dissertation, the following scientific contributions were published:

CONFERENCE ARTICLES:

H. Martinho, G. Araújo, and A. Leitão, "From macro to micro - An integrated algorithmic approach towards sustainable cities," in *Computer-Aided Architectural Design Research (CAADRIA)*, 2020. Bangkok.

G. Araújo, S. Roaf, M. Correia Guedes, A. Leitão, and J. Pinelo, "Back to the Future - Reverse-designing a shelter for extreme weather in Antarctica," in Proceedings of the 35th Passive and Low Energy Architecture (PLEA) Conference - Planning Post-Carbon Cities, 2020. A Coruña.

G. Araújo, M. C. Guedes, and A. Leitão, "Integrating algorithmic processes in informal urban and architectural planning: A case study of a Maputo's neighborhood," in Proceedings of the 35th Passive and Low Energy Architecture (PLEA) Conference - Planning Post-Carbon Cities, 2020. A Coruña.

BOOK CHAPTER:

G. Araújo, "Software Tools," in Bioclimatic Architecture in Warm Climates: A Guide for Best Practices in Africa, M. Correia Guedes and G. Cantuaria, Eds. Springer Nature, 2019, pp. 229–247.

AWARDS:

The conference article "Integrating algorithmic processes in informal urban and architectural planning: A case study of a Maputo's neighborhood" won the *Jeffrey Cook PLEA Student Travel Scholarship 2020* award.

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Acronyms

AD - Algorithmic Design
ADA - Algorithmic Design and Analysis
ASHRAE - American Society for Heating, Refrigeration, and Air-Conditioning Engineers
BIM - Building Information Modelling
BPS - Building Performance Simulation
BREEAM - Building Research Establishment Environmental Assessment Method
CAD - Computer-Aided Design
CDA - Continuous Daylight Autonomy
CDO - Computational Design Optimization
CFD - Computer-Fluid-Dynamics
DA - Daylight Autonomy
DF - Daylight Factor
DUAT - Direito ao Uso e Aproveitamento da Terra
HVAC - Heating, Ventilation, and Air-Conditioner
LEED - Leadership in Energy and Environmental Design
MOO - Multi-Objective Optimization
NSGAII - Non-Dominated Sorting Genetic Algorithm II
OSM - OpenStreetMaps
PMV - Predicted-Mean-Vote
PPD - Predicted Percentage Dissatisfied
PSO - Particle Swarm Optimization
RF - Random Forests
TA - Thermal Autonomy
UDI - Useful Daylight Illuminance
USGBC - United States Green Building Council
UTCI - Universal Thermal Climate Index
XPS - Extruded Polystyrene

INTRODUCTION

Motivation

As the world's urban areas' capacity reaches its saturation point and with urban development not showing any signs of slowing down, it is estimated that by 2050 there will be an increase from 54 to 66% of the world population living in urban areas, and 90% of this is predicted to be concentrated in Africa and Asia. Particularly, a great portion of this growth will happen in developing countries, suggesting a dramatic growth in slums and informal housing (United Nations 2019). The concern arises over the ability of informal housing and settlements to fit in these countries' economic, Health, and Climatic goals regarding City Urbanization (Haines et al. 2013). Most of this expansion is occurring with no effective planning and impoverished population occupies informal settlements that often show poor or non-existent living conditions such as clean water and sewage, and poor construction quality (Lizancos et al. 2014).

A demand for slum regeneration emerges as a consequence of this constantly increasing urban growth, for which there are few proposed solutions to deal with their regeneration. In the architectural field, this translates to a great need for efficient design and planning solutions at extremely affordable costs.

Modular architecture has achieved recognition as an efficient design strategy to deal with both large-scale settlement design and rehabilitation. Through the design process or modular improvements in materials, basic living conditions regarding building performance can be achieved. Thus, the motivation for this thesis emerges from the need to apply new, efficient, and robust architectural processes that deal with the fast, urban transition of rural and underdeveloped communities. Taking a new and less explored frontier of architectural and urban design towards the era of post-carbon cities.

Objectives

This thesis highlights the integration and potential of algorithmic design (AD), building performance simulation software (BPS) (Martinho, Araújo, and Leitão 2020), and Multi-Objective Optimization (MOO) processes (Pereira, Belém, and Leitão 2019) in improving and defining urban expansion regarding informal housing and settlements. Implementing parametric approaches while establishing a pre-emptive study of informal housing typologies and urban expansion trends might help mitigate extreme living conditions and promote a healthy living environment in informal areas.

Algorithmic design has been widely documented due to its application in form-finding processes, and performance results. The fusion between design and analysis within algorithmic processes has been described as an efficient and time-saving methodology able to be integrated from early to late design stages (Aguiar, Cardoso, and Leitão 2017). Using such tools and expertise provides suitable designs and constructions regarding climatic and sustainable concerns and opens new perspectives on architectural expressions. However, this is mostly applied to architectural programs inside high-density areas with good infrastructures, and it is rarely seen applied in the least developed countries that make up a large percentage of the world's population.

The AD tool used in this research has integrated connections, commonly known as *back-ends*, to several tools such as Computer-Aided Design (CAD), Building Information Modeling (BIM), and analysis (Sammer and Leitão 2020)(Martinho 2019). The flexibility of using this AD tool allows to export the same model prepared for different analysis such as lighting, energy, comfort, and airflow, and integrate it easily with its climatic and urban context (Araújo 2019).

Considering the above, it is possible to apply these tools towards a sustainable urban expansion, by (1) defining informal building typologies present within the area of study, (2) Discovering high impact design parameters for comfortable living conditions within these typologies, and (3) establishing guidelines within municipal urban expansion protocols that control and plan the growth and land-use of the city in a passive, sustainable, and cost-efficient way.

Methodology

To achieve these objectives, the approach is divided into a Background and a Workflow component comprising three stages that seek to structure data gathering, algorithmic processes, and application in a case study of a neighborhood in Maputo, Mozambique.

The Background component encompasses a brief literature review that fundaments the case study and methods applied in this thesis. Initially, the sustainability architecture will be described and discussed in its evolution and fundamentals, and comfort metrics will be identified and highlighted. Moreover, documentation and discussion of the integrated algorithmic processes in this thesis are explained and showcased, particularly, AD, BPS, and MOO.

The first stage of the Workflow component will comprise the determination of an informal settlement within the city of Maputo that is integrated into informal housing protocols. Its history, urban, and climatic contexts are researched in its history, building typologies, and weather data. Afterward having a case study, all the topography, buildings, and road networks will be implemented digitally through OpenStreetMaps (OSM) data and imported in the ad tool.

Stage 2 comprises the integration of data, parametric model generation, and simulation results visualization. By creating a parametric definition able to generate a 3d model of the neighborhood's urban fabric and a sample informal house typology from the area, it is possible to integrate parameters in the algorithm able to shift variables such as (**a**) glazing ratio by orientation; (**b**) building height; (**c**) floor area; and (**d**) construction materials. Through a sensitivity analysis, it is possible to compare and quantify the impact that the abovementioned design parameters have on the occupants living conditions.

By dynamizing (**a**), an acceptable amplitude of window sizes for each façade orientation can be determined, minimizing indoor heat gains while guaranteeing a comfortable indoor luminance. Through (b), the height can be controlled, regulate urban spread, incident radiation, airflow, and indoor comfort. (**c**) helps establish not only a safe and walkable urban open space, but also suitable areas according to comfort thresholds, and finally, (**d**) construction materials help to centralize economies by defining a range of local and affordable materials that might be used for the construction or rehabilitation of each land parcel.

In the third stage, results regarding comfort metrics, luminance, and airflow will show different combinations of parameters and impacts regarding efficiency, quality of living, and quality of the public space. This will allow the elaboration of guidelines and methods to follow by the field team that builds, applies, and regulates the land.

Structure

The first component of this dissertation, **Background**, is divided into two chapters:

1. **Sustainability in Architecture** – This chapter documents the development of passive design strategies throughout history, and the sustainable architecture paradigm shift in the last century. Green building certifications are highlighted accordingly, demonstrating an existing paradox between contemporary sustainability contexts in the built environment, and building design for a comfortable occupant condition. Subsequently, useful comfort metrics to assess building performance in a passive building system are documented and researched.
2. **Integrated Algorithmic Processes** – This research's integrated algorithmic processes are documented and discussed regarding their applicability in the architectural field. AD is reviewed through its history and motives, related BPS methodologies are described, and optimization processes are described and assessed.

The second component of this dissertation, **Framework**, is divided into three chapters:

3. **Workflow –** This chapter describes the proposed workflow to be applied in a case study. The specific roles of AD, BPS, and MOO processes are highlighted according to the **Background** component and detailed regarding their inputs and outputs.
4. **Case Study: Chamanculo C** – The successive application of the workflow, and the case study results are detailed in this chapter. Insights regarding the urban area and a sample building's glazing ratio, floor area, height, and material properties are unveiled regarding their impact in different comfort and performance metrics, while guidelines are elaborated accordingly.
5. **Evaluation and Discussion** – In this chapter, the application of the proposed workflow is evaluated and guidelines for a sustainable, affordable, and efficient urban regeneration process are presented.

The final component of this research, **Conclusions,** comprises a section overviewing the proposed research, final remarks regarding its applicability, and future developments regarding identified problems.

I – BACKGROUND

Chapter 1 – Sustainability in Architecture

Building sustainability has had several definitions and interpretations throughout history. However, its principles are arguably connected with efficient architecture. Sustainable and climatic concerns are usually associated with highly developed countries and their high levels of consumerism. These countries elaborate plans and laws to restrain carbon footprint. Under-developed countries, contrastingly, have a more fragile position in terms of land use policy. Some contributing factors are the lack of wealth and industrialization, associated with a high fertility rate, and many potential areas for urbanization (Mottelson 2019). These problems translate into a dramatical expansion of slums and informal areas, with no effective planning, and occupied by impoverished population that often show non-existent living conditions such as clean water and sewage, and poor construction quality (F1) (Lizancos et al. 2014).

F1 – Living conditions in Maputo, Mozambique.

Since there is a lack of proposed solutions, awareness towards such communities, and social unbalance witnessed in under-developed countries (F2), it is essential to develop affordable and sustainable housing strategies that can mediate this specific constant urbanization process in a satisfactory time frame. Such can be achieved, for instance, by concatenating several passive design strategies at a smaller scale, to provide ecological and efficient guidelines for building development and construction while ensuring a continuous process from the start.

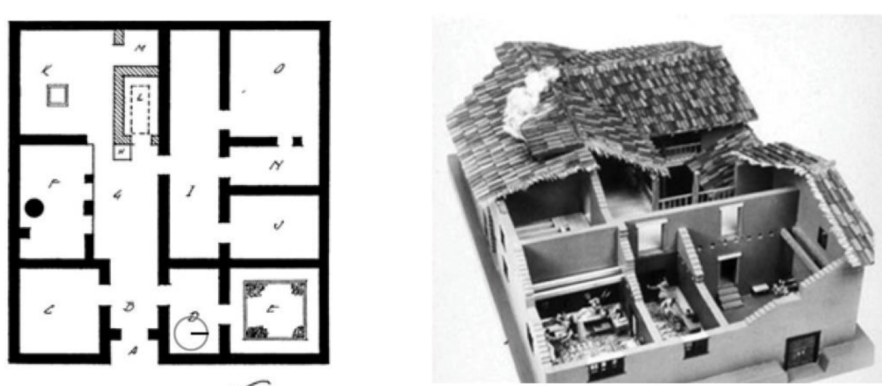
F2 – Upper- and lower-class contrast in Mumbai. Source: https://www.businessinsider.com/aerial-drone-photos-mumbai-extreme-wealth-slums-2018-9

Passive design strategies seek to increase indoor environmental comfort and simultaneously reduce energy consumption. Depending mainly on climatic and urban factors, these strategies adapt to different environments through design and material changes before recurring to any external energy source. These allow the correct development of the project protecting the building from regular climatic events such as sun exposure, wind direction, and rain, without using any active system (e.g., Air conditioning) (Correia Guedes 2017). The origin of passive design dates as far back as Architecture itself. Early examples of cities and settlements in history already show a focus on climate-responsiveness, to provide citizens with shelter, heating, cooling, sewage, and others (Olgyay 2015). This chapter illustrates the evolution and paradigm shifts of passive design, and sustainable architecture, and reviews contemporary occupant comfort metrics.

1.1. Passive Design

Ancient Greeks started employing sun path and seasonal knowledge in city planning, by exposing dwellings and public spaces to the lower Winter sunlight while protecting them from the higher Summer sunlight. On an architectural scale, the Greek Olynthian house was already designed through a heuristic process regarding climate-responsiveness (F3). Built in the late 4th and early 5th centuries BC (Mylonas 1940), the original Olynthian houses had a rectangular plan with the entrance located on the Eastside. The interior space was organized around a South-faced exterior portico higher than the floor's height, to provide shade during Summer and keep heat inside the house during Winter. The northern façade was absent of fenestration and covered with thick masonry, to shelter from the cold winds (Deviren and Tabb 2014).

The entrance of the house was caved in the walls to form a waiting area for guests (A). The corridor (B) gives passage to two adjacent rooms: a storage room, '*pitheon'* (C), to the south; and a lobby to the north (D), which served as a connector between a larger room (E), known as the banqueting hall or '*andron'* (Robinson and Graham 1938). The corridor leads directly to the central feature of the Olynthian house, the court (G). The court has a rectangular shape and its often open to the sky. It usually connects to an open hall (F) to the Southside, as well as three other rooms. These are divided by internal walls and form the kitchen (L), Bathroom (M), and the '*oecus'* (K), one of the most important rooms of the unit. This room was well lighted and ventilated throughout the day due to its adjacency to the court so that families could attend their duties and professions (Mylonas 1940). Finally, the Northside of the house is composed of a corridor, or '*pastas'* (I) that is always developed from East to West and walled in the Westside, forming the *'prostas'* and providing the rooms J, N, and O with a certain amount of privacy (Robinson and Graham 1938).



a b

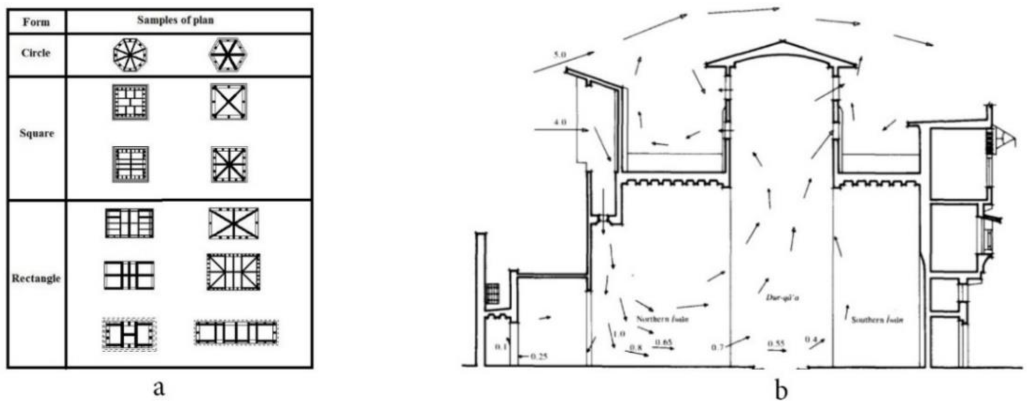
F3 - a) Plan of a typical Olynthian house, b) Reconstruction of an Olynthian House. Source: a) Mylonas (1940). b) https://slideplayer.com/slide/4622226/

In hot and arid regions like Central Asia, Middle East, and North Africa, people faced extreme heat and dry conditions during the day, although windy and cold nights were abundant. Around this area, we can identify numerous architectural features that gather incoming winds to bring natural ventilation and relative thermal comfort to interior spaces. The windcatcher is believed to have been developed in Persia around the 8th century and was extensively applied in cities (F4) (Deviren and Tabb 2014), even though ancient drawings were found portraying wind catchers in one of the tombs of an Egyptian Pharaoh (Roaf 1982). The wind catcher was generally a rectangular prism that protruded from the main volume of the building creating a turret open to all four cardinal directions to catch all possible breezes. The air circulation could be adjusted by covering or reducing the openings according to wind direction and intensity (Pirhayati et al. 2013). Wind catchers have had several types that have been categorized according to wind direction, as well as their plan and shape. They can be uni-, bi-, tri-, and quad-directional (Roaf 1982) and can take circular, square, and rectangular shapes F5 a) (Consulting 2005).

The air circulation of a building with an incorporated windcatcher is shown in F5 b), demonstrating (1) how it can be controlled to ventilate the whole building according to the wind direction and (2) how to ward off the hot air from the inside, through suction from the openings opposite to the wind direction. Additionally, these architectural features were often paired with other passive design strategies, such as evaporative cooling (El-Shorbagy 2010) and the use of materials with high thermal mass (Correia Guedes 2017). For evaporative cooling, clay porous pots filled with water were placed near the air inlet, to cool the air. By using materials with high thermal mass such as adobe or mudbricks, the high heat could be absorbed by the walls during the day and cooled off or sucked out by the wind catcher during the night.

a b

F4 – a) Windcatchers in Hyderabad; b) Wind catchers in Yazd. Source: a) https://www.insideflows.org/project/ancient-wind-catchers-in-hyderabad/ ; b) https://www.rankred.com/examples-of-green-architecture-technology/



F5 – a) Plans of different wind catchers; b) Air circulation and operation of a building with wind catchers. Source: a) Pirhayati et al. 2013; b) El-Shorbagy 2010

Early passive architectural solutions are spread worldwide and illustrate humanity's continuous search for a stable environment. Since environmental conditions and geographical location determine the needs of a building for either cooling or heating, numerous ingenious passive design strategies have sprawled and evolved globally throughout the ages. These strategies have been adapted and improved throughout history, but usually encompass solar control, form and layout, thermal insulation, control of internal heat gains, natural ventilation, and ground, radiative and evaporative cooling (Santamouris and Asimakopoulos 2013).

It was only in the last century that passive design strategies shifted paradigms as a consequence of industrialization (Attia 2018), and the appearance of Heating, Ventilation, and Air-Conditioner systems (HVAC)(Baralas 2013). The appearance of electricity and consequent HVAC systems allowed for an extremely precise indoor climate control, at the cost of electrical energy. Suddenly, indoor comfort was available on a mass scale, and by the late 1960s, most new homes in the United States had an HVAC system ("History of Air Conditioning" 2020). This, along with the energy crisis that emerged in the 1970s, triggered yet another shift in the architectural paradigm, mostly influenced by policies and consciousness towards energy consumption (Attia 2018).

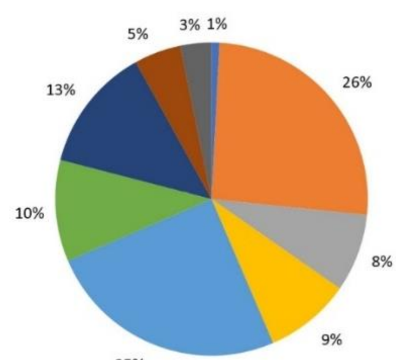
These technologies innovations, and the consequent energy crisis, were responsible for the appearance of several societies and architects that developed the very first concepts of energy-neutral buildings, renewable energy integrated systems, and the use of empirical simulations in prototypes to quantify building performance. Subsequently, in the 1990s and with all the studies and advocacies for a greener architecture concerning carbon emissions, energy consumption, and thermal comfort, building rating and certification systems such as the *"Leadership in Energy and Environmental Design"* (LEED) and the *"Building Research Establishment Environmental Assessment Method*" (BREEAM) emerged to categorize, rate, and certify a building according to their energy consumption, and overall performance. These building certification systems played a key role internationally, in advocating and uplifting the countries' housing markets (Cole and Valdebenito 2013).

The LEED certification system was developed by the United States Green Building Council (USGBC) to include a set of rating systems for the design, construction, and maintenance of buildings. LEED incorporates standards provided by the American Society for Heating Refrigeration and Air Conditioning Engineers (ASHRAE), and has 4 certification levels that are obtained by acquiring points in all categories encompassed: (1) Certified – 40 to 49 points; (2) – Silver – 50 to 59 points; (3) Gold – 60 to 79 points; and (4) Platinum – 80 Points and above (“US Green Building Council” 2020). Furthermore, these points are distributed along with categories and subcategories that award more or fewer points, thus determining each category's relevance in the whole process.

As seen in F6, the categories *‘Location and Transportation’*, and *‘Energy and Atmosphere’* represent 51% of the available points, and categories like *‘Innovation’*, *‘Regional priority’*, and *‘Integrative process’* represent the smallest portion of the points, comprising 9% of the total, in pair with *‘Sustainable Sites’* and *‘Water Efficiency’*. By taking a deeper look at the category Energy and Atmosphere (F7), we can see 18 possible points to attribute to *‘Optimize Energy Performance’*, representing 55% of the total points attributed in this category. This sub-category is the only one that is dedicated to energy efficiency. It promotes system improvement, such as HVAC, electrical, and renewable energies, in detriment to building energy performance through passive design. This ‘point-hunt’ approach certification presents several problems in its core, as many points are easily obtainable, and cheaper, as opposed to others. Alas, the tendency is to choose the former while still obtaining a good level of certification, and avoid expensive, and harder points (Shaviv 2018).

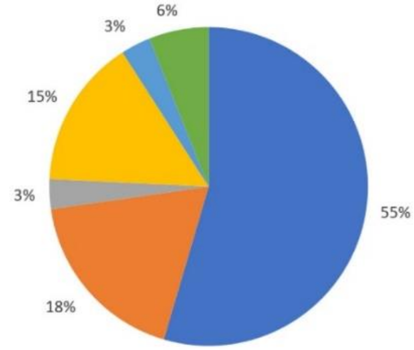
Certification	Points
Certified	40-49
Silver	50 - 59
Gold	60 - 79
Platinum	>80

Categories	Points
Integrative Process	1
Location and Transportation	32
Sustainable Sites	10
Water Efficiency	11
Energy and atmosphere	31
Materials and Resources	13
Indoor Environmental Quality	16
Innovation	6
Regional Priority	4
	124



F6 – Leadership in Energy and Environmental Design (LEED) certifications and Point distribution per categories

	Sub-categories	Points
Energy and Atmosphere	Optimize Energy Performance	18
	Enhanced Commisioning	6
	Advanced Energy Metering	1
	Renewable Energy	5
	Enhanced Refrigerant Management	1
	Grid Harmonization	2



F7 Energy and Atmosphere points distribution per sub-categories

A relevant example credited with LEED gold certification was the Molecular Foundry Research Laboratory, in Berkeley, completed in 2006 (F8). The building performs according to the local building code, and its construction was developed sustainably from its waste to the materials used. Other relevant features of this building include the innovative water treatment system, and the optimized electrical and mechanical system. Additionally, public and green transportation accessibility is assured with shuttles and bicycle stations (Krotz 2007).

F8 – North, West (left), South, and East (Right) façades of the Molecular Foundry building.

Shaviv (2008) registers and discusses the Molecular Foundry Building LEED points obtained in 2007, and shows that despite its good accreditation, there is a lack of passive design features that aim to improve the building's comfort, and consequently its energy performance. This is illustrated, for instance, by the absence of shades in the West, East, and South façade windows. Shaviv further compares it with the San Francisco Federal Building, which was expected to obtain a platinum certification due to its narrow shape and other passive features applied, which provided daylight, cross-ventilation, and thermal mass to all offices (Shaviv 2018)(Shaviv 2008).

