Integrating algorithmic processes in informal urban and architectural planning

A case study of a Maputo's neighborhood

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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 into the analysis 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 conflicting nature between different design objectives, and the architect's role in the tackled design problems.
KEYWORDS: Informal Housing, Sustainable Development, Algorithmic Design, Software & Simulations, Optimization

1. INTRODUCTION

As urban development is steadily increasing, 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 [1]. This suggests an urbanization growth in many underdeveloped countries, highlighting the concern over the way informal housing and settlements fit in the economic, health, and climatic goals of these countries [2]. Most of this expansion has had no effective planning and, therefore, populations are living in slums that often show poor living conditions, with no clean water, insufficient infrastructures, and poor construction quality [3]. The research here presented proposes strategies to address the urban transition of rural and underdeveloped communities, bridging a less explored frontier of architectural and urban design, towards the era of post-carbon cities.

An example of enabling strategies in slums is the case of Mozambique, which approved a regulation and the corresponding manual of procedures regarding *land use and appropriation rights*: DUAT *(Direito ao uso e aproveitamento de Terra)* [4]. The country is currently applying this housing regulation strategy with the two specific goals of having instruments for adequate soil management and neighborhood improvement. The manual of procedures describes 11 stages towards correct land management and is being applied in a case-study known as the HABITAT Project, located in Maputo's neighborhood of Chamanculo C. Some of the stages of the manual of procedures are related to street regulation and assessment of land parcels to each owner. However, throughout the manual, no consideration is given to architectural decisions and housing rehabilitation. Nevertheless, it is appropriate to improve users' thermal comfort by including passive design and sustainable modular rehabilitation processes that follow the urban program applied in each land parcel [5, 6].

Passive design, along with similar approaches, can be modeled and analyzed on a larger scale through Algorithmic Design (AD) and Building Performance Simulation (BPS). AD facilitates the creation of shapes through mathematical and logical concepts represented in algorithms [7, 8], while BPS helps to predict building performance when there is no possibility to test it empirically.

AD and BPS tools can be combined to provide valuable insights in every design stage, by focusing on multiple building performance goals [9]. This research's literature review documents the development of passive design strategies throughout history [10], and the paradigm shift of sustainable architecture in the last century. Green building certifications are highlighted, demonstrating an existing paradox between contemporary sustainability contexts in the built environment and design for a comfortable occupant condition [11]. Subsequently, useful comfort metrics to assess building performance in a passive system are documented and researched [12-17].

Integrated algorithmic processes are documented and discussed regarding their applicability in the architectural field. AD is reviewed through its history and motives [7, 8, 18, 19], related BPS methodologies are described, and optimization processes are listed and assessed [17, 20–22].

This research explores the combination potential of AD and BPS in improving urban expansion. This is achieved by implementing algorithmic approaches while establishing a preliminary study of informal housing typologies and urban expansion trends in the area. Moreover, design metrics and rehabilitation scenarios were tested regarding the impact they have on indoor comfort, through an analysis of the design parameters.

To address the limitations pointed out by previous research [9, 23, 24] regarding parameter exclusion, time spent setting up the simulation environment, and lack of harmony between processes, we will use an AD tool that integrates CAD, BIM, analysis, and optimization tools, allowing a seamless flow between design and analysis [25].

2. WORKFLOW

We propose a three-phased workflow to structure data gathering and algorithmic processes, towards neighborhood rehabilitation (*F*1). The first phase comprises the definition of the case study's urban fabric and its respective building typology.

Phase two includes model generation and performance simulations. By algorithmically modeling the studied urban fabric from OpenStreetMap (OSM) data, it is possible to measure the impact of different factors on people's comfort, namely (**a**) material scenarios, (**b**) design dimensions (height, area), and (**c**) glazing ratios. The latter is easily applied in the field and regulated for future constructions, while the former two are suitable for modular rehabilitation processes.

Finally, phase three will employ the obtained results to yield guidelines for urban rehabilitation and architectural design regarding thermal, illuminance, and airflow comfort for the specified urban area.

2.1 Case study – Chamanculo C

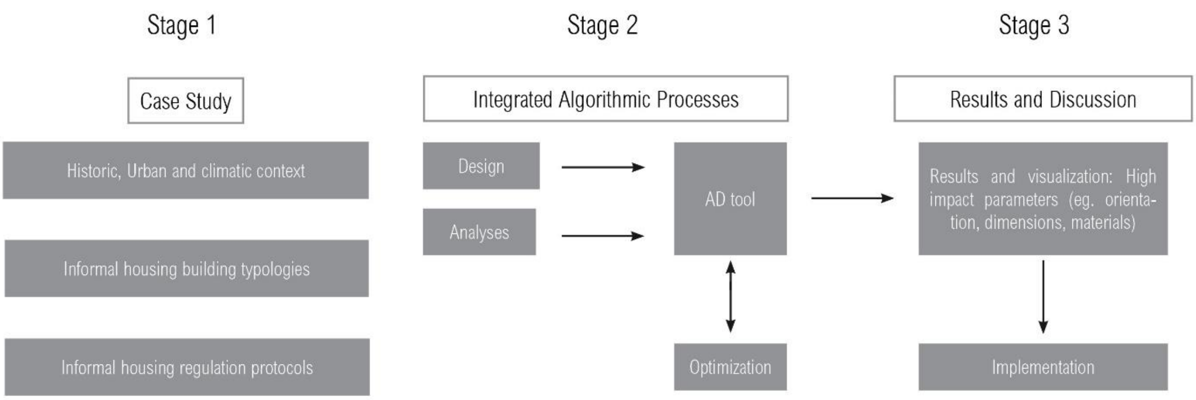
Chamanculo C is a neighborhood in the city of Maputo, district of Nhlamankulu, characterized as an old suburb type A. These are mainly described as basic infrastructures composed of zinc cladding and/or cement bricks, densely distributed in non-delimited areas, and showing high population density with very narrow public spaces [26]. To represent the urban fabric, we used OSM data to 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 the identification of critical areas for rehabilitation, mitigating construction, and rehabilitation costs (*F2*).