San Francisco Federal Building's different façades show a northern side with vertical glass serving as brise-soleils, and the southern windows with perforated metal skin, which provides transparency and shading for the glass (Shaviv 2008). The performance of the design was assessed through simulation tools, and the buildings consume only about 33% of the power of a regular office tower. Because of the absence of mechanical systems for heating, cooling, and ventilation, the building failed to get the required points in the Energy and Atmosphere category and even failed to obtain any LEED accreditation.

F9 – San Francisco Federal building's South façade with perforated metal as shade (left); North façade with vertical glass as brise-soleils.

A paradox emerges with this specific green building certification, in which a building that does not consume electrical energy through mechanical systems of ventilation, heating, and/or cooling, is not considered a sustainable building. Thus, according to the LEED system, actual building design does not influence its respective accreditation.

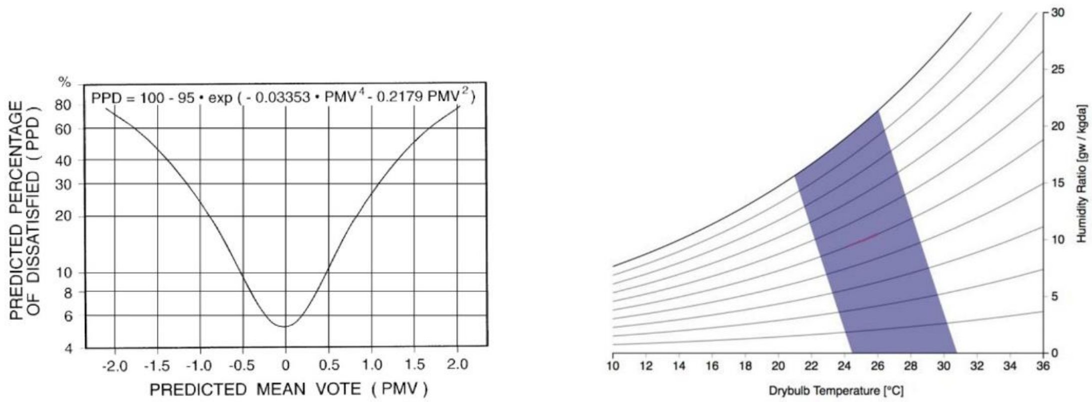
As we experience a paradigm shift, through global warming, and towards post-carbon cities, green building certifications should focus less in expensive systems that are applied in the building to reduce its energy demand and more in careful and environmentally planned designs (Stamp 2008) that take into account the comfort performance of the building, reducing or even avoiding the use of electrical systems at all.

1.2. Comfort Metrics

As seen in the previous section, sustainability in architecture has experienced several paradigm shifts, which ultimately focuses on maximizing the user's comfort through the design, and not by incorporating technical features available in the market. There are numerous comfort metrics and indexes (Blazejczyk and Epstein 2012), most of them encompassing thermal, visual, acoustic, and airflow metrics to assess if a user is comfortable in a specific environment. However, controversy regarding developed comfort models emerged, and numerous models have risen throughout past research. This section documents and discusses researched comfort models regarding thermal, illuminance, and airflow comfort.

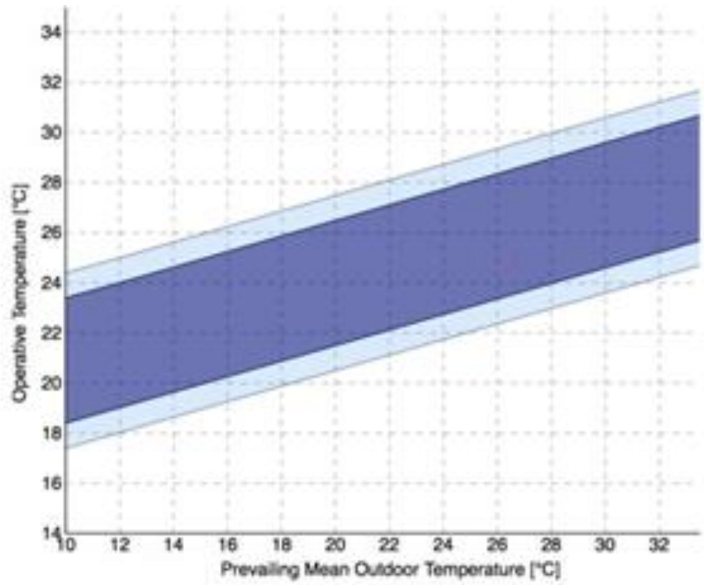
1.2.1. Thermal

Regarding thermal comfort, there have been many models to assess the thermal comfort of a building's occupant, however, two have risen above others: The Predicted-Mean-Vote (PMV) model, and the Adaptive Comfort model. The first was developed using surveys, in which subjects were asked about their thermal sensation on a scale while standing on a climate-controlled room, correlating their answers with the room's air temperature, mean radiant temperature, relative humidity, airspeed, metabolic rate, and clothing insulation (Fanger 1970). Finally, the PMV model quantifies the thermal sensation of the occupant from a value of -3 to 3, according to the conditions of these six factors. The model is represented as a function of the Predicted Percentage of Dissatisfied people (PPD), and it is calculated through the psychrometric chart, with the comfort area (between -1 and 1) being highlighted in the chart (F10).



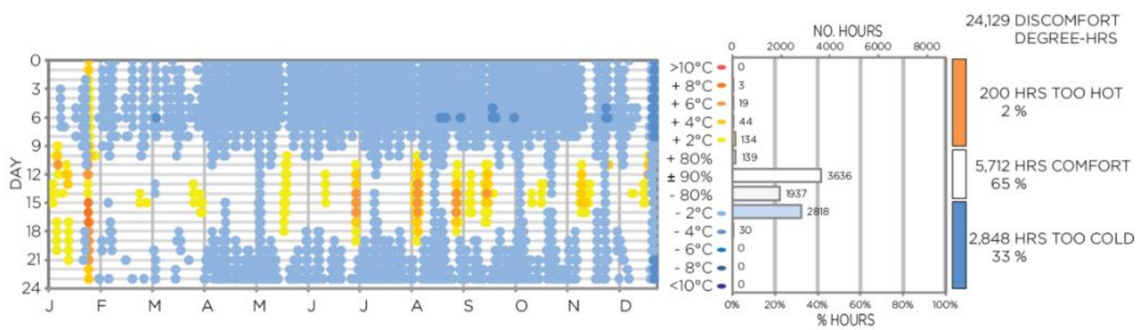
F10 – Predicted-Mean_Vote as a function of the Predicted Percentage Dissatisfied (Left), Psychrometric chart with PMV comfort area. Source: https://support.sefaira.com/hc/article_attachments/115000947631/Screen_Shot_2017-07-07_at_15.32.36.png; https://commons.wikimedia.org/wiki/File:Psychrometric_chart_-_PMV_method.pdf?uselang=es.

Even though the PMV model is applied on a global scale, it does not consider people's adaptation mechanisms and was portrayed as inaccurate in non-conditioned buildings, particularly in hot climates (Nicol and Humphreys 2002). The adaptive model emerged from surveys within this building type and was based on a direct correlation between the outdoor, and indoor temperatures, and assumes that humans can adapt to different contexts (Dear and Brager 1998). Results were later incorporated in the ASHRAE 55-2004 report as the adaptive comfort chart (ANSI/ASHRAE Standard 55 2017), which highlights two proportional areas in which 80, and 90% of the surveyed occupants were comfortable (F11**).** Unfortunately, these metrics only describe an occupant's comfort within a point in space and time, failing to represent building performance regarding thermal comfort throughout diurnal, weekly, and seasonal patterns.



F11 - Adaptive Comfort Chart with comfort areas highlighted for 80, and 90% satisfaction. https://commons.wikimedia.org/wiki/File:Adaptive_chart_-_adaptive_method.pdf

Levitt (2013) introduces Thermal Autonomy (TA) both as a metric and a design process, defining it as space's ability to provide acceptable thermal comfort, through passive means only (Levitt et al. 2013). Specifically, this metric quantifies the percentage of occupied hours during a typical year in which a thermal zone meets or exceeds 80% of occupant satisfaction in the adaptive thermal comfort chart (F12). Thus, it provides visual insights regarding diurnal, and seasonal patterns of thermal comfort expected to be delivered by an architectural project.

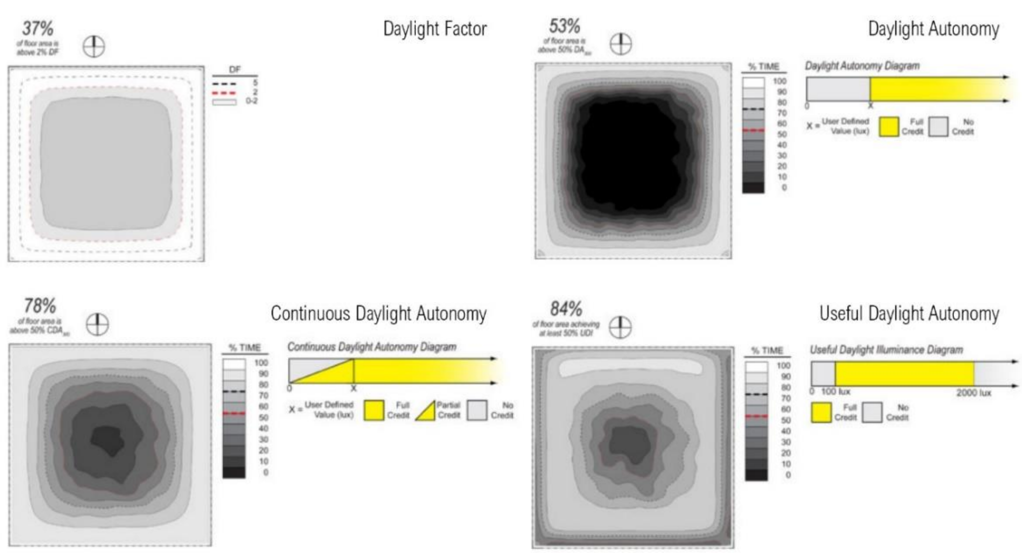


F12 – Annual Temperature heatmap for a thermal zone (left); Thermal autonomy calculation and outliers (right). Source: Levitt, B (2013).

1.2.2. Illuminance

Occupant visual comfort has been a subject of a wide range of studies and categories throughout the last decades. One can evaluate the glare effects caused in a building by high levels of illuminance, or the building's overall use of daylight. Several metrics and processes have emerged trying to quantify both glare and daylighting use such as Daylight Factor (DF), Daylight Autonomy (DA), Continuous Daylight Autonomy (CDA), Useful Daylight Illuminance (UDI), and more (Advanced Buildings 2020). The wide number of metrics evaluated and published can create confusion and controversy among experts about the way to correctly assess a building's performance of daylighting use.

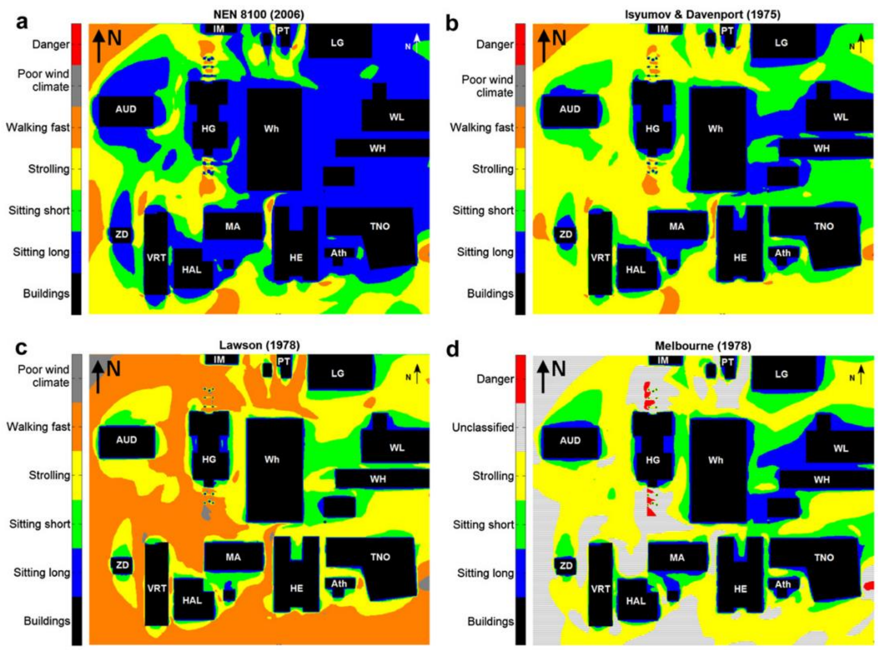
DF is defined as a ratio between the indoor illuminance at a point in the building and the unshaded outdoor horizontal illuminance, calculated with an overcast sky (95% of the sky covered with clouds) (Reinhart, Mardaljevic, and Rogers 2006). Outputs are helpful for quick assessments of relative light penetration in the building but can be arguably less valuable in climates with high sun exposure (Waldram 1925). DA accounts for dynamic daylight in geographical locations and represents the percentage of time from an analysis period (usually annual) that an indoor point in the building is over a certain illuminance threshold (Reinhart and Walkenhorst 2001). This threshold can be defined by the user, according to labor and building regulations around the world. This metric has been modified by Rogers (2006), who proposed the attribution of partial credits when the results were below the defined threshold (Reinhart, Mardaljevic, and Rogers 2006). Alas, none of these metrics considered high illuminance values which can also cause visual discomfort and glare effects. In response to this problem, Mardaljevic and Nabil (2005) propose UDI, which is, again, a modification of DA. It proposes the attribution of full credit if the point is at least 50% of the time above 100 lux and below 2000 lux, suggesting that any value outside of this range is useless (F13) (Nabil and Mardaljevic 2005).



F13 – Calculation diagrams and respective visualization of Daylight Factor, Daylight Autonomy, Continuous Daylight Autonomy, and Useful Daylight Autonomy. Source: http://patternguide.advancedbuildings.net/using-this-guide/analysis-methods/

1.2.3. – Wind speed

Since the 1970s, authors have established distinct criteria for the general acceptability of wind conditions for human comfort (Melbourne 1978). Particularly, Janssen (2013) compared four wind comfort criteria that have emerged since then: Isyumov and Davenport's (Isyumov and Davenport 1975); Lawson's (Lawson 1978), Melbourne's (Melbourne 1978), and the Dutch wind nuisance standard NEN 8100 (W. D. Janssen, Blocken, and van Hooff 2013)(NEN 2006) (F14). These were chosen mainly because they all consist of the limit value of the wind speed and a maximum allowed probability of exceeding these values. Additionally, they all address a range of pedestrian activities such as sitting, strolling, walking, and more.



F14 – Heatmap of CFD wind tunnel analysis illustrated with 4 different wind criteria. Source: Janssen (2013).

Despite being very similar in their calculation, the models have subtle differences in their probability and wind speed thresholds, and the range of addressed activities. Isyumov and Davenport's criteria consider a threshold of up to 3.6 m/s to sit during a long period, 5.3 m/s to sit for a short duration, 7.6 m/s for strolling, 9.8 m/s to walk fast, and 15.1 m/s for unacceptable wind conditions (Isyumov and Davenport 1975). Melbourne's criteria differ slightly in wind speed values and include gusts by the account of the turbulent fluctuation's standard deviation (Melbourne 1978). The NEN 8100 Dutch standard comprises only 5 m/s and 15 m/s (Dangerous) as thresholds, and the probability to exceed these speeds varies according to the activities range (NEN 2006). Lawson's criteria appear to be the strictest of the four (W. D. Janssen, Blocken, and van Hooff 2013), showing thresholds of 1.8 m/s (sitting long), 3.6 m/s (sitting short), 5.3 m/s (strolling), and 7.6 m/s (walking fast) (Lawson 1978). However, it does not consider any danger or uncomfortable wind speed threshold. Lawson's criteria are currently provided by SimScale©, a validated cloud-based Computer-Fluid-Dynamics (CFD) simulation tool (Winter 2013).

Chapter 2 - Integrated Algorithmic Processes

Architecture has experienced a paradigm shift in the way project visualization and conception is made. Towards the end of the last century, some architects and designers shifted from technical hand to CAD drawings. These systems contain a database of geometries and processes to perform many rigorous and detailed drawings of complex geometrical objects. This accelerated the process in architectural projects and facilitated design representation, using only a fraction of the resources. However, the complexity, constant experimentation, and editing required in architectural projects still made the design a time-consuming task, particularly in the late stages of the design.

With the advances in computing disciplines, it was possible to program procedures capable of solving a described problem in a finite number of steps: Algorithms. (Terzidis 2002) Algorithms use variables called parameters that describe the logic inherent to the specified problem (or function)Therefore, processes and databases of geometries inherent to CAD systems that had to be inserted manually, could also be automated and applied. AD emerged as a way to conceive architectural projects, creating algorithms capable of solving a design problem given the specified parameters (Terzidis 2002). The computational use of algorithmic processes allowed to perform shifts in the design model almost instantly, without disregarding other design parameters (Terzidis 2006). Consequently, AD propelled design experiments and processes performed by architects and designers alike, with some using them as a way to generate new shapes(Schumacher 2011), improve building performance through BPS (Branko Kolarevic 2004), or simply improving design efficiency and resources (P. Janssen 2006).

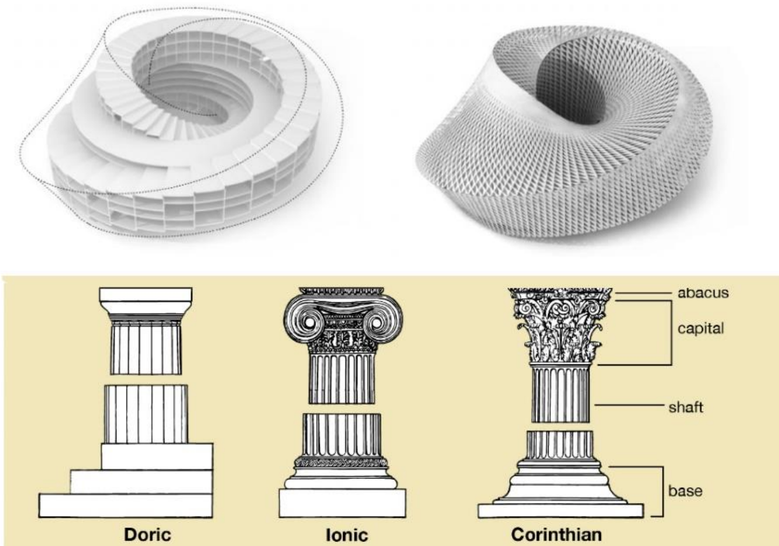
Throughout this chapter, algorithmic processes integrated within this research are reviewed, discussed, and outlined. AD history and approaches, integration of BPS tools and methods, and processes and MOO processes and theories are documented and discussed. This critical review sustains the core knowledge applied in this research and allows us to comprehend the proposed workflow.

2.1. Algorithmic Design

Throughout the last couple of decades, the urban fabric and architecture of developed countries' financial areas experienced an abrupt shift in their skyline, with new, innovative, and provocative building shapes that resulted from the integration of AD and parameters in the form-finding, representational, and construction methods. These new methods of representation and construction industry advance allowed the production of irregular components as easily as standardized parts, and birthed new and complex architectural shapes (Branco Kolarevic 2001). Many architects and researchers employed AD in design projects (F15), and controversy over a new architectural style emerged. Patrick Schumacher (2011) defines “Parametricism” as the great new style after modernism, describing Postmodernism and Deconstructivism as “transitional episodes” (Schumacher 2008).

F15 - Harbin Opera house (2015) (left); Big's The Twist (2019) (right). Source: http://www.i-mad.com/work/harbin-cultural-center/?cid=4; https://big.dk/#projects-kis

Despite its association with new architectural styles and motives (Schumacher 2011), AD is described by Janssen (2015) as an assembly of processes, such as object modeling, associative, dataflow, and procedural, and illustrates AD, not as a style or movement, but as a method to achieve (P. Janssen and Stouffs 2015). Frazer (1995) describes AD as a complete design system from inception to development, including optimization and execution (Frazer 1995). The author illustrates his vision by comparing any contemporary building with the canons of Greek columns, given that both cases use parameters to define their styles and geometric motives (F16).



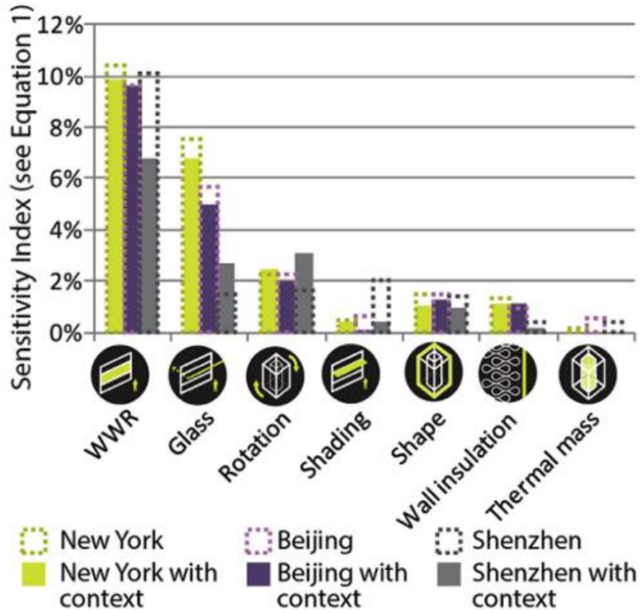
F16 – Astana National Library 2008 (Top), Greek's Doric, Ionic, and Corinthian column elements. Source: https://big.dk/#projects-anl; https://www.britannica.com/technology/column-architecture.

2.2. Integrated Building Performance Simulation

One of the multiple applications of AD is the integration and automation of BPS tasks in the design process, which allow the creation of iterative cycles of design variations and assess their performance in several stages of a project (Eltaweel and Su 2017). When AD and BPS tools are combined, they create a method described as performance-based design, or Computational Design Optimization (CDO) which focuses on building performance regarding indoor air temperature, energy consumption, acoustics, and many more (Touloupaki and Theodosiou 2017). However, the use of such methods in early design stages is still recent, given the need for a shared understanding between design and engineering disciplines. This can be achieved through an integrative process that simplifies simulation inputs, making it easier for architects to grasp specific concepts regarding building physics and performance (Toth et al. 2011).

Moya et al. (2014) developed an integrated BPS approach to assess the wind impact in different variations of an urban shelter. The authors explored barriers, deflectors, and porous membranes in a CFD tool and a physical wind tunnel. Results demonstrated that the membranes reduced the wind speed and the turbulence within the shelter, with the distinct similarity between practical and simulation tests (Moya et al. 2014).

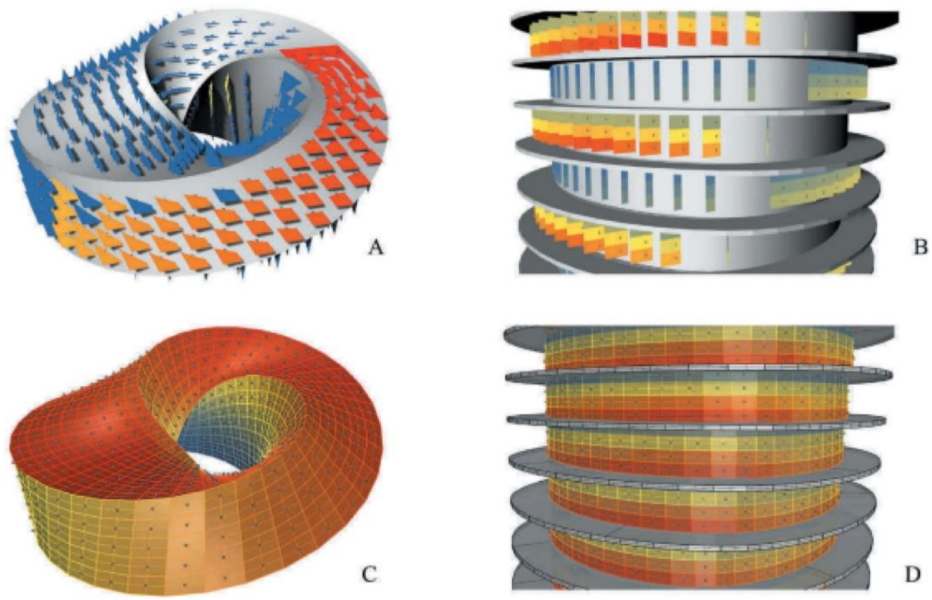
Samuelson et al. (presented a method to provide early-stage guidance in a design project regarding energy consumption by integrating BPS in a parametric system. A prototype residential building was developed to shift parameters such as building shape, rotation, glazing ratio, glass type, window shadings, wall insulation, low or high thermal mass, and plug-loads. Finally, a sensitivity index is attributed that aims to quantify each parameter's impact on energy usage (F17) (Samuelson et al. 2016).



F17 – Sensitivity index of the building's design parameters. Source: Samuelson et al. (2016)

Taleb and Musleh (2015) developed an urban parametric design approach to improve architectural solutions regarding environmental factors (e.g., wind speed, solar radiation, and energy consumption). The case study, located in the United Arab Emirates, comprised several simple house units that were tested with different parameters for height and volume, to achieve independent optimal solutions for each type of simulation. However, the authors highlight existing limitations regarding parameter exclusion, time spent by the designer setting up the simulation environment, and lack of harmony between processes as crucial factors for research success (Taleb and Musleh 2015).

Aguiar et al. (2017) propose an innovative approach to solve the abovementioned problems, named Algorithmic Design and Analysis (ADA). The authors present a workflow integrating several BPS tools with an AD tool in early design stages and perform several automated sets of design variations analysis in two case studies, testing their structural and lighting performance. The proposed workflow is compared with a traditional analysis workflow (Aguiar, Cardoso, and Leitão 2017), highlighting the time and resources saved by the former, and errors resulting from the latter (F18). Martinho et al (2019) further extended the ADA workflow, integrating energy simulations for the performance analysis and optimization of adaptive façades (Martinho et al. 2019). Additional work has been developed towards illustrating the impact of single buildings in the urban fabric, and how these integrated approaches can help improve the general performance of the urban area or even prevent future damage that can result from poor design decisions (Martinho, Araújo, and Leitão 2020).



F18 – Algorithmic Design and Analysis Workflow (bottom), traditional analysis workflow approaches (Top). Source: Aguiar et al. (2017).

2.3. Optimization

When both design generation and evaluation processes are automated, the potential to integrate optimization processes in design workflows emerges, which facilitates the search for optimal solutions within design variations (C. Belém and Leitão 2018). Optimization is mathematically defined as the process of finding the best solution from a set of variables that affect the resulting outcome. When applied in architecture, optimizing a building's performance is making it as functional and efficient as possible according to user-specified parameters and objectives (Nguyen, Reiter, and Rigo 2014). This can be done by integrating optimization algorithms with BPS and AD (C. Belém and Leitão 2018).

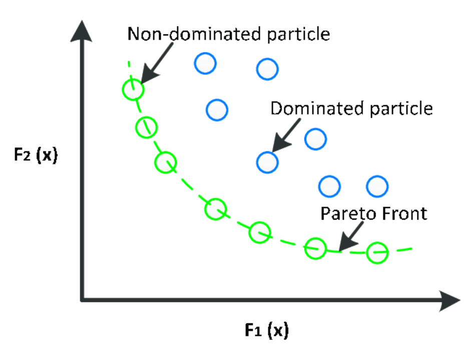
Optimization algorithms are numerous but restrictive according to the optimization problem. From their wide variety, those applied in the architecture field mainly comprise black-box optimization algorithms (Pereira, Belém, and Leitão 2020). These explore the defined objectives without any prior information to the optimization problem and can encompass different assumptions and properties from previously performed simulations. Black-box algorithms can be (1) metaheuristics, which focus on biological and physical analogies, (2) direct-search, which evaluate a set of solutions proposed by a deterministic strategy, (3) model-based, which create approximations of the objective functions target domain based on previously evaluated solutions, which are used to iteratively refine the set of optimal solutions (Wortmann et al. 2015).

An optimization process can be single- or multi-objective but when dealing with complex architectural systems, an architect must typically address multiple goals such as costs, thermal, and illuminance. (Khazaii 2016). Alas, the optimization problem becomes increasingly complex, particularly when there is a high number of parameters and when conflicting objectives are found (e.g., higher costs usually translate in better performances) (Wortmann et al. 2015).

A set of components are required to apply a generic optimization process comprising fixed and variable inputs, constraints, objective functions, and outputs (Cardoso 2017). Fixed and variable inputs comprise the information required to run the simulation. The first encompasses information that cannot be changed (e.g., weather data), and the second information that can vary (e.g., construction materials, design dimensions). Constraints act as thresholds to the target parameters domain of values, avoiding unrealistic results. Objective functions represent the values to be maximized, minimized, or kept within a certain range (e.g., thermal comfort, costs). Finally, the outputs are the results yielded by the optimization algorithm and list all the values obtained for each set of variables tested.

Nguyen et al. (2014) sub-divide optimization in three stages: a pre-processing, a final optimization, and a post-processing stage (Nguyen, Reiter, and Rigo 2014). The pre-processing stage entails the formulation of the optimization problem by defining the abovementioned components and performing a sensitivity analysis to further refine the domain of possible solutions. Additionally, optimization algorithms are reviewed and discussed according to their output's performance, since no optimization algorithm outperforms all others for all optimization problems (Wolpert and Macready 1997). The optimization stage plays a significant role in the finetuning of the process, generally comprising the monitoring of the results, which allows detecting errors or simulation failures. Finally, the post-processing stage comprises the visualization and interpretation of the results.

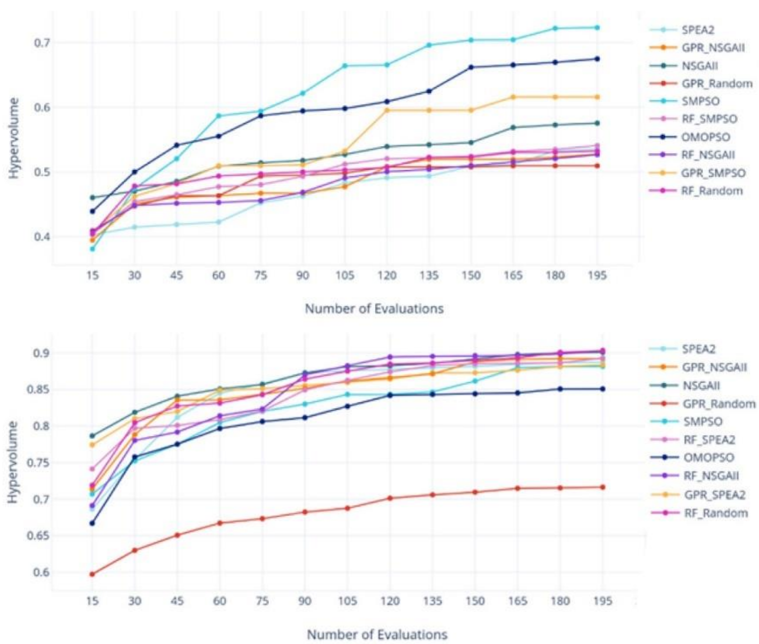
Visualizing results for a single objective optimization is a relatively simple task and can be done through graphs, which represent the used variables, and their respective objective function result. However, in a multi-objective optimization (MOO) process, using this approach becomes confusing when assessing all the objectives independently without considering their conflictive nature. A solution to understand how each objective affects the other is the application of a Pareto front (F19). This method identifies optimal solutions from all the tested combinations of parameters (non-dominated solutions), in which it is impossible to improve one objective without harming others (Khazaii 2016)(Wortmann 2017).



F19 – Illustration of a Pareto front representation. Source: Kumar (2016)(Mahesh, Nallagownden, and Elamvazuthi 2016).

The integration of MOO processes in the architectural field has been researched extensively regarding process speed and efficiency (Pereira and Leitão 2020), its application in case studies (Yu et al. 2015), and the use of diverse algorithms for different problems (C. Belém and Leitão 2018)(Waibel et al. 2019).

Pereira et al. (2019) optimize an exhibition space for maximum UDI and minimum costs, with a skylight's dimensions as parameters (Pereira, Belém, and Leitão 2019). This is done through a complementary tool that performs the connection between two vast open-source libraries of optimization algorithms and the AD tool (C. G. Belém 2019). The work is further extended by comparing the performance of 6 metaheuristics and 4 model-based optimization algorithms in two case studies through their respective hypervolume[1] (Pereira, Belém, and Leitão 2020)(While et al. 2006): (1) the exhibition space's UDI, and (2) in a structural problem, minimizing a complex shape's structural displacement with minimum costs. From the tested algorithms, the Particle Swarm Optimization (PSO) group of algorithms (Nebro et al. 2009)(Kiranyaz 2014) revealed the best results in the structural problem, and the worse in the illuminance problem(FIG), while the Random Forests (RF) algorithms (Pavlov 2019) revealed the opposite (F20). Additionally, the evolutionary algorithm Non-Dominated Sorting Genetic Algorithm II (NSGAII) (Deb et al. 2002) complemented with model-based algorithms seemed to obtain the most constant performance in both cases. Despite not being able to identify an outstanding algorithm for both cases, the authors were able to refine the optimal solutions and confirm the importance of testing multiple algorithms within the same optimization problem (Nguyen, Reiter, and Rigo 2014)(Wolpert and Macready 1997).



F20 – Best performing algorithms for Structural performance (left), and for daylighting (right). Source: Pereira 2020.

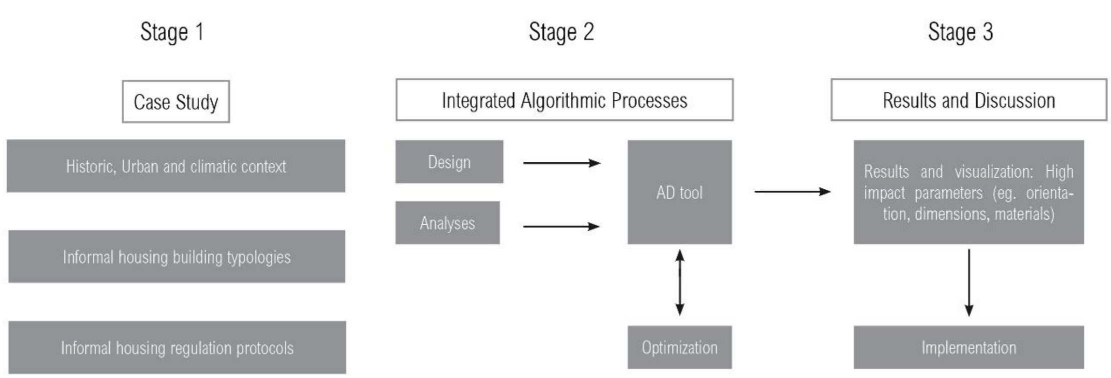
[1] "The hypervolume of a set of solutions measures the size of the portion of objective space that is dominated by those solutions collectively"

II FRAMEWORK

Chapter 3 – Workflow

At the beginning of this document, the proposed objectives of (1) defining parametric informal building typologies present within the area of study, (2) discovering high impact parameters of comfort and living conditions within these typologies, and (3) establishing guidelines within municipal urban expansion protocols are proposed. To achieve those objectives, a workflow divided into three stages is integrated. Stage 1 comprises the documenting and interpretation of the case study data, stage 2 integrates algorithmic processes, and stage 3 performs a sensitivity analysis and optimization (F21). The first stage comprises a study and definition of the urban fabric and its respective building typology regarding its development and demographic situation. Stage two includes model generation, performance simulations, and optimization processes. Stage three analyses the obtained results which reflect how each scenario and design parameters impact indoor comfort.

By creating an algorithmic definition capable of generating the neighborhood's urban fabric from OSM data, it is possible to test and optimize several construction solutions regarding their impact on people's comfort, fairness, and cost. On a smaller scale, the house typology is algorithmically defined and tested for material scenarios and design dimensions (height, area). The latter is easily applied and regulated in the field for future constructions while the former is suitable for modular rehabilitation processes.



F21 – Proposed Workflow Diagram

3.1 Case Study

Stage one comprises the identification of the case study, its respective area of analysis, urban morphology, and climatic context. The analysis area is retrieved from OSM and after an extensive study of the area and its respective climatic context, a yearly in-depth analysis of the case study can be provided. This analysis includes the review of previous work, as well as the interpretation of several generated charts and heatmaps of dry bulb temperature, relative humidity, Universal Thermal Climate Index (UTCI), and stereographic diagrams. From this analysis, we can (1) discern impactful parameters to apply and test in urban rehabilitation and architectural design, and (2) provide a representational model of the neighborhood and a sample house, to (3) define BPS and optimization inputs and outputs.

3.2 Integrated Algorithmic Processes

In this second stage, algorithmic processes are integrated into a rehabilitation and design case study, which facilitates the visualization and interpretation of the urban area and each building. Moreover, their integration in a single tool creates a seamless flow between design, analyses, and optimization. Algorithmic processes encompassed by this stage are AD, BPS, and MOO.

3.2.1 Algorithmic Design

The AD process starts with the generation of an algorithm capable of modeling the specified urban area from OSM in a CAD environment. This model comprises all the design parameters considered for each existing building design, such as glazing ratio, window design, construction solutions specifications, building height, area, and typology. In parallel, the geometry must be prepared algorithmically to fit all the inputs required by the BPS tools to be used to simulate thermal, illuminance, and airflow comfort.

3.2.2 Building Performance Simulations

The applied performance simulations return specific comfort metrics, particularly thermal, illuminance, and airflow, reviewed in Chapter 1, for every building in the case study. Results will generate data- and area-dependent results, which will be analyzed and visualized directly in the CAD platform or the AD tool.

Thermal

The selected comfort metric for the thermal comfort analysis output was Thermal Autonomy (TA). TA represents the percentage of the analysis period in which the tested zone(s) is(are) comfortable (Levitt et al. 2013). To retrieve this output, it is necessary to simulate for a specified analysis period and other inputs. These inputs are defined by the climate analysis of the site, which allows us to understand and specify periods that are more suitable for some type of analysis and specify other inputs such as materials, construction solutions, glazing ratio, ventilation schedules, and geometry. They can be either parametric or not, according to the design stage and/or analysis. In this research, the studied parameters in the urban model were the materials of the walls and roof, along with the floor area, height, and glazing ratio of a house.

Results will be interpreted through visual heatmaps of the urban model, charts, and tables, and evaluated according to the impact of the tested parameters. The TA results in the urban area will also be correlated with the buildings' respective rehabilitation cost by multiplying the price per area of each construction scenario by each building's respective wall and roof areas. This will yield recommendations and guidelines regarding the specified parameters, that can be elaborated for futures designs or rehabilitation in the selected case study.

Illuminance

The illuminance comfort analysis will return the Useful Daylighting Illuminance (UDI) for each building. The UDI represents the percentage of the simulated area that fits between an illuminance threshold from 100 to 2000 lux, which is arguably useful during daily periods (Nabil and Mardaljevic 2005). However, it is suitable for informal housing and neighborhoods due to the characteristically low resources of those areas and their use of daylighting.

To obtain the UDI, the retrieved geometry from OSM must be used to generate test points per building and its respective floor area. These points are defined according to the required simulation quality, representing a chosen percentage of the building area[2]. Grid-based simulations were made using a climate-based sky, generated with the information in the case study’s weather file. From the illuminance (Lux) of each simulated test point, it is possible to calculate which of these points sit within the UDI ranges and, hence, calculate the UDI for the desired buildings.

The studied parameters in the illuminance analysis were the glazing ratio for the urban area simulations, while the floor area and two window designs were added as parameters for the single building simulations. Results will highlight how the levels of UDI affect building design and rehabilitation through the interpretation of urban model heatmaps, and data charts. This will provide enough data to define glazing ratio policies for respective floor areas in the case of building design, and each building, in the case of a neighborhood or urban rehabilitation.

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[2]*Example: a square grid of 3x3m that fits in an analysis surface area of 9 m^2 has 3 test points located in the center of the squares.*

Airflow

Airflow is directly related to sanitation and a building's thermal, and physical comfort. Low ventilation areas are prone to the sprawl of diseases, and high wind speeds can cause uncomfortable periods depending on the level of activity of a person (Lawson 1978). However, correct ventilation both indoor and outdoor can improve the livability, comfort, and sanitation of a space.

Airflow comfort analyses comprise the interpretation of results obtained from computer fluid dynamics (CFD) simulations of both the urban area of the case study and a sample building. The selected wind comfort metric for the urban area was Lawson's pedestrian wind acceptability criteria, which is more restrictive than the others studied (Chapter 1). However, all these criteria are based on the percentage of time that an area has comfortable wind speed according to the defined activity (W. D. Janssen, Blocken, and van Hooff 2013) (e.g., a person sitting in a living room, or a person jogging in the sidewalk). Therefore, the CFD simulation will return wind speed and flow values for the case study urban model at pedestrian height, and a sample building's indoor airflow value. Afterward, wind circulation and comfort will be discussed at both scales.

In the case of the urban area model, the analysis will not comprise construction solutions or glazing ratio, but rather an overall evaluation of the space, which will help identify areas that may pose potential threats. In the sample building typology, however, different glazing ratios with potential cross-ventilation sections will be simulated, and posteriorly evaluated according to the selected criteria.

3.2.3 Multi-Objective Optimization

Extensive research has been made showing the advantages optimization brings to the architectural field. However, the integration of Multi-Objective Optimization (MOO) processes in this field usually comprise problems of a conflicting nature (Wortmann et al. 2015)(Khazaii 2016). The proposed process in this research is directly related to BPS as it uses the results and sets of analyzed parameters as inputs to return acceptable combinations that fit the defined objectives. Within the proposed research workflow, optimization processes available in the AD tool can be applied in both illuminance and thermal comfort analysis, by considering objectives such as maximum comfort performances and minimum cost. However, given the extensive amount of computational resources and time required by each simulation (Pereira and Leitão 2020), only one comfort optimization process will be applied in this research.

The thermal comfort results and their adjacent variable parameters in an urban area were chosen to have a MOO process applied. Three objective functions were developed to optimize the thermal comfort in the studied urban area. This is done by shifting the parameters of construction solutions, defined in the case study, to minimize the rehabilitation process cost while maintaining a fair level of comfort between the analyzed buildings. Therefore, equation (a) illustrates the maximization of the average TA of all the buildings, each with a possible construction solution; equation (b) the minimization of the total cost of construction; and

(c) the minimization of the standard deviation of TA between buildings, which guarantees fairness and equality of comfort among the building sample.

$$\max\ f(x_1, x_2, \dots, x_n) = \frac{\sum_{i=1}^{n} ThermalAutonomy(x_i)}{n} \qquad (a)$$

$$\min g(x_1, x_2, \dots, x_n) = \sum_{i=1}^{n} Cost(x_i) \qquad (b)$$

$$\min\ h(x_1, x_2, \dots, x_n) = \sigma(ThermalAutonomy(x_i)) \qquad (c)$$

Within the AD tool, several optimization algorithms from two vast open source libraries can be used with a complementary tool that is easily integrated with the AD geometric description (C. G. Belém 2019) In this thesis, the metaheuristic algorithm NSGAII (Deb et al. 2002) was tested and then used as a solver for the Random Forest Regressor model-based algorithm (Pavlov 2019) (Chapter 2). The solution provided by the algorithms will be showcased and discussed through several charts and graphs, and their utility will be compared against the results obtained from the BPS analyses.

3.3 Stage 3 – Evaluation and Discussion

The results of the previous stage will yield valuable insights regarding rehabilitation and future construction within the case study area. In this stage, an overview of the results is presented and discussed, along with the identification of possible errors that might have influenced the proposed workflow. Conclusions regarding the best construction solutions and glazing ratios, according to building area and location, will be presented and weaved into a set of recommendations and guidelines to further improve the case study's current rehabilitation program.

3.4 Tools

The proposed workflow encompasses the integration and automation of different processes in all stages of this research, such as geometric model generation, BPS, and MOO. The main tools used to develop and apply the proposed workflow are listed and described in the following section.

Khepri[3]

An algorithmic design tool that seeks to unify a single algorithmic description to generate equivalent models in platforms such as analyses, CAD, and game engines. Khepri uses the programming language Julia and is still in development, being used to support an architectural course at Instituto Superior Técnico in Lisbon, Portugal. In this work, Khepri will generate the 3D model from the gathered data, parametrizing, and integrating the defined impact factors. It will prepare and export the models ready for analyses with the correct modeling requirements for each respective tool and integrate the optimization processes applied through a complementary tool that performs the connection to a vast collection of open-source optimization algorithms.

Rhino 6[4]

A computer-aided design platform similar to Autocad. It comprises a different geometry processing and is fully integrated within grasshopper, python script, and rhino script. In this research, Rhino 6 will be used as the standard CAD platform for all the geometric models generated and visualization of analysis results, except for the CFD analysis.

Grasshopper[5]

A graphical algorithm editor that is compatible with Rhino's modeling tools. Grasshopper allows designers to build form generators from simple parameters, using a visual programming style connecting inputs to outputs through nodes and batteries. One of its main advantages is the wide existent community and plug-ins available like Ladybug, Honeybee, and butterfly. These allow easy integration of analysis software such as Radiance, Energy Plus, and Open Foam.

Ladybug&Honeybee[6]

Grasshopper plug-in capable of importing and visualizing weather data, setting required simulation input information, and preparing the model for a simulation regarding construction materials, context, and program. It will be used to layout a definition that allows changing material properties of the Kehpri generated design, and run luminance, and comfort simulations required for the study by communicating directly with Radiance and EnergyPlus.

[3] https://algorithmicdesign.github.io/tools.html
[4] https://www.rhino3d.com/6/
[5] https://www.grasshopper3d.com/
[6] https://www.ladybug.tools/honeybee.html

Autodesk CFD[7]

A student-free, CFD software. Autodesk CFD has a wide community of engineers, researchers, and architects. It comprises features to solve complex fluid flows like turbulence, heat transfer, acoustics, and electromagnetics. For the presented research, it will be used to run wind tunnel and airflow analyses to retrieve wind speeds and directions.

EnergyPlus[8]

A validated software used by engineers, architects, and researchers to model energy consumption for heating, cooling, ventilation, illuminance, and loads. It allows running several analyses regarding different metrics such as comfort, HVAC, energy, and surface temperature. Along with this work, the percentage of hours that the models fit the adaptive comfort chart will be retrieved and integrated With Honeybee within Khepri to process and set up the proposed optimization processes.

Radiance[9]

An open-source software created at Berkley. It is employed to create room luminance maps, used to determine glare and daylight availability. Radiance will elaborate luminance studies within areas of context and generated 3d models through Honeybee and the Khepri.

[7] https://www.autodesk.com/products/cfd/overview

[8] https://energyplus.net/

[9] https://www.radiance-online.org/

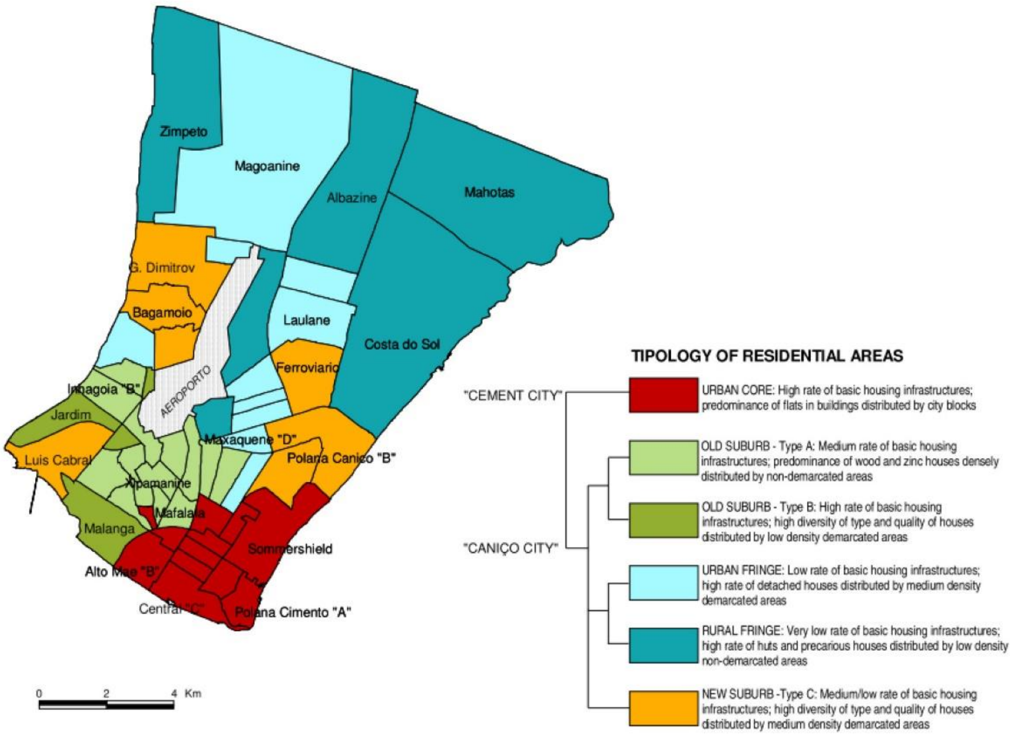
Chapter 4 – Case Study: Chamanculo C

The proposed workflow was employed in a case study comprising the rehabilitation of a neighborhood in Maputo, Mozambique to evaluate its applicability. The historical, urban, climatic, and architectural context of the case study will be researched and structured to define the necessary inputs and outputs. The integrated algorithmic strategy encompasses (1) the use of AD to generate the urban area's geometric model, as well as the model of a sample house based on the informal building typologies commonly seen in the area; (2) a sensitivity analysis of the specified design parameters regarding thermal, illuminance, and airflow comfort metrics through BPS; and (3) a MOO process regarding rehabilitation cost, fairness, and thermal comfort of the neighborhood residents.

4.1. Historical, Urban, and Climatic Context

Mozambique was a Portuguese colony from the 16th century until 1975. Following a ten-year war for independence, a civil war emerged between the country's different political parties. Such led to democracy being proclaimed only in 1994 when elections considered free and fair were held (Sheldon and Penvenne 2015)(Brown and Morgan 2006). Based on these events, Mozambique has seen itself in the list of least-developed countries in the world since 1988 (UN Committee for Development Policy 2019).

Henriques and Ribeiro (2005) characterize Maputo's land use according to their neighborhood types and building typologies, particularly regarding materials and living conditions (F22) (Henriques and Ribeiro 2005). The authors list 6 types of neighborhoods: "Urban core", "Old suburb type A", "Old suburb type B", "Urban fringe", "Rural Fringe", and "New suburb type C". The "Urban core" is defined by a high rate of cement constructions and represents only 9.1% of the total area of Maputo's municipality. In 1997, 15.7% of the city's population lived in this area. The "Old suburb type A" and "B" characterize the areas of the city that were inhabited during the colonial period. Having experienced a fast and sudden increase in population density, the buildings in these neighborhood types were distributed in an unplanned way, with narrow paths and scarce open spaces, and built using easily assembled materials such as cement bricks and zinc. "Urban fringe" and "Rural fringe" represent a very low rate of basic housing infrastructures, with a high density of huts and detached houses. Finally, "New suburbs type C" comprises diverse neighborhoods with different housing typologies and qualities.



F22 – Residential areas' typologies in Maputo, Mozambique. Source: Henriques and Ribeiro (2005)

Cities such as Maputo are strongly related to the existence of a high percentage of informal or illegal housing and settlements. People living in these areas often see themselves secluded from economic and cultural society and experience poor living and environmental conditions. On a micro-scale, slums represent institutional failures that are often poorly addressed through measures as eviction and demolition. However, positive results were obtained with slum upgrade programs, resettlements, and most recently, the adoption of enabling strategies (Arimah 2001). These strategies provide the target population with the means to address and mitigate the existent amplitude between social classes while promoting a sustainable environment.

An example of enabling strategies in Maputo's slums is the manual of procedures for land use and appropriation rights - *Direito ao Uso e Aproveitamento de Terra* (DUAT) -, released in 2015 (Conselho Municipal de Maputo and Direcção Municipal de Planeamento Urbano e Ambiente 2018). The municipality's urban growth program, PROMAPUTO II[10], is currently applying an informal housing regulation strategy intending to provide instruments for adequate soil management and neighborhood improvement. The DUAT methodology describes 11 stages, each with specific objectives that build towards correct land management. This method is successfully applied in a case study located in the Chamanculo C neighborhood, an "Old suburb type A" presenting narrow paths and haphazardly distributed infrastructures (F23).

[10] https://projects.worldbank.org/en/projects-operations/project-detail/P096332?lang=en

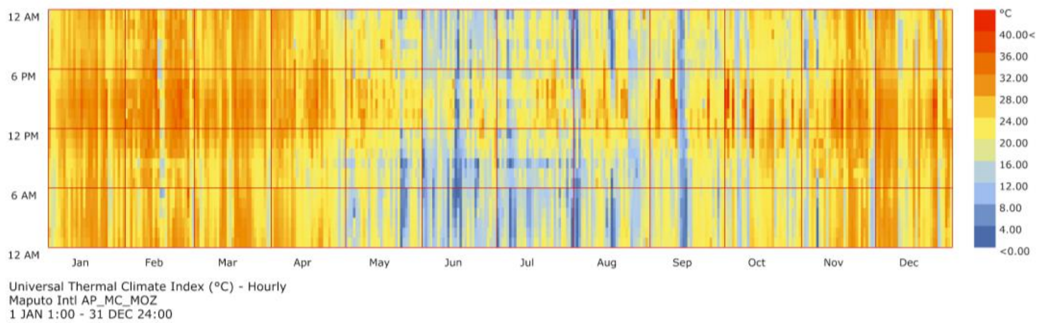
F23 – Chamanculo C atmospheres and environment

One of the most common vernacular houses seen in Chamanculo C is the "Ventoinha[11]" house (F24). Landowners add units incrementally according to the family's needs and financial availability. The units usually have the same dimensions and are rotated so that the roof angles create a fan-like shape, hence the house's name. Most of these houses include rooms with areas ranging from 9 m^2 to 12 m^2 with exterior washrooms, are not conditioned, and are usually built with (1) zinc walls and zinc roofs, or (2) cement brick walls and zinc roofs, depending on the family's budget and location (Lizancos et al. 2014b).

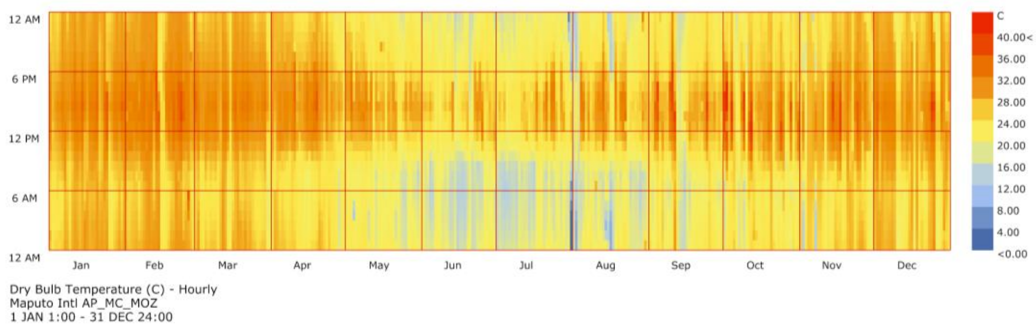
F24 – Ventoinha houses in Maputo.

[11] Ventoinha: Portuguese word for fan/ventilator.

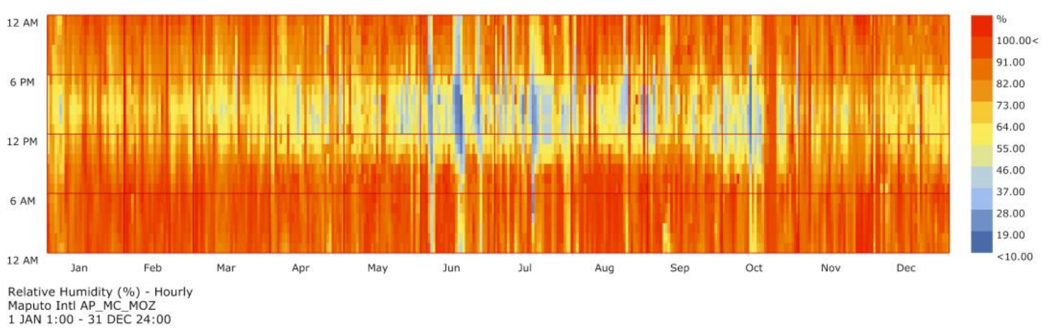
With a tropical savanna climate, Maputo is characterized by a UTCI (F25) with higher thermal amplitude than the recorded dry-bulb temperatures. From May to October, temperatures can range from 8 ºC to 36 ºC, reaching up to 40 ºC (F26). Such reveals a high thermal amplitude which suggests some concerns regarding occupant comfort. For instance, by increasing thermal mass through material choices, the thermal amplitude in interior spaces can be reduced. Furthermore, the relative humidity (F27) is consistent throughout the year, with higher values during nighttime and in Summer.



F25 - Annual Universal Thermal Climate Index for the city of Maputo.

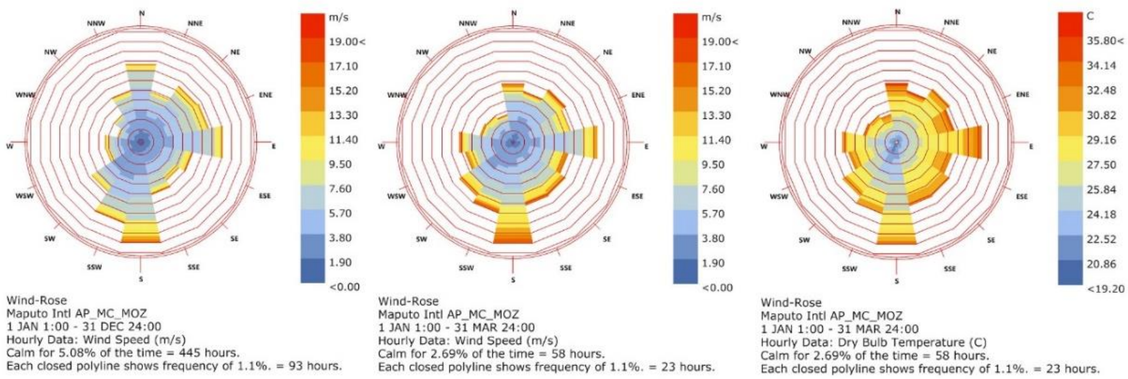


F26 - Annual dry-bulb temperature for the city of Maputo.



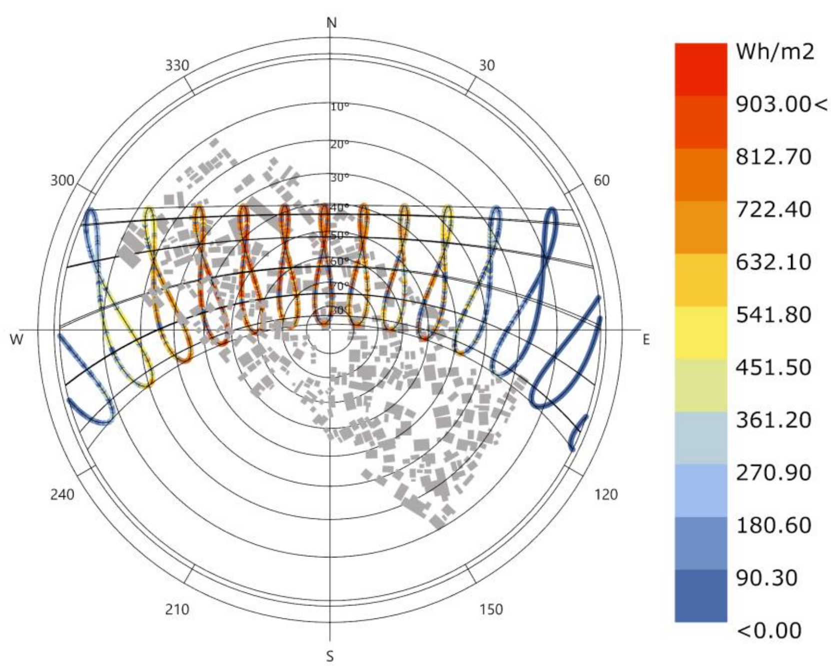
F27 - Annual relative humidity in the city of Maputo.

The annual wind speed shows frequent winds from North, East, and South, with speeds hitting as high as 19 m/s (72 Km/h)(F28a). There is a high similarity with the wind rose data for the Summer months. However, winds show more intensity from the South, constantly reaching speeds of 40 km/h (F28b). By cross-referencing the hourly outdoor temperature and the hourly wind speed during summer months, we see that the coldest winds come from South and Southwest (F28c). This is relevant especially for summertime, given that natural ventilation and changes in the glazing ratio of buildings can provide cooling and night flushing. However, since the glazing ratio directly affects thermal mass, the buildings' location and orientation need to be considered based on the area's incident radiation levels.



F28 – a) Annual wind rose in Maputo; b) Summer wind rose; c) Summer temperature wind rose.

From the stereographic diagram (F29), the relation between incident radiation and thermal mass can be further analyzed. The direct normal radiation in Chamanculo C has a higher incidence on the Northern side since the neighborhood is located in the southern hemisphere. Hence, North-faced facades ought to be controlled regarding solar gains, ventilation, and shading. On the West and East sides, low values for radiation are recorded, and higher levels are observed near the solstice periods.



F29 – Stereographic diagram centered in Chamanculo C neighborhood.

4.2. Models and parameters

Chamanculo C is characterized as an old suburb type A. These are described as basic infrastructures composed of zinc cladding and/or cement bricks, densely distributed in non-delimited areas, and showing high population density with very narrow public spaces (Henriques and Ribeiro 2005). To represent the urban fabric, we developed an algorithm to extract OSM data and generate 3D models of the corresponding houses that match the urban landscape, covering a total of 334 building units. This allows an urban-scale analysis of different construction solutions and an evaluation of their impact on each structure of the neighborhood, which helps in the mapping of critical areas for rehabilitation and the reduction of construction and rehabilitation costs (F30).

F30 – Chamanculo C satellite image (above), and algorithmically generated urban model (below).

Considering the described climatic context and building urban typology, five scenarios for walls, and two scenarios for roof solutions were tested (F31). Scenario W1+R1 represents the original building typology for the indexed neighborhood. For comfort simulations, the non-existing interior walls were simulated using an air wall resistance material to ensure that the air circulates between thermal zones. A window-to-wall ratio of 0.1 was applied in each façade, and a height of 3 meters was set.

Walls		
Scenario	Layer	Material
W1	1	Zinc
W2	1	Cement brick
W3	1	Zinc
	2	Air gap
	3	Zinc
W4	1	Cement brick
	2	Air gap
	3	Cement brick
W5	1	Zinc
	2	Air gap
	3	Cement brick

Roof		
Scenario	Layer	Material
R1	1	Zinc
R2	1	Zinc
	2	XPS
	3	Air gap
	4	Zinc

F31 – Roof and wall construction scenarios chosen for the case study.

The heat flow between ground and floor is considered one of the most important aspects of buildings' thermal performance. Research shows that results can vary significantly in different simulation tools and, in the case of EnergyPlus, even though most houses in Chamanculo C are built with soil as the floor, it is advisable to use a slab-on-grade floor type (Costa et al. 2017).

Material costs were obtained from an estimate of the local market, and properties were obtained from the EnergyPlus library for the wall-air resistance. However, cement bricks and extruded polystyrene show differences according to the manufacturing processes and their type. In this case, properties were retrieved from tables for common construction materials[12] (F32).

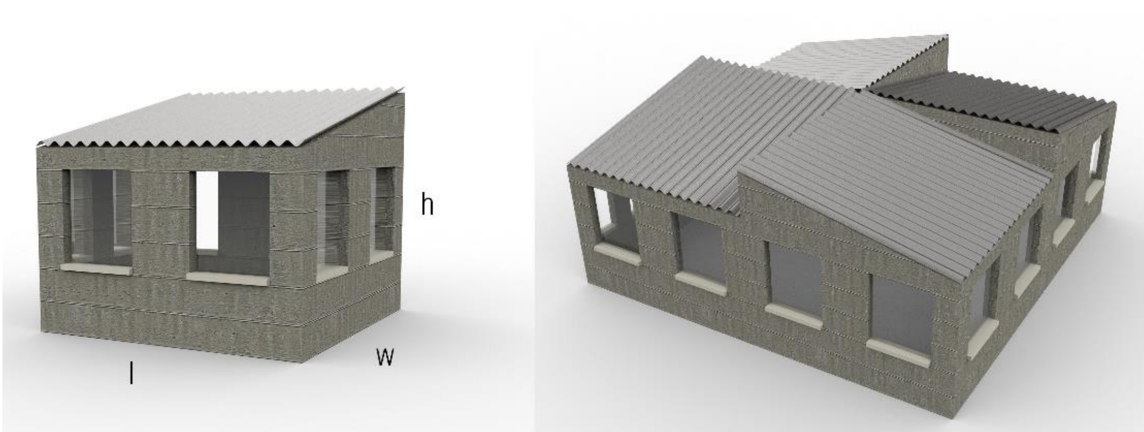
	Zinc	XPS	Cement Brick
Thickness (m)	0.002	0.06	0.12
Conductivity (W/m-K)	122	0.034	1
Density (kg/m3)	1442	20.8	2085
Specific heat (j/kg-K)	380	1131	900
Absorptance	0.25	0.7	0.9
Cost (€ / m2)	6	4	12

F32 – Material properties for construction scenarios inputs.

[12] *https://www.engineeringtoolbox.com/material-properties-t_24.html*

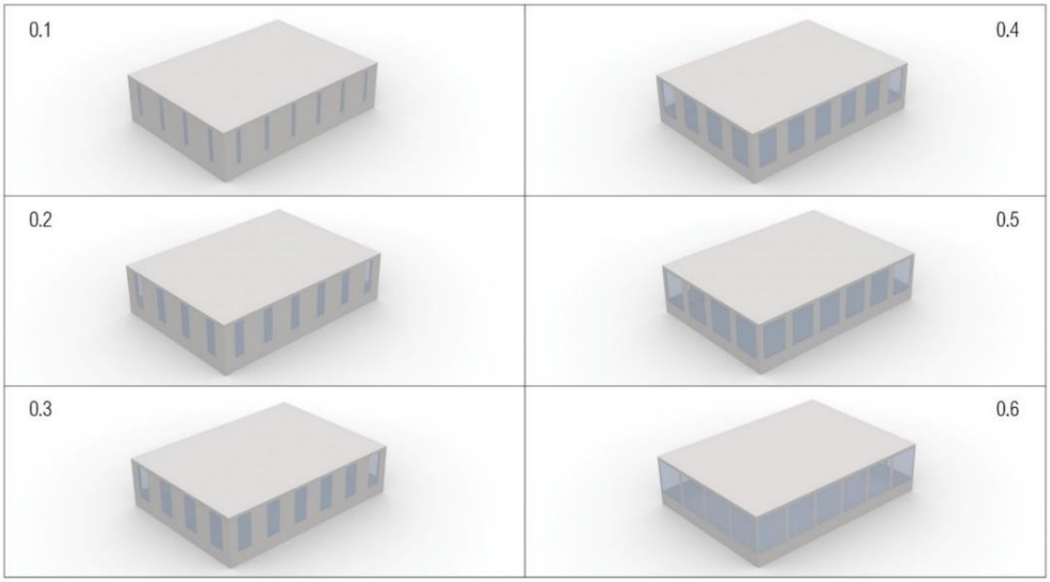
Simulation outputs include adaptive charts indicating (1) the indoor and outdoor temperature distribution for the defined analysis period, and (2) the percentage of time in which each house is within the comfort zone of the ASHRAE adaptive chart, a metric known as TA (Levitt et al. 2013). This analysis was made from January to March, from 10 AM to 8 PM, as it comprises the warmest hours of the year. The results of these simulations were compared with the results of the original scenario (W1+R1 - zinc cladding), to quantify and visualize the impact of each upgrade and evaluate the suitability of each scenario for each building.

After the material analysis, the impact of design parameters on the TA of the "Ventoinha" house was researched. To this end, an iterative simulation cycle was implemented in a single house, with different values for the height and floor area and using the selected construction scenarios and glazing ratio. This quantifies the TA variation towards the establishment of design thresholds to regulate informal construction. To this end, we started from one rectangular unit with variable length (*l*), width (*w*), and height (*h*), and a triangular prism with the same length and width, but with variable height according to the desired roof angle. To form a complete house, this starting unit is incrementally rotated four times around a unit corner. Each unit can be parametrized with a different total length and width. However, this type of design change is not ideal for informal housing settlements, as the production of construction materials often relies on their modular qualities. For this reason, the same dimensions were used for every unit (F33).



F33 – Algorithmic model of the *Ventoinha* house.

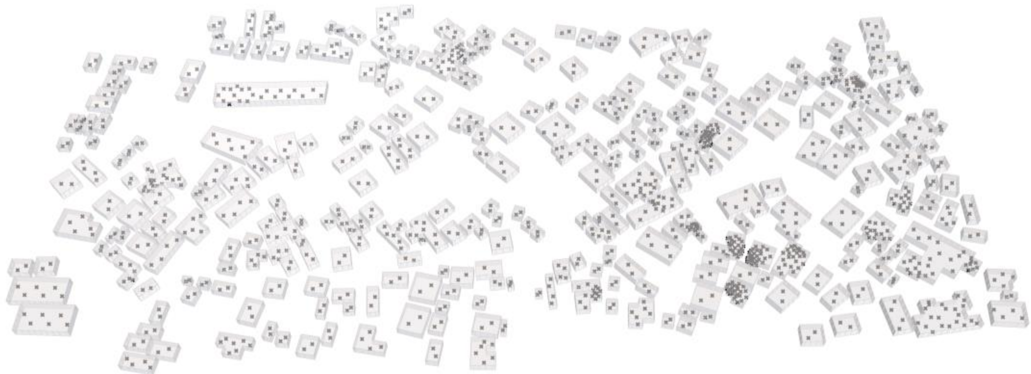
For the illuminance study at both urban and building scales, an analysis plane intersecting each building with their respective analysis test points was created for every 5x5m square composing the floor area, at a height of 1,5 m. The performed analysis encompassed a grid-based simulation, with a climate-based sky for the summer solstice day, with a 4-hour time-step ranging from 6 AM to 6 PM. Glazing ratios from 0,1 to 0,6 were tested (F34). At a building scale, two types of window designs were also analyzed and compared with the glazing ratios and each building's UDI (F35). These parameters can help determine if there is a more suitable window design for each building according to its surroundings, and define regulations that standardize values for the building's glazing ratio according to the building area, and/or geographic location in the case of rehabilitation. The presented analysis focuses only on Illuminance comfort and does not consider the thermal impact of the assigned glazing. Typically, high glazing ratios such as 0,6 can result in poor comfort levels.



F34 – Sample house in Chamanculo with assigned glazing ratio.

F35 – *Ventoinha* house window design 1 and 2.(south-western perspective view)

Some problems were found in the definition of the analysis grids that were created from the 3D model. The points created by the surface division were not equidistant within the building surfaces, which happened due to the triangulation made by the OSM file upon extraction. The AD tool imported the triangulated geometry in Rhino and the points were divided according to each triangle. This resulted in some houses having more test points than others. However, for the methodology, the minimum number of points to produce acceptable results was achieved in every analyzed house (F36).



F36 – Chamanculo C test points for the illuminance urban study.

In the airflow analysis, wind speed and airflow were tested for glazing ratios ranging between 0,1 to 0,4. Two windows were opened in the North and South façades, working as air outlets and inlets, respectively. The results were compared and discussed according to the values of wind speed and air circulation in the area, which are obtained from each design iteration test. Additionally, windows were added in the roof walls of each unit, to promote cross-ventilation between rooms. Several patterns of cross ventilation can be tested using the presented workflow. However, its application would be time-consuming unless a high number of computing resources were available. Thus, the tested ventilation scheme comprises only two open windows in windward and leeward walls, and all the roof windows opened, except for the windward one (F37).

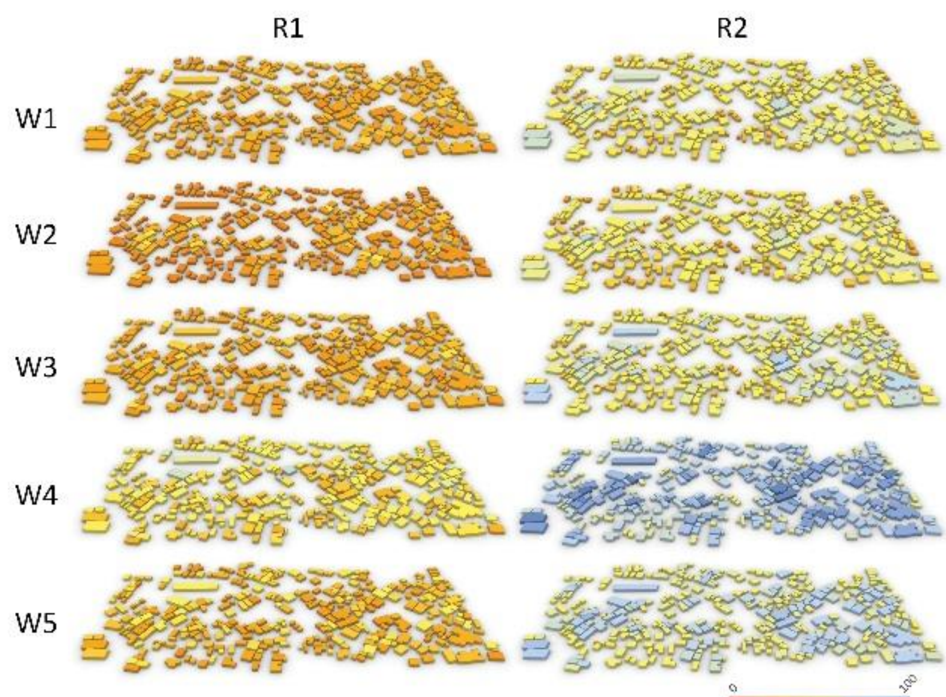
F37 – Cross Ventilation Scheme with added roof windows in a 0.3 glazing ratio house (south-eastern perspective view).

4.3. Integrated Building Performance Simulations

Nowadays, there are several tools available for BPS. Whether for energy or structural analysis, these tools work as a powerful development and support resources for the conceptualization, design, and execution of a project. With these tools, one can predict indoor comfort levels and building energy consumptions, which support the development of solutions with less costly improvements according to different comfort metrics. This can be crucial for sustainability-based projects that tackle areas with extreme climate conditions and third world countries that are not able to facilitate construction or even respond to temporary housing needs for catastrophe victims, refugees, and informal settlements. Furthermore, besides helping with design solutions, it might be valuable to determine construction and planning policies for the country, regarding energy consumption, building height, construction materials, and any other factor that might influence the urban morphology of the country, while assuring basic living conditions.

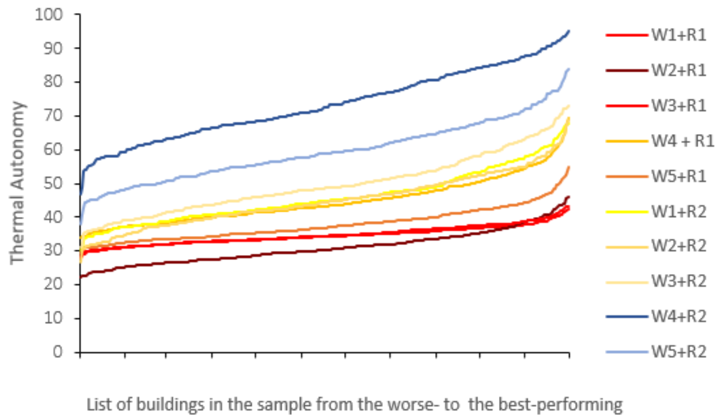
4.3.1. Thermal

Looking at the results in F38, it is easily visible that walls W1, W2, and W3 have similar, lower performance, while W4 and W5 have better performance. It is also clear that every wall scenario benefits from the application of R2. Consequently, and regardless of the wall construction, changing the roof's construction emerges as the most viable option of slum upgrade.



F38 – Thermal Autonomy per building in Chamanculo for each construction scenario.

Houses in different areas of the neighborhood vary their TA according to not only their floor area but also their context and surroundings. Thus, it is possible to define separate rehabilitation plans for neighborhood areas that require more urgent upgrades, using different constructions and materials for different zones. Although most performance improvements can be identified in the heatmap, a better way to visualize these results is through a line chart from worse- to best-performing buildings within the same construction scenario, allowing the determination of each material's comfort spectrum (F39).



F39 Line chart illustrating the range of comfort in the urban area for buildings with each construction scenario.

Overall, the best-performing construction solution is W4+R2, comprising a double pane of cement brick with a wall air gap and a roof composed of double zinc cladding with air space and Extruded Polystyrene (XPS) as insulation. Scenario W5+R2, composed of one layer of zinc cladding, wall air space, and one cement brick pane, also shows promising results and has the advantage of being a better solution for rehabilitation, due to its adaptability to the identified building typologies in Chamanculo.

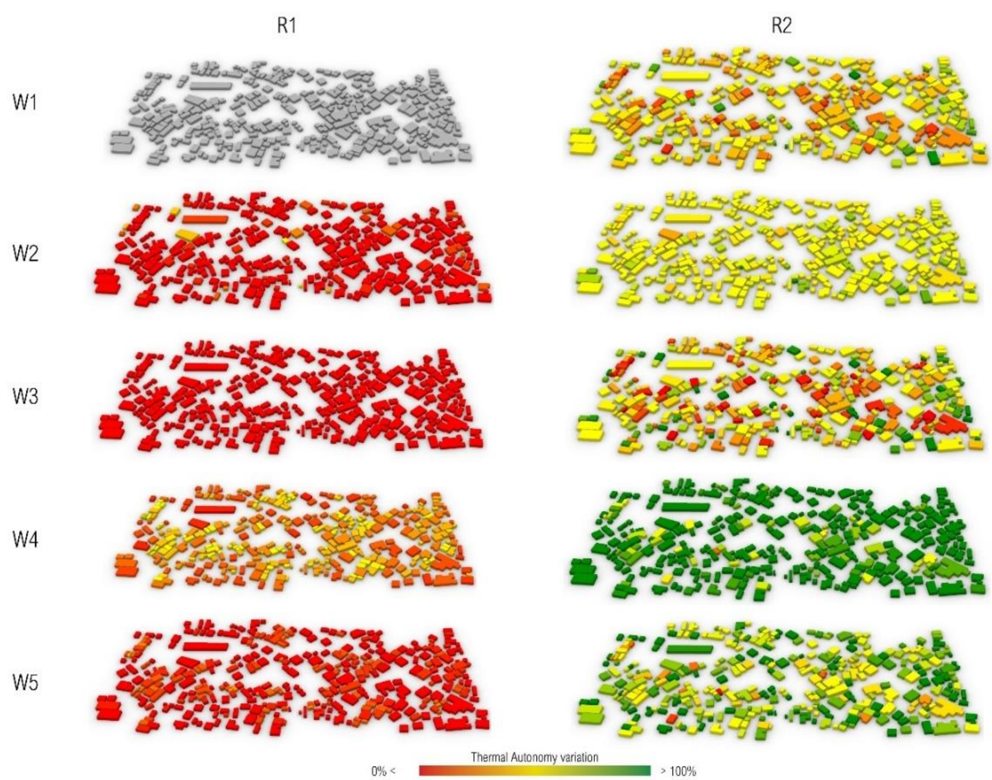
A larger performance discrepancy between wall solutions is visible when roof R2 is applied. Buildings with W4+R1 have roughly the same performance as W1+R2, with results showing, respectively, a minimum TA of 30% and 33%, a maximum of 69% and 67%, and an average of 45% and 46%. Furthermore, W5, which had similar performance to walls W1 and W3 when combined with roof R1, shows a larger improvement when roof R2 is applied. Consequently, roofs behave differently with each wall construction and show different levels of improvement in each building.

These improvements can be quantified by analyzing the variation in TA between the buildings with scenario W1 and the buildings with all other construction scenarios, with and without roof improvement (F40). Results show that some houses have a reduction in TA reaching up to 40%. On average, the TA variation ranges from -10% up to 114%, with maximum increases reaching 218%. While scenarios W4 and W5 show the largest improvements, some buildings show a neutral or negative impact from these upgrades, either because of sun exposure, building density, or floor area, which emphasizes the need for a spatially contextualized analysis.

	AVG	MAX	MIN
W2+R1	-10%	52%	-41%
W3+R1	1%	4%	-5%
W4+R1	29%	70%	9%
W5+R1	9%	34%	-1%
W1+R2	34%	105%	-26%
W2+R2	31%	101%	-26%
W3+R2	45%	120%	-24%
W4+R2	114%	218%	21%
W5+R2	73%	156%	0%

F40 – Table illustrating the percentage of thermal autonomy improvement when compared with the original scenario.

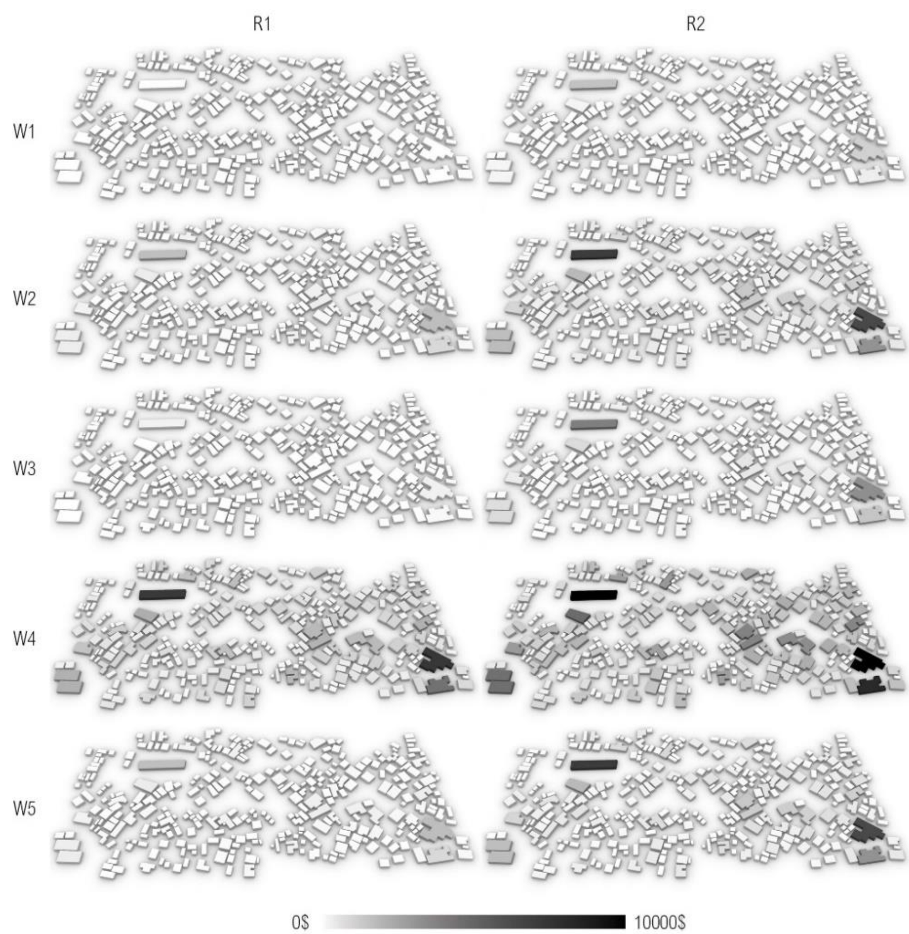
To better understand the TA variation results, F41 illustrates the percentage of TA variation in each building in the urban model, on a scale from 0% or below (in red) to 100% or above (in green). As seen, the performance of the wall scenarios is highly sensible to the roof construction, which acts as a catalyst for comfort improvement. Such is demonstrated by scenarios W4 and W5, which return little to no improvements with roof R1, and the best-performing solutions with roof R2. However, many buildings have significant TA increases with less costly walls and/or roof rehabilitation scenarios.



F41 – Heatmap illustrating the percentage of thermal autonomy improvements compared with the original scenario (Top left corner).

The TA variation study was made using the same construction solution in all the buildings that compose the urban model. However, each of the 334 buildings is a separate variable and, therefore, their construction solutions can be individually changed. The wide range of viable construction solutions for each building, corresponding impact factors, and price can be hard and time-consuming to analyze and control. Moreover, large improvements in TA are not necessarily proportional to the cost of the corresponding building. For instance, shifting from the original scenario, W1+R1, to scenario W1+R2 would cost as much, or even less as rehabilitating W1+R1 with any better wall scenario (F42), while yielding similar and, in some cases, better results, reflecting the conflictive nature of TA and costs.

MOO can be used to shorten the required time to find a suitable combination of construction solutions for the Chamanculo neighborhood. By automating a large number of consecutive analysis, the determination of less costly solutions in specific ranges of TA improvement is facilitated. This way, materials are applied by the optimization algorithm in each building, according to the total TA of the urban area, its standard deviation, and cost of rehabilitation, ensuring that all houses have the minimum deviation possible from each other, and the best possible comfort level, at minimum costs.



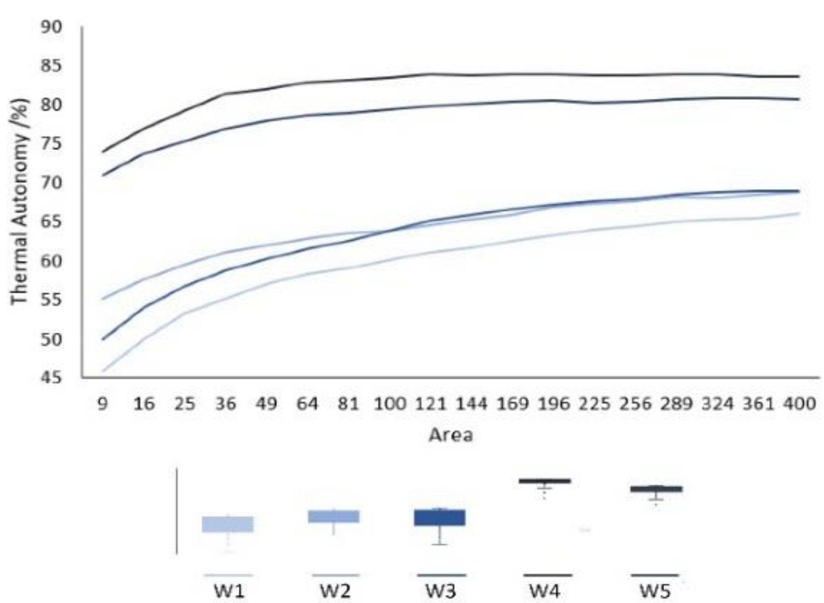
F42 – Heatmap of the cost per building for each construction solution.

The next analysis focuses on the impact of the buildings' floor area, height, and glazing ratio in their TA. The simulated model comprises a single house with scenario W5+R2, a height range from 2,25 m to 3,5 m, and a unit floor area from 6,25 m^2 to 16 m^2. The natural ventilation is activated when the outdoor temperature is between 16°C and 28°C. Preliminary results show a decrease of up to 4% as the height increases and an improvement of 4% to 7% as the area increases (F43).

area (m2) \ height (m)	2.25	2.5	3	3.5	
6.25	70.8	70.2	69.5	68.1	-4%
9	72.1	71.9	70.9	70.4	-2%
12.3	73.2	72.9	72.7	71.8	-2%
16	74.2	73.9	73.6	73.1	-1%
	5%	5%	6%	7%	Δ%

F43 – Thermal Autonomy for the tested *Ventoinha* house floor areas and heights, and their respective variation.

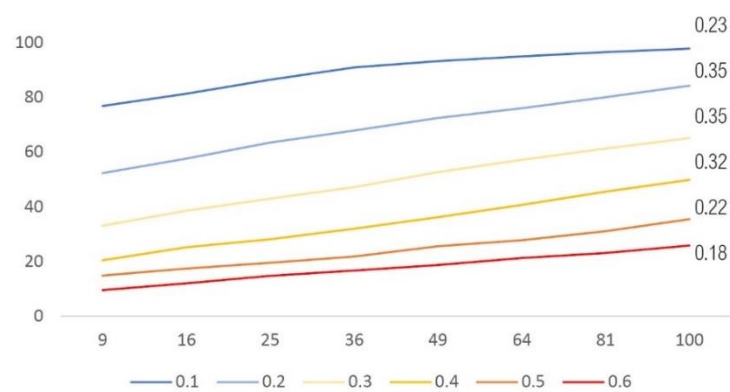
At a single-house scale, variations in height and area do not have as much significance in TA as changing construction scenarios, and the comfort decrease might result from air stratification or sensor positioning in the analysis tool. Nevertheless, further experiments were made to assess the performance variation of each wall scenario and glazing ratio as the unit area increases (F44). In these experiments, the roof scenario used for the unit was R2 due to its better performance.



F44 – Thermal Autonomy per area in the *Ventoinha* house for each wall scenario (Top). Box plot of Thermal autonomy per area in *Ventoinha* house for each wall scenario.

TA increases with larger areas, and scenario W2 proves to perform better than W1 and W3 in areas up to 100 m^2. However, the TA of scenario W3 is similar to the one of scenario W2 for areas larger than 100 m^2. Additionally, scenarios W1, W2, W3, W4, and W5 show maximum increases of 44%, 21%, 34%, 13%, and 8%, respectively. Two scenarios (W4 and W5) easily stand out as better construction solutions regarding the impact of floor area in comfort and their comfort amplitude according to the floor area.

To understand the impact of the glazing ratio in the *Ventoinha* house with the construction solution W5+R2, 6 iterative analysis cycles for a house with variable areas were simulated for different glazing ratios (from 0,1 to 0,6) (F45). TA appears to improve almost in a linear proportion along with the floor area for every ratio. If this improvement is treated as such, it is possible to understand how much TA increases per square meter for each glazing ratio. Ratios of 0,2 and 0,3 demonstrate higher TA proportional growth, with a 0,35% of TA increase per m^2, while a ratio of 0,6 glazing shows only an increase of 0,18%. From the graphic, one can assume that the TA increases at a higher rate per area for ratios up to 0,4. This translates into bigger areas requiring higher glazing ratios to obtain levels of UDI similar to smaller ratios.

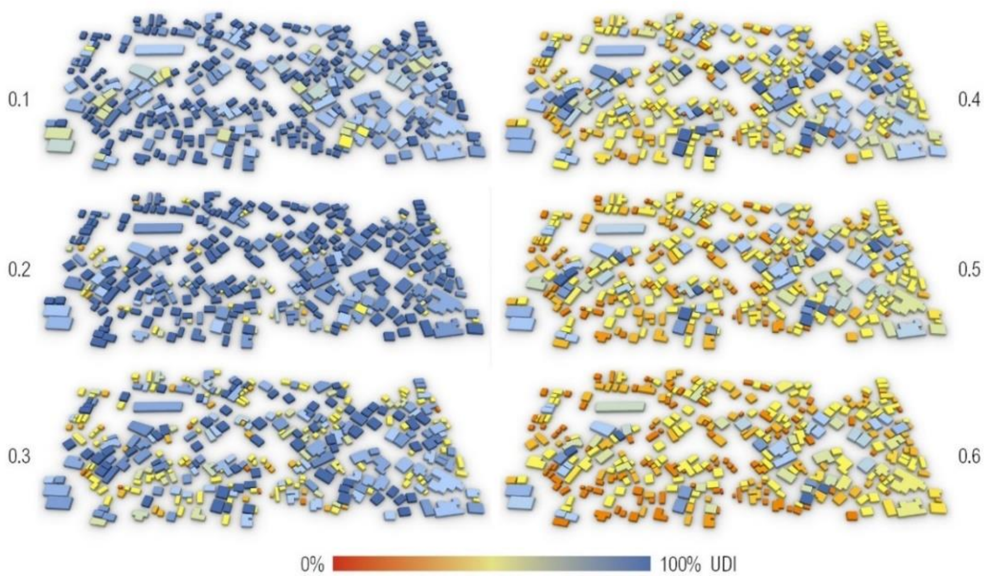


F45 - Thermal autonomy per area for each glazing ratio, and its respective slope (rate of change).

4.3.2. Illuminance

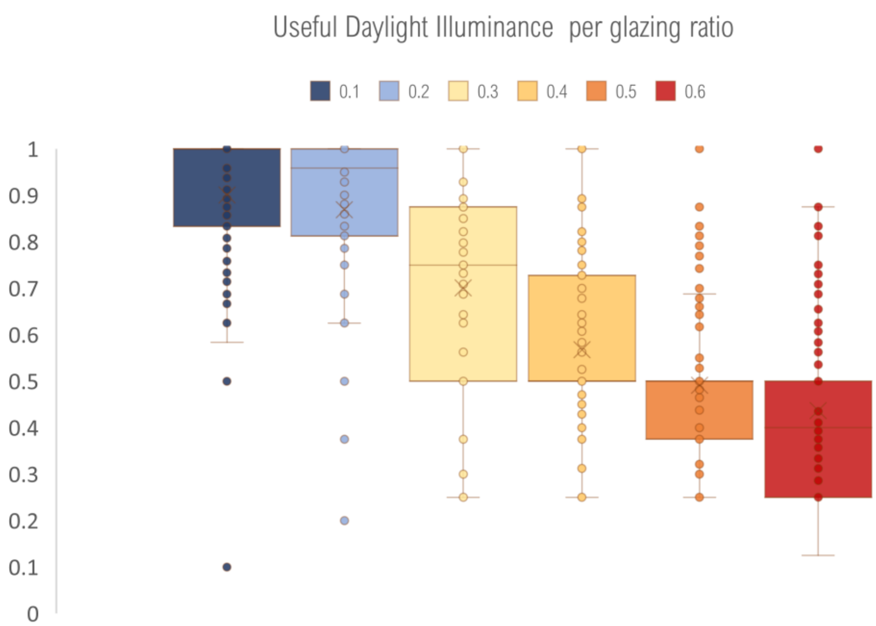
The illuminance was tested for the whole neighborhood during the Summer solstice, at 6 AM, 10 AM, 2 PM, and 6 PM. It considered the building's original disposition according to the OSM file, two types of window design, and glazing ratios from 0,1 to 0,6. In the urban area, the glazing ratio was analyzed by applying the same value for every building in the model and documenting the results, while for the *Ventoinha* house, two types of window design, and different floor areas were tested for the selected glazing ratios.

The outputs of the illuminance analysis at an urban scale show the average UDI of each building during the proposed analysis period. As seen in the heatmaps of F46, lower values of glazing ratio are associated with better UDI values. Additionally, the type of visualization provided by the heatmap can aid in the identification of specific glazing ratios that are suitable for each separate building.



F46 – UDI heatmap of the urban model for selected glazing ratios.

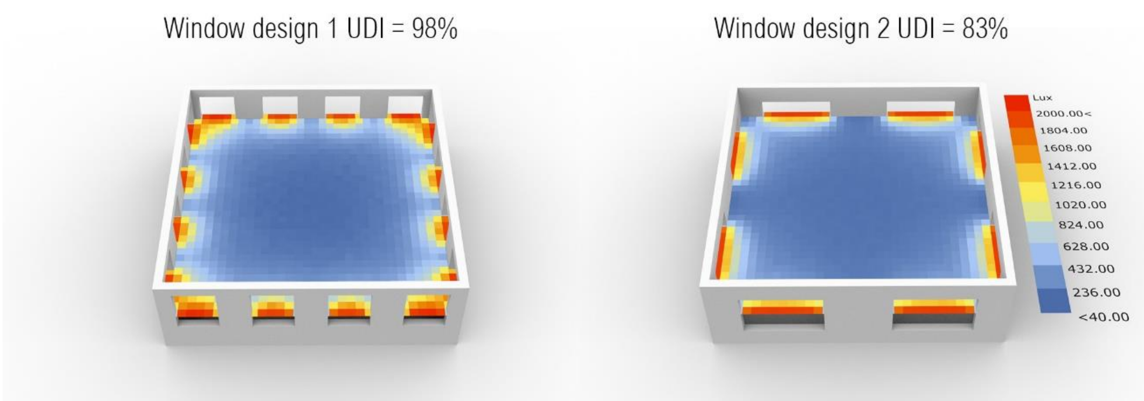
The box plot in F47 shows a stratification in the relation between glazing ratio and UDI results. Particularly, the ratios can be divided in three layers: (1) 0,1 to 0,2, (2) 0,3 to 0,4, and (3) 0,5 to 0,6. While the first layer corresponds to the best overall UDI values, ranging from 80% to 100%, the latter represents the lowest UDI percentages, ranging from 30% to 50%.



F47 – Box plot of UDI distribution for each building in the urban model, for selected glazing ratios.

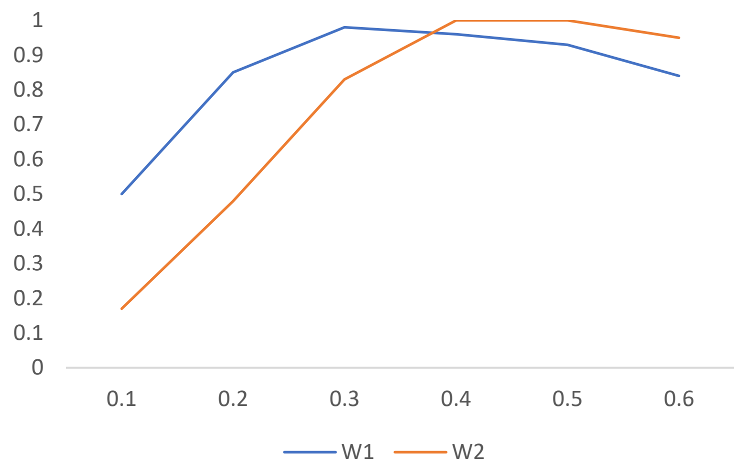
Finally, and following the lines of the comfort analysis in an urban area, a problem emerges when each building is considered a variable and six possible values for the glazing ratio can be taken for 334 buildings. This creates an almost infinite number of possible combinations, and in the case of finding solutions with different glazing ratios for each building, a MOO process can be integrated with two objectives to (1) maximize each buildings UDI, (2) minimize the standard deviation, guaranteeing fairness and equality among the urban model, (3) Minimize construction costs.

In the *Ventoinha* house illuminance analysis, two types of window design were tested: (1) an array of windows following a specified glazing ratio, and (2) a single centered window per each unit's façade (F48). Initially, a test simulation using a glazing ratio of 0,3 for each window design was performed, to understand the impact in the house's illuminance. Preliminary results show that design 1 a higher illuminance, with a UDI of 98% against a UDI of 83% for design 2. Moreover, a better light distribution is visible in the illuminance heatmap of design 1, since it creates more openings promoting the spread of natural lighting to the center, corresponding to the area where fewer light hits.



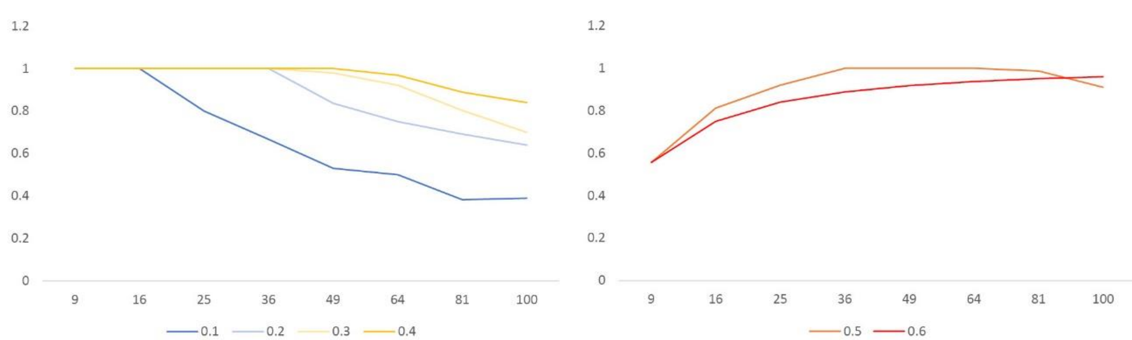
F48 – Illuminance heatmap per area for the *Ventoinha* house with 0.3 glazing ratio and window type 1 (left) and 2 (right).

The same two window designs were tested a second time for different glazing ratios. In the graph shown in F49, we can observe a shift on which is the best-performing window design, following the increase in glazing ratio. This happens when the upper threshold of the UDI metric is surpassed (> 2000 lux), which might create potentially uncomfortable and glare-prone areas. In this case, it occurs when the glazing ratio reaches a value of approximately 0,4, from which onwards design 2 shows higher UDI values and a slower performance decay rate. These results indicate that design 1 is more suitable for a building with lower glazing ratios, and window design 2 for higher ones.



F49 – UDI per glazing ratio of *Ventoinha* house with window design 1 and 2.

To understand how different floor areas could benefit from specific glazing ratios, the UDI of houses with floor areas from 9 to 100 m^2 was iteratively simulated for increasing glazing ratios (F50). From the obtained results, we can observe that in a house with window design 1 and a glazing ratio of 0,1, the interior space gets significantly darker when the floor area surpasses 16 m^2, reaching levels as low as 40% of UDI when this area approaches a value of 100 m^2. At around 36 m^2 of floor area, houses with a glazing ratio of 0,2, 0,3, and 0,4 start to get darker, with the latter showing a smaller decay rate. Furthermore, glazing ratios of 0,5 and 0,6 prove to be inadequate for smaller areas, creating uncomfortably bright spaces. However, these are more adequate for areas of 36 m^2 and above. Finally, for future constructions in Chamanculo, a glazing ratio of no more than 0,3 is recommended for floor areas no bigger than 50 m^2, and glazing ratios of 0,5 or 0,6 for higher areas.

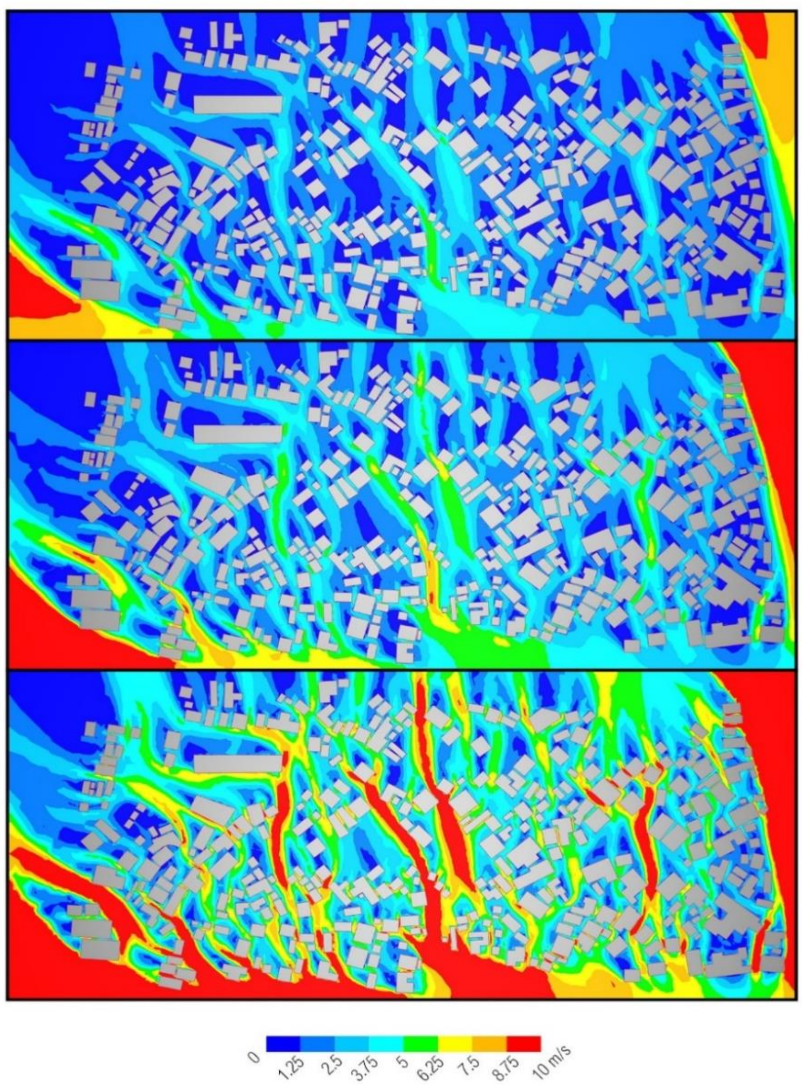


F50 – UDI per area for window design 1 with 0.1, 0.2, 0.3, and 0.4 (left), 0.5, and 0.6 (right).

4.3.3. Indoor and Outdoor Airflow

Lawson's Wind comfort criteria (Janssen, Blocken, and Van Hooff 2013) was chosen to identify areas in Chamanculo that are comfortable for certain activities based on the velocity magnitude in the area, and the Isyumov and Davenport's criteria (1975) to assess which areas are prone to infrastructure damage (see Chapter 1). Finally, the *Ventoinha* house was tested for indoor air circulation speed, flow, and pressure. This was done with a set of glazing ratios from 0,1 to 0,4, and the above-mentioned cross-ventilation scheme following the studied predominant wind speeds.

By looking at the wind rose graph and stereographic diagram reported above, it is possible to discern the annual percentage of wind speeds for each direction. In this case, during the year, Maputo had winds up to 19 m/s, and for roughly 60% of the year, the wind did not exceed 7.5 m/s. Three wind tunnel tests were made in Chamanculo C for the southern winds, comprising values of 3.5 m/s, 5 m/s, and 9 m/s. The latter serves as a threshold, since 93% of the time, in all directions, the wind speed did not exceed this value.



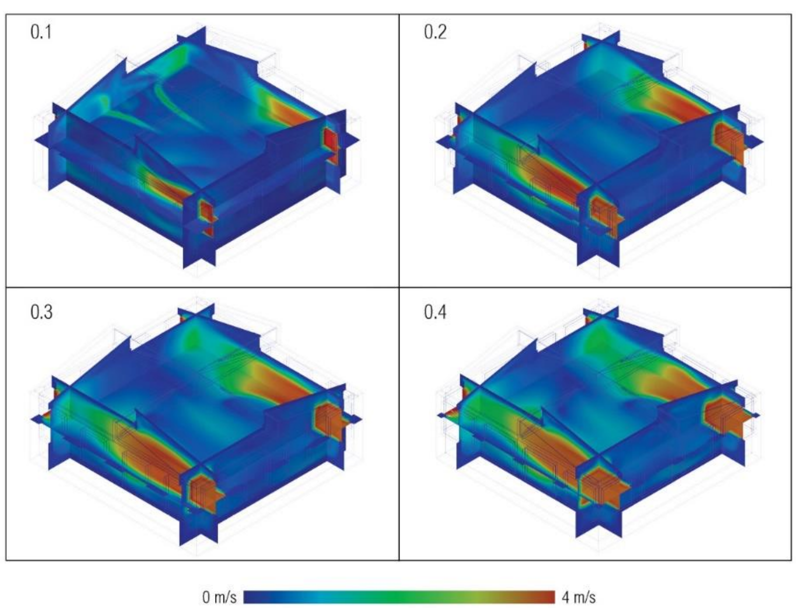
F51 – Wind speed magnitude heatmap for southern wind speeds of 3.5, 5, and 9 m/s (from top to bottom).

Results are illustrated according to the selected comfort criteria (F51) and show that a southern wind of 3.5 m/s creates some corridors of speeds up to 6.25 m/s, which places in Lawson's comfort criteria as comfortable for walking. However, with higher wind speeds, these corridors create uncomfortable areas and in the 9m/s test several critical public areas, with values over 10 m/s can be identified, prevented, and better planned. In the case of storms and gales, which hit speeds of 24 m/s and above, the obtained results show high-risk areas prone to damage in public areas, and in adjacent infrastructures. These effects can be avoided with a careful floor/area ratio planning, and by deploying vegetation, such as trees, to protect identified areas.

The *Ventoinha* house's airflow was tested using two windows as inlets in the South façade, along with a boundary condition expressing a velocity of 3.5 m/s. The opposite windows in the Northern façade were set as outlets. Additionally, four simulations of the building model with glazing ratios of 0.1, 0.2, 0.3, and 0.4 were tested to compare the air circulation and speed. The velocity magnitude is illustrated in heatmaps of four vertical planes, and one horizontal, which represents the speed in that area (F52).

From the heatmaps, we can identify a vortex in the house with a glazing ratio of 0,1. The air revolves in the northern corners and gathers in the center, hitting speeds up to 2 m/s. This phenomenon is only visible in this specific iteration. However, with higher ratios, the vertical planes show wind speeds of 4 m/s occurring in larger areas, while the horizontal plane shows an overall increase of wind speed in the house, with the 0.4 iterations showing the worse results. Furthermore, smaller speed vortexes are seen in some roof corners, indicating improper ventilation of the house.

Considering the obtained results and taking advantage of the house's modular algorithmic description, it is possible to run the same tests with the added roof windows in each unit. This will yield insights regarding the identified problems of high wind speed per area of higher glazing ratios and the roof vortexes created from the lack of upper outlets.

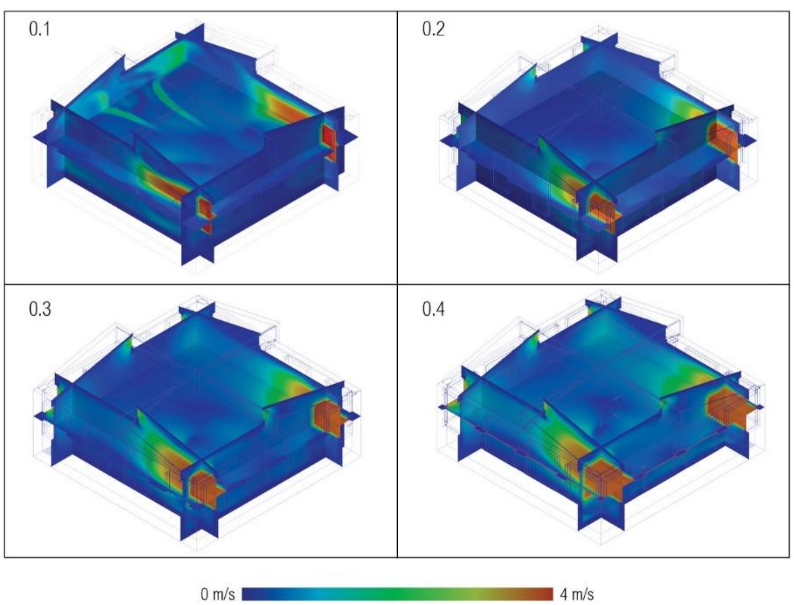


F52 – Wind speed inside *Ventoinha* house with 3.5 m/s south inlets for different glazing ratios.

With roof windows as upper outlets (F53), results of the indoor air speed show less transversal incidence from the southern to the northern façade, average lower speeds in the horizontal plane, and the proper ventilation of each unit are assured. Outlet speeds seen in the vertical planes, reach values of up to 2 m/s in the exhausting areas and do not create the observed vortexes in the roof corners.

Overall, these results bring a substantial improvement from the roof windows addition, creating a fan-like exhausting mechanism, that promotes even air circulation, and reduces the overall wind speed in the area. According to the areas the user wants to cool and ventilate. Additionally, the urban area analysis yielded relevant results regarding critical areas that may prove uncomfortable and cause public, and infrastructure damage. Other analyses and simulations that may be performed with this tool encompass heat flow, temperature stratification, static pressure, and more.

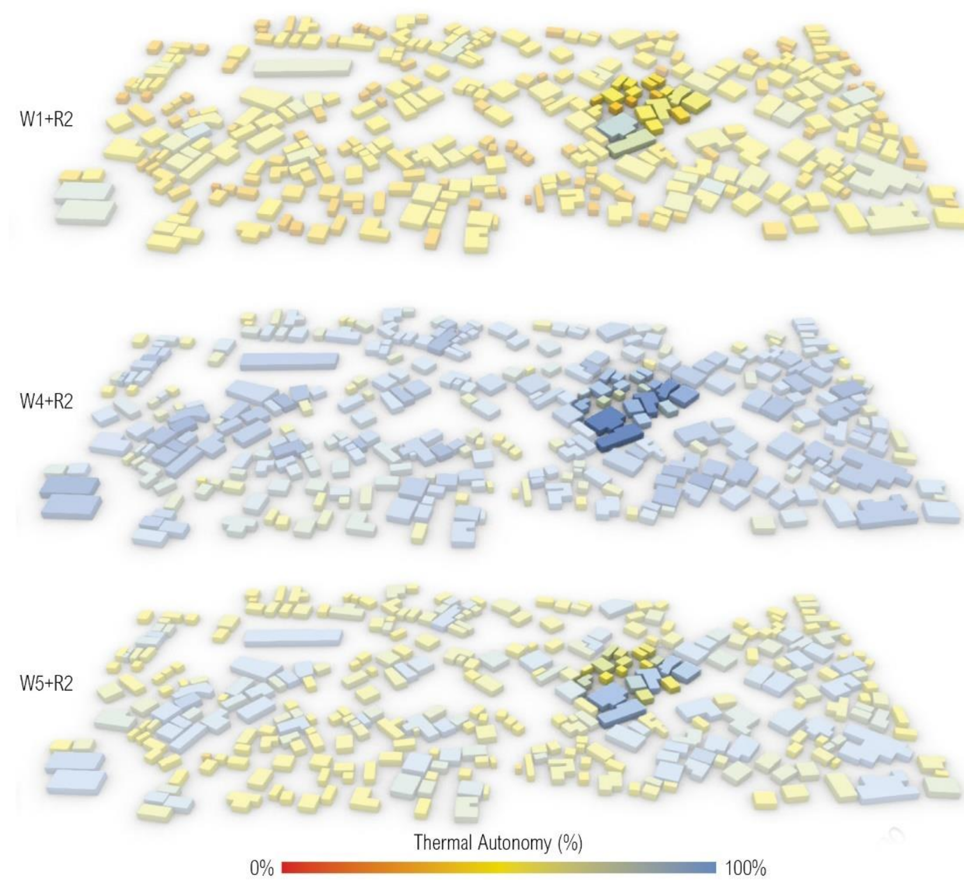
With the obtained analysis results, it is possible to integrate several optimization processes to enhance a future design or rehabilitation project's performance. In this case, wind speed and airflow analysis are useful for a pre-emptive study. However, with the resultant static pressure from the wind in the area, it is possible to calculate the wind loads impact in each building, and through the use of these as inputs, structural analyses can be performed for several design iterations concerning the number of materials and structural typology of the project. This can help minimize costs and materials required for a structure, or an urban area, to resist recurrent storms or high winds, which is particularly interesting for emergency-response situations and refugee settlements design and practice.



F53 - Wind speed inside *Ventoinha* house with 3.5 m/s south inlets for different glazing ratios, and roof windows as outlets.

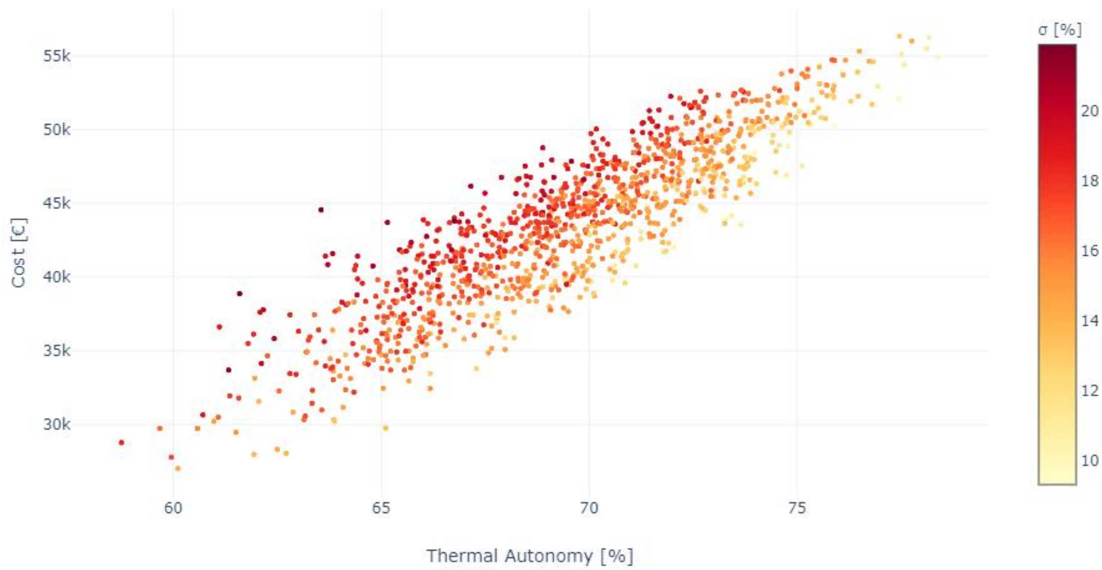
4.4. Multi-Objective Optimization

If the full urban area rehabilitation, which comprises 334 building units, was considered for the optimization process, it would take almost a month to complete with a single standard computer. Since the focus of this research is the methodology applicability, it was chosen a sample of 20 houses from the Chamanculo C Urban area to optimize regarding comfort, cost, and fairness (standard deviation). Alas, 20 building units, each with 10 possible construction solutions, still comprise an enormous solution space, which would require many evaluations before the optimization algorithm yields an acceptable range of optimal solutions. Fortunately, from the thermal comfort analyses in the urban area, it is possible to narrow down the construction solutions to a much lower number. TA results show a much larger improvement with the application of a better roof solution (R2), which not only provides better results than any wall solution with the original zinc roof (R1) but also acts as a catalyst for wall performances. Particularly, acceptable construction solutions identified in the former analyses were Wall 4 with Roof 2 (W4+R2), Wall 5 with Roof 2 (W5+R2), and W1 with Roof 2 (W1+R2) (F54). The latter does not show the best comfort results but rather represents the cheapest solution with acceptable TA, which acts as a threshold when comparing the obtained optimal solutions.



F54 – Thermal Autonomy per building in Chamanculo for the three selected construction solutions. Optimization sample highlighted.

The solutions tested by the NSGAII (Deb et al. 2002) are illustrated in a heatmap of a scatter plot (F55), which performed 1200 evaluations, each evaluation representing a combination of constructions for the 20 buildings. Solutions were found in a range from 27000 € to 56000 € for the full rehabilitation cost of these buildings, with an average TA between 58% and 78%, and a standard deviation (σ) varying from 9.3% to 22%. Additionally, the heatmap shows a successful approach in finding values of maximum TA with lower costs and σ. However, a lower number of solutions were found with medium and lower values of TA, but with higher σ. Thus, the fairer solutions found by the algorithm are the most comfortable, but also the most expensive.

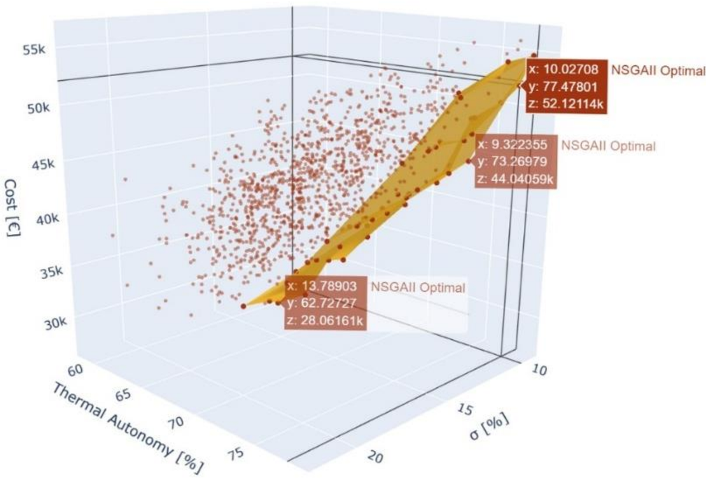


F55 – Heatmap scatter plot of all the tested solutions cost, thermal autonomy, and standard deviation.

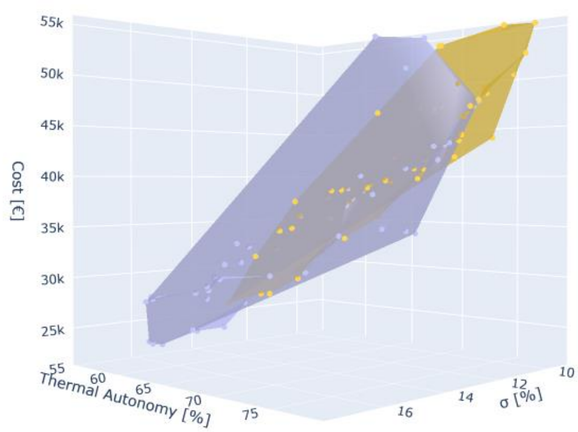
The scatter plot can be better visualized with three axes according to the three defined objectives, and through the Pareto front (See Chapter 2), a surface from the optimal solutions found can be generated. The resulting surface demonstrates to be wider in higher costs, higher TA, and lower σ; and narrower in lower costs and TA results. Furthermore, according to the desired values for the established objectives, one can choose a solution that fits their criteria (i.e., fits a specific budget). In this case, three optimal solutions were chosen according to different costs and compared with the previous results of comfort and cost: (1) a high-cost and high performance with low σ, (2) a medium cost and performance with low σ, and (3) a low cost and performance with the lowest possible σ (F56).

To understand if fairer and less costly solutions can be found for all comfort levels, the results produced by the NSGAII (Deb et al. 2002) were used as a starting point for a model-based algorithm, in this case, the RF Regressor (Pavlov 2019). This allowed us to use 600 more evaluations, to refine the previous results and explore other promising solutions (F57).

Results show an improvement in the cost and σ for lower levels of TA. Comparing them with the NSGAII results, the latter shows better solutions for higher levels of TA with higher costs, but the former widens the range of possible fair and less costly solutions of rehabilitation. This is seen in the surface graph of the model-based algorithm, which particularly shows new optimal solutions in ranges of TA from 55% to 70%, cost from 20000 € and 33000 €, and standard deviation (σ) from 9.7 % to 15%.



F56 – 3D scatter plot of all tested solutions results, and a 3D Surface generated from the respective Pareto front.

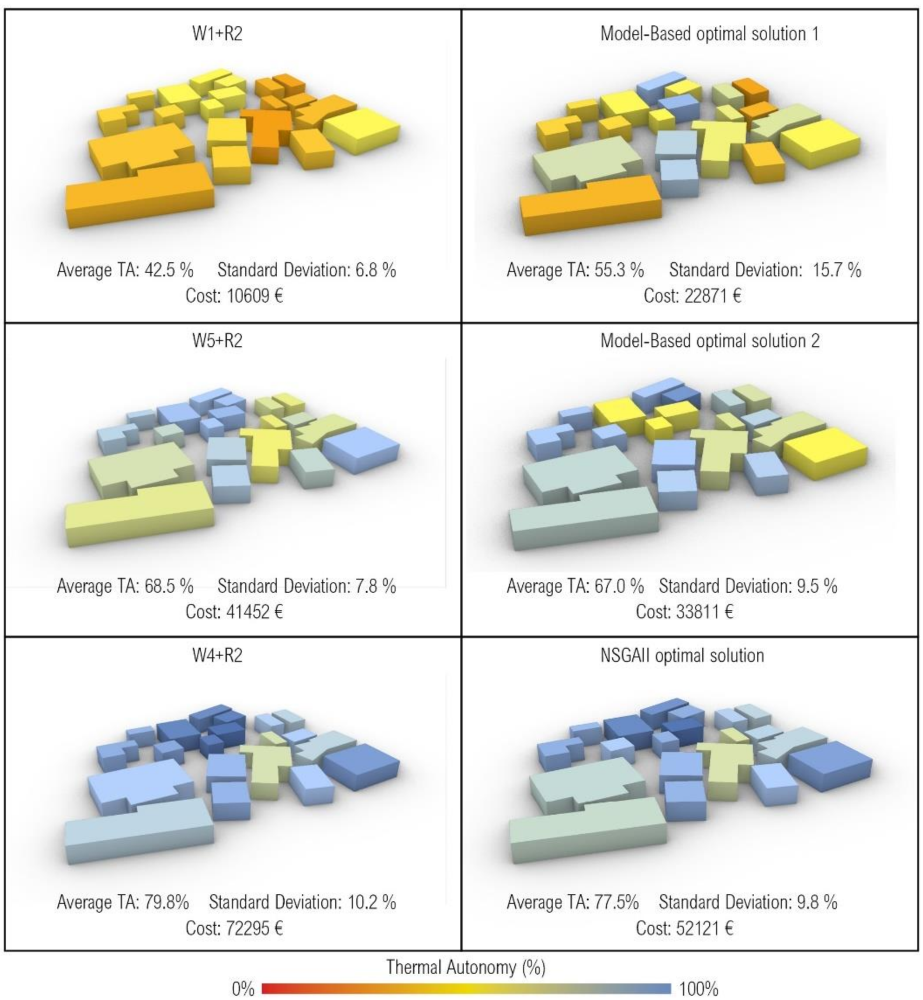


F57 – Pareto front of the NSGAII (Yellow), and the Random Forest Regressor (Blue).

Finally, three optimal solutions similar to full rehabilitations with W1+R2, W5+R2, and W4+R2 were identified (F58). By comparing the first selected construction solution (W1+R2), which consisted only of a roof upgrade, with the cheapest optimal solution found by the Model-Based algorithm, it is visible an overall increase of 30 % of the average TA with scenario W1+R2. However, the cost and standard deviation (σ) increase respectively by roughly 12000 €, and to 15.7%. This, combined with the heatmap scatter plot, suggests that some buildings are more comfortable than others, and the increase in cost represents an unfair increase in buildings TA.

W5+R2, consisting of a roof and wall upgrade, shows a rehabilitation cost of 41452 €, and a standard deviation (σ) of 7.8%, for an increase of 61 % in average TA against scenario W1+R2. In this case, the Model-Based algorithm found a solution with similar results, but with fewer costs, showing an increase of 57% in average TA, for a standard deviation of 9.5 % and a cost of 33811 €. These results show a solution with similar comfort levels in all the buildings, and roughly 7500 € cheaper than with scenario W5+R2.

Solution W4+R2 represents the best-identified solution regarding comfort performance, but also the costliest. The 20 buildings rehabilitated with this solution would have an average TA of 79.8%, which represents an increase of 88% against scenario W1+R2, with a standard deviation of 10.2 %, for a cost of 72295 €. By comparing the buildings' comfort heatmap from this solution, with the optimal solution found by the NSGAII algorithm, the latter shows an increase of average TA of 82% against scenario W1+R2, but with less standard deviation (σ), and roughly 20000 € (28%) cheaper.



F58 – Comparison between cost, comfort, and deviation of the 20 buildings with each selected construction, and the optimal combinations of constructions found with the optimization process.

Chapter 5 – Evaluation and Discussion

The presented research integrated algorithmic processes in informal urban and architectural planning to yield insights regarding the impact of design parameters in the occupants' thermal, visual, and wind comfort. AD was integrated with BPS and optimization tools to perform several evaluations to quantify the impact of location, positioning, glazing ratio, material properties, and floor area in the design and planning of such building typologies. Considering the presented results, the research outline and discussion are separated into two sub-sections: (1) Urban area rehabilitation and planning; (2) Architectural Planning.

5.1 Urban Planning and Rehabilitation

From the results of the outdoor airflow study, Chamanculo C was evaluated for the existing main wind speeds and directions in the area. This allowed to identify critical places within the public space that are prone to be dangerous/uncomfortable based on wind comfort criteria, and suggest interventions by:

- Better planning and distribution of the existing floor/area ratio and landscape, according to identified critical areas.
- Apply an optimization process to minimize structures deformation according to the recorded wind loads.

The illuminance study for urban rehabilitation depicts a high influence of the glazing ratio in the comfort of the occupants. Results show an overall good performance from 0.1 to 0.3 glazing ratio. Additionally, several buildings provide different visual comfort with the same glazing ratio, either because of their positioning, or their context environment. From the obtained heatmaps, it is possible to discern which buildings have acceptable comfort levels with each glazing ratio. This allows establishing thresholds in each land parcel regarding the adequate glazing ratio. From the study, it is also noticeable that some buildings are prone to better illuminance performances than others. Thus, it is recommended to:

- Map each building according to the acceptable visual comfort value established, and their respective identified threshold of glazing ratio.
- Apply an optimization process with each building façade as a variable of glazing ratio to optimize the visual comfort performance of each building.

The latter can help to further refine the obtained thresholds from the former, according to each building façades orientation and location, and not only the same glazing ratio for each building.

The thermal comfort study in the urban area yielded interesting results regarding building rehabilitation, cost, and thermal performance. On one hand, it showed that, in all houses, a roof upgrade (W1+R2), a double-pane cement wall (W4+R2), and a zinc and cement wall (W5+R2) have a higher general impact in the thermal performance, respectively showing an average increase of 34 %, 114% and 73% of the original scenario's results. On the other, it highlighted the conflictive nature between cost and thermal performance, showing higher costs and levels of comfort, and that specific buildings do not require necessarily the best, and most costly materials available to obtain acceptable levels of comfort.

An optimization process, comprising a metaheuristic and a model-based algorithm, was applied in a sample of 20 buildings to maximize their thermal comfort while minimizing rehabilitation costs and their standard deviation of comfort. These three objectives seek to find optimal combinations of construction solutions for each building, to provide similar levels of comfort as the ones in a rehabilitation scenario with only one construction, but with less cost and similar deviation. This optimization process shows promising results in finding construction solutions for each building that provide higher thermal comfort with fewer costs. Thus, if the building sample is increased, this would allow us to save up to hundreds of thousands, or even millions, in future rehabilitation of large informal areas.

Finally, from the urban thermal comfort study, two heuristics can be drawn regarding urban rehabilitation:

- Upgrade roof.
- Upgrade walls using optimization processes as guidance for possible construction combinations that provide high, and fair levels of comfort for all the occupants, with the least possible cost.

5.2 Architectural Planning and Design

These analyses focus on one of the most famous houses seen in the area, the *Ventoinha* house design. Parameters tested in these analyses include glazing ratio, floor area, material properties, and design variations for the illuminance and ventilation. These are then analyzed and compared to understand how each parameter affects the others, and their respective impact on thermal, visual, and airflow comfort.

The indoor airflow analyses show that implementing ventilation windows in the roof walls, considerably decreases the frequency of indoor vortexes and wind speed. Additionally, the glazing ratio is shown to have more impact on indoor wind speed without these roof walls, with 0.4, 0.3, and 0.2 showing acceptable results regarding Lawson's wind comfort criteria. However, in both design variations, 0.1 glazing ratios shows the creation of vortexes in the northern area of the house, near the outlets. This suggests that the width of the windows created is too narrow and can be solved by changing the design algorithm.

The illuminance study initially comprised the comparison between the UDI of two types of window design in the house. Results revealed that window design 2 performs better with higher glazing ratios, opposite to design 1. Afterward, the window design analyses, the impact of the glazing ratio with a certain floor area was evaluated. This allowed us to identify thresholds of floor areas where the specified glazing ratios start experiencing decay in performance. This decay can happen for areas that are too bright, or too dark. Specifically, a house with a 0.1 glazing ratio has 100% UDI up to 16 m^2, which goes down to 39% up to 100 m^2. The same behavior is visible with glazing ratios of 0,2, 0,3, 0,4, 0.5, and 0.6 which have 100% UDI up to 36, 49, 49, 64, and 81 m^2 respectively. Different behavior is seen for glazing ratios of 0.5 and 0.6. These are too bright for lower areas but respectively hit 100% UDI at 36 m^2 and 100 m^2.

Thermal comfort results for the *Ventoinha* house analyzed the impact of several design parameters in the building's TA, particularly, height, floor area, glazing ratio, and materials. In this case, building height and floor area have demonstrated little impact with areas up to 16 m^2. However, further analyses comparing the influence of higher floor areas for different materials in the house's thermal comfort revealed different area thresholds for the maximum comfort obtained by different constructions. Additionally, different glazing ratios were tested with variable floor areas for a specific construction solution, which unveiled that the first has a high influence in a building's thermal comfort, but this influence varies along with the floor area.

If the illuminance and thermal comfort results are cross-referenced between their common analyses, an unavoidable conflict is visible between them. Particularly, by comparing a UDI and TA heatmaps of the glazing ratio per floor area (F59), it is visible that results achieved by glazing ratio and areas in one, go against some of the best results achieved by the other. Consequently, the architect plays an important role in the decision-making process regarding the performance of the house and its goals.

F59 – Thermal Autonomy (left), and Useful Daylight illuminance (right) heatmaps of 'Ventoinha' house with defined design parameters.

CONCLUSION

Overview

Over the past decades, disaster-related events have been responsible for the displacement of millions of people around the world, and roughly 90% of those are weather-related (World Bank 2017). Buildings are increasingly failing because of the escalating impacts of climate trends and weather events (Roaf 2018). Moreover, as urban development increases, it is estimated that, by 2050, 66% of the world population will live in urban areas, 90% of which is predicted to be concentrated in Africa and Asia (United Nations 2019).

Around the world, programs such as Africa HABITAT are addressing ways to improve people's living conditions, particularly for refugees and in informal areas. In Mozambique, DUAT (Land use and appropriation rights) is positively improving land use. However, it fails to address important topics such as planning and rehabilitation towards occupants' comfort and well-being.

This research highlights the integration of algorithmic processes in informal architectural and urban planning, to identify how different construction scenarios and design parameters affect all building's levels of comfort. By integrating AD to perform sets of design iterations comprising all the defined parameters, it was possible to test them with BPS tools according to researched thermal, illuminance, and wind comfort metrics.

Results are outlined in two sections regarding architectural design and urban planning. Both revealed that besides different levels of impact being identified and categorized, the impact of different construction solutions, glazing ratios, and floor area are co-dependent, and reveal the conflictive nature of the parameters studied. To solve this problem, an optimization process was successfully employed in the urban area rehabilitation case. Thus, allowing to identify fair combinations of construction solutions in buildings that, in some cases, performed as well as the best-identified construction solution, but almost 30% cheaper overall.

Although weather data and other input sources may be a cause for model uncertainty, the integration of Building Performance Simulation in an algorithmic design workflow helps architects perceive the future impact of the developed project solutions. Informal housing programs, and non-governmental organizations, can act as vessels for the practical application of this kind of architectural research, and contribute to a more affordable and climate-friendly approach towards a comfortable and healthy living environment for all.

Final Remarks

Workflow

The integration of algorithmic processes such as AD, MOO, and iterative BPS yielded positive results regarding the time and labor required to perform all the simulations and design variations present in this document. Particularly, it allowed to effortlessly generate a parametric 3d urban model of any global area with recorded geospatial data, and a building commonly seen in the area case study. The variable design parameters combined with iterative cycles of model generation allowed us to integrate building performance simulation tools to perform multiple tests and simulations regarding different metrics. Thus, the time required to set up the models and analyses reduces drastically. Additionally, the employed MOO process allowed to test, and identify an otherwise impossible number of combinations of material solutions for an urban area, revealing less costly and fairer combinations to achieve similar, or even better comfort results.

Results

Obtained results have revealed the conflictive nature of certain design parameters regarding occupants' visual and thermal comfort. Namely, the costliest construction solutions are also the best performing ones, and the glazing ratio per floor area revealed a different order of values for visual, and thermal comfort. Furthermore, design and rehabilitation thresholds were identified through heatmaps and graphs, which allowed to better plan informal urban sprawl, and future architecture. However, since model inputs such as weather and geospatial data can be sources of uncertainty in the model, further practical and theoretical validation is required to understand the accuracy depth of the obtained results,

Applicability

Despite the existing vast application of AD and BPS, little to no exploration of this subject is being applied for “architecture where the other 90% live”. These processes are usually associated with expensive, high-performance, and cutting edge projects, however, their applicability rises beyond that, to the possibility of analyzing, improving, and preventing what-if scenarios that otherwise would take much more time to assess. By integrating these processes in architectural and urban practices, it is possible to adapt design solutions to fit certain comfort and utility criteria. Enabling to do so, while identifying parameter solutions that represent lower costs and/or resources. Finally, methodologies such as these, provide precious guidance in the planning, and rise of post-carbon cities.

Future Work

Throughout this document, several areas of research have been documented and developed. Particularly, algorithmic processes were integrated to yield design and planning guidelines regarding informal housing. These were visualized and presented in a series of representational methods that were considered adequate for their interpretation. Despite the methodology success in achieving the proposed objectives, there is also room to further complement the variety of algorithmic processes and building performance analyses, as well as improve their results accuracy, visualization, and interpretation.

Integrated Algorithmic Processes

AD, integrated BPS, result visualization, and MOO algorithms, all comprise algorithmic processes applied in this methodology. However, the used CFD tool is still not fully integrated. This results in time-consuming airflow analyses for different parameters and presents itself as a barrier in further complementing design and planning exploration. Currently, with the integration of new and existing tools, their subsequent potential is being improved, not only regarding airflow, but also structural, thermal, and illuminance analyses. Furthermore, some simulations and algorithmic processes are still resource- and time-consuming. To address this issue, promising work is being developed in task parallelization, allowing to have several computers performing different simulations, or even optimizations, simultaneously.

Methodology

New developments in algorithmic processes such as AD, BPS, and MOO, request new methodologies to fit these changes. Mostly, these processes are heading towards unification, simplifying their interconnectivity. Further improvements in the methodology can be achieved with the application of different metrics, contexts, and the incorporation of architectural libraries for features and processes such as optimization algorithms and integrated simulations. This can lead to wider use by the scientific and professional community, allowing the application of such methodologies not only in informal housing but also in other contexts.

Results Accuracy and Visualization

Further work is being done in results visualization, particularly in integrating game engines and virtual reality visualization features. The use of such features can further improve the efficiency in results and project communication. Namely, it can prove efficient in the communication between the field and project team by sharing real-time data from either side, such as rehabilitation solutions, results, and map possible outliers in the building samples. Finally, there is a strong necessity to compare rehabilitation practical and theoretical data by implementing the guidelines developed throughout this thesis. This can be done through data-loggers in the field and can quantify the methodology results' accuracy and the actual improvements.

Bibliography

Advanced Buildings. 2020. "Daylighting Pattern Guide." Accessed July 30. http://patternguide.advancedbuildings.net/using-this-guide/analysis-methods/daylight-factor.

Aguiar, Rita, Carmo Cardoso, and António Leitão. 2017. "Algorithmic Design and Analysis Fusing Disciplines." *Disciplines and Disruption - Proceedings Catalog of the 37th Annual Conference of the Association for Computer Aided Design in Architecture, ACADIA 2017*, 28–37.

ANSI/ASHRAE Standard 55. 2017. "Thermal Environmental Conditions for Human Occupancy."

Araújo, Gonçalo. 2019. "Software Tools." In *Bioclimatic Architecture in Warm Climates: A Guide for Best Practices in Africa*, edited by Manuel Correia Guedes and Gustavo Cantuaria, 229–47. Springer Nature. doi:10.1007/978-3-030-12036-8_7.

Arimah, Ben C. 2001. "Slums as Expression of Social Exclusion: Explaining the Prevalence of Slums in African Countries." *United Nations Human Settlements Programme*, 1–33. http://www.oecd.org/dev/pgd/46837274.pdf.

Attia, Shady. 2018. "Modern History of Sustainable Architecture." In *Regenerative and Positive Impact Architecture: Learning From Case Studies*, 7–11. doi:10.1007/978-3-319-66718-8_1.

Baralas, C. 2013. "Cooling in Buildings." In *Passive Cooling of Buildings*, 1–12. doi:10.4324/9781315073668.

Belém, Catarina Garcia. 2019. "Optimization of Time-Consuming Objective Functions Derivative-Free Approaches and Their Application in Architecture Examination Committee." http://web.ist.utl.pt/antonio.menezes.leitao/ADA/documents/theses_docs/2019_OptimizationOfTime-ConsumingObjectiveFunctions.pdf.

Belém, Catarina, and António Leitão. 2018. "From Design to Optimized Design An Algorithmic-Based Approach." In *ECAADe 36*, 2:549–58.

Blazejczyk, Krzysztof, and Yoram Epstein. 2012. "Comparison of UTCI to Selected Thermal Indices," 515–35. doi:10.1007/s00484-011-0453-2.

Brown, Christopher Leslie, and Philip D. Morgan. 2006. *Arming Slaves: From Classical Times to the Modern Age*. *Arming Slaves: From Classical Times To The Modern Age*.

Cardoso, Carmo. 2017. "Performance-Based Design : From Form Making to Form Finding." Técnico Lisboa.

Cole, Raymond J., and Maria Jose Valdebenito. 2013. "The Importation of Building Environmental Certification Systems: International Usages of BREEAM and LEED." *Building Research and Information* 41 (6): 662–76. doi:10.1080/09613218.2013.802115.

Conselho Municipal de Maputo, and Direcção Municipal de Planeamento Urbano e Ambiente. 2018. *Manual de Procedimentos: Metodologia de Regularização de DUAT'S*. Maputo: World Bank.

Consulting, B. M. 2005. "Ahmadinezhad (Translator),'Wind Towers.'" In *Proceeding of Passive and Low Energy Cooling in Buildings Conference, Greece*, 23–29.

Correia Guedes, Manuel. 2017. *Arquitectura Sustentável Em São Tomé e Príncipe*. IST Press.

Costa, Vanessa Aparecida Caieiro da, Victor Figueiredo Roriz, Karin Maria Soares Chvatal, Vanessa Aparecida Caieiro da Costa, Victor Figueiredo Roriz, and Karin Maria Soares Chvatal. 2017. "Modeling of Slab-on-Grade Heat Transfer in EnergyPlus Simulation Program." *Ambiente Construído* 17 (3). Associação Nacional de Tecnologia do Ambiente Construído - ANTAC: 117–35. doi:10.1590/s1678-86212017000300166.

Dear, Richard de, and G. S. Brager. 1998. "Developing an Adaptive Model of Thermal Comfort and Preference." *ASHRAE*

Transactions 104.

Deb, Kalyanmoy, Amrit Pratap, Sameer Agarwal, and T. Meyarivan. 2002. "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II." *IEEE Transactions on Evolutionary Computation* 6 (2): 182–97. doi:10.1109/4235.996017.

Deviren, A, and P J Tabb. 2014. *The Greening of Architecture: A Critical History and Survey of Contemporary Sustainable Architecture and Urban Design*. Ashgate Publishing ltd.

El-Shorbagy, Abdel-moniem. 2010. "Design with Nature : Windcatcher as a Paradigm of Natural Ventilation Device in Buildings." *International Journal of Civil & Environmental Engineering*, no. 03: 21–26. http://www.ijens.org/105403-6868 ijcee-ijens.pdf.

Eltaweel, Ahmad, and Yuehong Su. 2017. "Parametric Design and Daylighting : A Literature Review" 73 (October 2016): 1086–1103. doi:10.1016/j.rser.2017.02.011.

Fanger, Povl Ole. 1970. *Thermal Comfort: Analysis and Applications in Environmental Engineering*. Mcgraw-Hill.

Frazer, John. 1995. "An Evolutionary Architecture."

Haines, Andy, Nigel Bruce, Sandy Cairncross, Michael Davies, Katie Greenland, Alexandra Hiscox, Steve Lindsay, Tom Lindsay, David Satterthwaite, and Paul Wilkinson. 2013. "Promoting Health and Advancing Development through Improved Housing in Low-Income Settings." *Journal of Urban Health* 90 (5): 810–31. doi:10.1007/s11524-012-9773-8.

Henriques, Cristina Delgado, and Jorge T Ribeiro. 2005. "HABITAT TYPOLOGY IN THE AFRICAN CITY – CONTRIBUTION FOR THE CHARACTERIZATION OF THE RESIDENTIAL LAND USE IN MAPUTO USING Contribution for the Characterization of the Residential Land Use in Maputo Using," no. April.

"History of Air Conditioning." 2020. Accessed July 28. https://www.energy.gov/articles/history-air-conditioning.

Isyumov, N., and A. G. Davenport. 1975. "The Ground Level Wind Environment in Built-up Areas." In *Proceedings of the 4th International Conference on Wind Effects on Buildings and Structures*, 403–22. Heathrow 1975.

Janssen, Patrick. 2006. "A Generative Evolutionary Design Method." *Digital Creativity* 17 (1): 49–63. doi:10.1080/14626260600665736.

Janssen, Patrick, and Rudi Stouffs. 2015. "Types of Parametric Modelling." *CAADRIA 2015 - 20th International Conference on Computer-Aided Architectural Design Research in Asia: Emerging Experiences in the Past, Present and Future of Digital Architecture*, no. August: 157–66.

Janssen, W. D., B. Blocken, and T. van Hooff. 2013. "Pedestrian Wind Comfort around Buildings: Comparison of Wind Comfort Criteria Based on Whole-Flow Field Data for a Complex Case Study." *Building and Environment* 59. Elsevier Ltd: 547–62. doi:10.1016/j.buildenv.2012.10.012.

Khazaii, Javad. 2016. *Advanced Decision Making for HVAC Engineers: Creating Energy Efficient Smart Buildings*. *Advanced Decision Making for HVAC Engineers: Creating Energy Efficient Smart Buildings*. doi:10.1007/978-3-319-33328-1.

Kiranyaz, Serkan. 2014. "Particle Swarm Optimization." *Adaptation, Learning, and Optimization* 15: 45–82. doi:10.1007/978-3-642-37846-1_3.

Kolarevic, Branco. 2001. "Designing and Manufacturing Architecture in the Digital Age." *19th ECAADe Conference Proceedings*, no. Architectural Information Management: 117–23. doi:10.1260/147807703771799210.

Kolarevic, Branko. 2004. "Back to the Future?" *International Journal of Architectural Computing* 2 (1): 43–50. doi:https://doi.org/10.1260/1478077041220205.

Krotz, Dan. 2007. "Molecular Foundry Receives LEED Gold Certification." https://www2.lbl.gov/Science-

Articles/Archive/MSD-Foundry-rating.html.

Lawson, T. V. 1978. “The Wind Content of the Built Environment.” *Journal of Wind Engineering and Industrial Aerodynamics* 3 (2–3): 93–105.

Levitt, Brendon, M Ubbelohde, George Loisos, and Nathan Brown. 2013. “Thermal Autonomy as Metric and Design Process.” *CaGBC National Conference and Expo: Pushing the Boundary–Net Positive Buildings*, 47–58.

Lizancos, Placido, Dolores Otero-chans, Luis Lage, and Henry Vicente. 2014a. *Inhabited Processes Architectures Where the Other 90 % Lives*.

———. 2014b. *Inhabited Processes Architectures Where the Other 90 % Lives . Procesos Habitados Las Arquitecturas En Las Que Vive El Otro 90 %. Procesos Habitados As Arquitecturas Nas Que Vive o Ou ... Procesos Habitados As Arquitecturas Nas Que Vive o Outro 90 %. Proc*.

Mahesh, Kumar, Perumal Nallagownden, and Irraivan Elamvazuthi. 2016. “Advanced Pareto Front Non-Dominated Sorting Multi-Objective Particle Swarm Optimization for Optimal Placement and Sizing of Distributed Generation.” *Energies* 9 (12): 982. doi:10.3390/en9120982.

Martinho, Helena. 2019. “Adaptive Façades An Integrated Algorithmic Approach.” Técnico Lisboa.

Martinho, Helena, Gonçalo Araújo, and António Leitão. 2020. “From Macro to Micro - An Integrated Algorithmic Approach towards Sustainable Cities.” In *Computer-Aided Architectural Design Research (CAADRIA)*. doi:10.1109/MVT.2012.2190222.

Martinho, Helena, Catarina Belém, António Leitão, Roel Loonen, and M Glória Gomes. 2019. “ALGORITHMIC DESIGN AND PERFORMANCE ANALYSIS OF ADAPTIVE FAÇADES.” In *Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019*, 1:685–94.

Melbourne, W. H. 1978. “Criteria for Environmental Wind Conditions.” *Journal of Wind Engineering and Industrial Aerodynamics* 3 (2–3): 241–49. doi:https://doi.org/10.1016/0167-6105(78)90013-2.

Mottelson, Johan. 2019. *Interpositions - Architectural Interventions in Mafalala, Mozambique*. The Royal Danish Academy of Fine Arts.

Moya, Rafael, Daniel Prohasky, Simon Watkins, Yan Ding, and Jane Burry. 2014. “Aerodynamic Strategy Applied in an Urban Shelter Design Simulation and Analysis of Aerodynamic Phenomena in an Urban Context.” In *ECAADe 32*, 1:137–44.

Mylonas, George E. 1940. “The Olynthian House of the Classical Period.” *The Classical Journal* 35 (7). The Classical Association of the Middle West and South: 389–402. http://www.jstor.org/stable/3291258.

Nabil, A, and J Mardaljevic. 2005. “Useful Daylight Illuminance : A New Paradigm for Assessing Daylight in Buildings.” *Lighting Research & Technology* 37 (1): 41–59. doi:https://doi.org/10.1191/1365782805li128oa.

Nebro, A. J., J. J. Durillo, García Nieto, C. A.Coello Coello, F. Luna, and E. Alba. 2009. “SMPSO: A New Pso-Based Metaheuristic for Multi-Objective Optimization.” *2009 IEEE Symposium on Computational Intelligence in Multi-Criteria Decision-Making, MCDM 2009 - Proceedings*, no. 2: 66–73. doi:10.1109/MCDM.2009.4938830.

NEN. 2006. “Wind Comfort and Wind Danger in the Built Environment.”

Nguyen, Anh-tuan, Sigrid Reiter, and Philippe Rigo. 2014. “A Review on Simulation-Based Optimization Methods Applied to Building Performance Analysis.” *APPLIED ENERGY* 113. Elsevier Ltd: 1043–58. doi:10.1016/j.apenergy.2013.08.061.

Nicol, J. F., and M. A. Humphreys. 2002. “Adaptive Thermal Comfort and Sustainable Thermal Standards for Buildings.” *Energy and Buildings* 34 (6): 563–72. doi:10.1016/S0378-7788(02)00006-3.

Olgyay, Victor. 2015. *Design With Climate: Bioclimatic Approach to Architectural Regionalism - New and Expanded Edition*. Princeton University Press.

Pavlov, Yu L. 2019. "Random Forests." *Machine LEarning* 45 (1): 1–122. doi:10.1201/9780367816377-11.

Pereira, Inês, Catarina Belém, and António Leitão. 2019. "Optimizing Exhibition Spaces: A Multi-Objective Approach." In *Proceedings of the ECAADe 37 / SIGraDI 23*, 3:53–62.

———. 2020. "Escaping Evolution." In *Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020*, 1:295–304.

Pereira, Inês, and António Leitão. 2020. "The Cost of Daylight A Parallelized Approach to Multi-Objective Optimization." In *Passive and Low Energy Architecture 2020: Planning Post Carbon Cities*. A Coruna.

Pirhayati, Mehdi, Shahrzad Ainechi, Milad Torkjazi, and Elnaz Ashrafi. 2013. "Ancient Iran, the Origin Land of Wind Catcher in the World." *Research Journal of Environmental and Earth Sciences* 5 (8): 433–39. doi:10.19026/rjees.5.5671.

Reinhart, Christoph F, John Mardaljevic, and Zack Rogers. 2006. "Dynamic Daylight Performance Metrics for Sustainable Building Design." *The Journal of the Illuminating Engineering Society of North America Sustainable Building Design Sustainable Building Design* 3 (1): 7–31. doi:10.1582/LEUKOS.2006.03.01.001.

Reinhart, Christoph F, and Oliver Walkenhorst. 2001. "Validation of Dynamic RADIANCE-Based Daylight Simulations for a Test of ® Ce with External Blinds." *Energy and Buildings* 33 (7): 683–97.

Roaf, Sue. 1982. *Wind Catchers, Living with the Desert*. Airs & Phillips, London (1982).

———. 2018. "Thermal Landscaping of Buildings: Climate-Proofing Design." In *Activism in Architecture: The Bright Dreams of Passive Energy Design*, 145–74. Taylor and Francis Ltd.

Robinson, David Moore, and James Walter Graham. 1938. *The Hellenic House: A Study of the Houses Found at Olynthus with a Detailed Account of Those Excavated in 1931 and 1934*. Johns Hopkins Press.

Sammer, Maria João, and António Leitão. 2020. "Visual Input Mechanisms in Textual Programming for Architecture." In *ECAADe 37 /SIGraDi 23*, 3:7–16. doi:10.5151/proceedings-ecaadesigradi2019_216.

Samuelson, Holly, Sebastian Claussnitzer, Apoorv Goyal, Yujiao Chen, and Alejandra Romo-Castillo. 2016. "Parametric Energy Simulation in Early Design: High-Rise Residential Buildings in Urban Contexts." *Building and Environment* 101: 19–31. doi:10.1016/j.buildenv.2016.02.018.

Santamouris, M, and D. Asimakopoulos. 2013. "Preface." In *Passive Cooling of Buildings*, IX. doi:10.4324/9781315073668.

Schumacher, Patrik. 2011. *The Autopoiesis of Architecture Vol.1: A New Framework for Architecture*. John Wiley & Sons.

Schumacher, Patrik. 2008. "Parametricism as Style - Parametricist Manifesto." https://patrikschumacher.com/Texts/Parametricism as Style.htm.

Shaviv, Edna. 2008. "Passive and Low Energy Architecture (PLEA) VS Green Architecture (LEED)." In *PLEA 2008 - Towards Zero Energy Building: 25th PLEA International Conference on Passive and Low Energy Architecture, Conference Proceedings*.

———. 2018. "Why PLEA Buildings Didn ' t Glow with Green Architecture ? Can It Be Changed ? Are Green Buildings Designed as Passive and Low." In *Keynote Speach of the 34th Passive and Low Energy Architecture (PLEA)*.

Sheldon, Kathleen Eddy, and Jeanne Marie Penvenne. 2015. "Mozambique." *Encyclopedia Britannica*. https://www.britannica.com/place/Mozambique.

Stamp, Jimmy. 2008. “Greener Than Thou: Fed Building Too Green For LEED.” https://sf.curbed.com/2008/2/12/10578008/greener-than-thou-fed-building-too-green-for-leed.

Taleb, Hanan, and Mousa A. Musleh. 2015. “Applying Urban Parametric Design Optimisation Processes to a Hot Climate: Case Study of the UAE.” *Sustainable Cities and Society* 14 (February). Elsevier: 236–53. doi:10.1016/J.SCS.2014.09.001.

Terzidis, Kostas. 2002. “The Nature of Computation Algorithmic Design: A Paradigm Shift in Architecture?,” 201–7. http://www.bol.ucla.edu/~kostas/.

———. 2006. *Algorithmic Architecture*. Routledge.

Toth, Bianca, Flora Salim, Robin Drogemuller, John Frazer, and Jane Burry. 2011. “CLOSING THE LOOP OF DESIGN AND ANALYSIS Parametric Modelling Tools for Early Decision Support.” In *Proceedings of the 16th International Conference on Computer-Aided Architectural Design Research in Asia(CAADRIA)*, 525–34.

Touloupaki, Eleftheria, and Theodoros Theodosiou. 2017. “Performance Simulation Integrated in Parametric 3D Modeling as a Method for Early Stage Design.” *Energies* 10 (5): 637. doi:10.3390/en10050637.

UN Committee for Development Policy. 2019. “List of Least Developed Countries (as of December 2018).” *United Nations Committee for Development Policy*. https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/publication/ldc_list.pdf.

United Nations. 2019. “United Nations Sustainable Development Action 2015.” https://www.un.org/sustainabledevelopment/cities.

“US Green Building Council.” 2020. Accessed July 29. https://www.usgbc.org.

Waibel, Christoph, Thomas Wortmann, Ralph Evins, and Jan Carmeliet. 2019. “Building Energy Optimization: An Extensive Benchmark of Global Search Algorithms.” *Energy and Buildings* 187. Elsevier B.V.: 218–40. doi:10.1016/j.enbuild.2019.01.048.

Waldram, P. J. 1925. “The Natural and Artificial Lighting of Buildings.” *The Journal of the Royal Institute of British Architects* 32 (13): 9.

While, Lyndon, Phil Hingston, Luigi Barone, and Simon Huband. 2006. “A Faster Algorithm for Calculating Hypervolume.” *IEEE Transactions on Evolutionary Computation* 10 (1): 29–38. doi:10.1109/TEVC.2005.851275.

Winter, Magnus. 2013. “Benchmark and Validation of Open Source CFD Codes, with Focus on Compressible and Rotating Capabilities.” doi:10.1007/BF03192151.

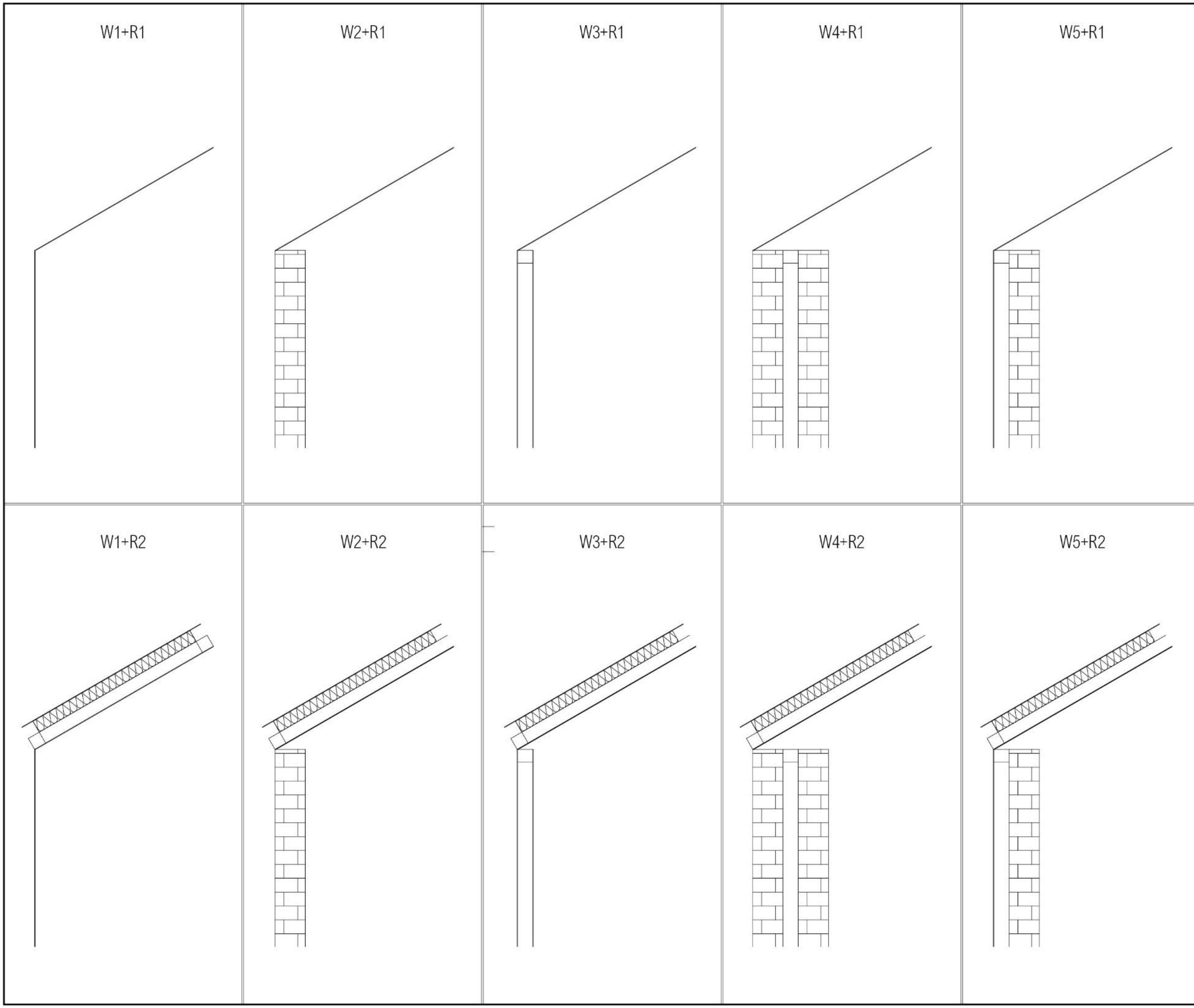
Wolpert, D. H., and W. G. Macready. 1997. “No Free Lunch Theorems for Optimization.” *IEEE Transactions on Evolutionary Computation* 1 (1): 67–82. doi:10.1109/4235.585893.

World Bank. 2017. “Disaster-Related New Displacements by Hazard Category. Internal Displacement Monitoring Centre.” https://www.internal-displacement.org/database/displacement-data/.

Wortmann, Thomas. 2017. “Opossum.” In *CAADRIA 2017 - 22nd International Conference on Computer-Aided Architectural Design Research in Asia: Protocols, Flows and Glitches*, 283–92. doi:10.2307/j.ctv4g1rch.43.

Wortmann, Thomas, Alberto Costa, Giacomo Nannicini, and Thomas Schroepfer. 2015. “Advantages of Surrogate Models for Architectural Design Optimization.” *Arti�cial Intelligence for Engineering Design , Analysis and and Manufacturing* 29 (4): 471–81. doi:10.1017/S0890060415000451.

Yu, Wei, Baizhan Li, Hongyuan Jia, Ming Zhang, and Di Wang. 2015. “Application of Multi-Objective Genetic Algorithm to Optimize Energy Efficiency and Thermal Comfort in Building Design.” *Energy and Buildings* 88. Elsevier B.V.: 135–43. doi:10.1016/j.enbuild.2014.11.063.



Construction solutions tested in Chamanculo C

Walls

Scenario	Layer	Material
W1	1	Zinc
W2	1	Cement brick
W3	1	Zinc
	2	Air gap
	3	Zinc
W4	1	Cement brick
	2	Air gap
	3	Cement brick
W5	1	Zinc
	2	Air gap
	3	Cement brick

Roof

Scenario	Layer	Material
R1	1	Zinc
R2	1	Zinc
	2	XPS
	3	Air gap
	4	Zinc