*F*2 – Chamanculo C satellite image and model.

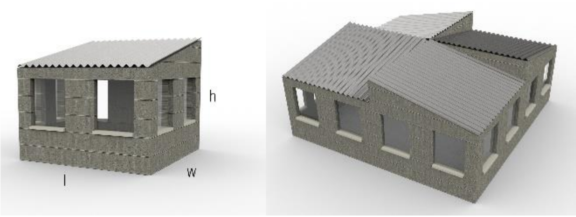
One of the most common self-made houses seen in the area is the "Ventoinha" (fan) house. Landowners add units incrementally according to the family's needs and financial availability. These units usually have the same dimensions and are rotated so that the roof angles create a fan-like shape, hence the house's name. Most of these houses comprise rooms with areas ranging from 9 to 12 m^2 with exterior washrooms [27].

2.2 Algorithmic design description and parameters

When planning incremental informal housing in developing nations that face housing-provision challenges, it is useful to design these building typologies parametrically. To this end, we started from one cuboid unit with variable length (*l*), width (*w*), and height (*h*), and a triangular prism with the same length and width, but with relative height depending on the roof angle. To form a complete house, this starting unit is rotated four times around the unit's corner, at the center corner of the house (*F3*).

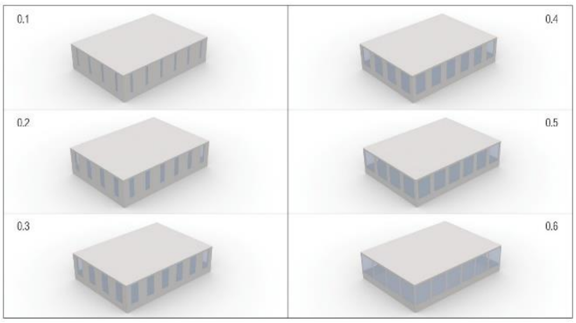


*F*1 – Proposed workflow.

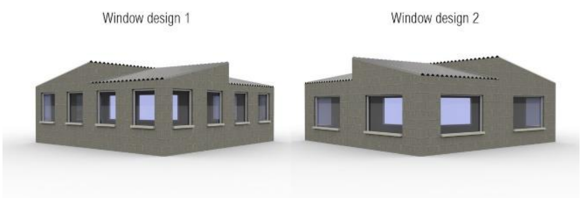


*F*3 – “Ventoinha” house and parameters.

For the illuminance study at an urban and architectural scale, an analysis plane intersecting each building was created. Analysis test points were created in this plane for every 5x5m square composing the floor area, at a 1.5m height. The performed analysis encompassed a grid-based simulation, with a climate-based sky for one day, with a 4-hour time-step ranging from 6 to 18 h. Glazing ratios from 0.1 to 0.6 were tested (*F4*) at an urban and architectural scale, however, in the latter, the surface area, and two types of window design are also analyzed and compared with the glazing ratio and the building’s respective Useful Daylight Illuminance (UDI) (*F5*). These parameters can help determine if there is a suitable window design for each building according to its context and define thresholds for the building's glazing ratio in the case of rehabilitation. However, this analysis focuses only on Illuminance comfort and does not consider the thermal impacts of the assigned glazing.



*F*4 – Sample in Chamanculo with assigned glazing ratios.



*F*5 – “Ventoinha” house window design 1 and 2. (south-western perspective view)

In the airflow analysis, besides the urban area model, the “Ventoinha” house was tested with glazing ratios from 0.1 to 0.4 for its wind speed and airflow. Two windows were opened in the northern and southern façade, working as outlets and inlets, respectively. The results were compared and discussed according to the values of wind speed and air circulation in the area, which were 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 natural ventilation can be tested in this way. However, its application would be time-consuming unless multiple computing resources were available. Thus, the ventilation scheme used in the house comprises only two opened windows in the windward and leeward walls, and all roof windows opened, except for the windward one (*F6*).

*F*6 – Cross Ventilation Scheme with added roof windows in a 0.3 glazing ratio house (south-eastern perspective view).

2.3 Simulations, inputs, and outputs

Considering the described building and urban typology, five scenarios for wall construction materials, and two scenarios for roof solutions were tested (Table 1). For analysis purposes, the non-existing interior walls were simulated using air wall material to ensure that the air circulates between thermal zones. A window-to-wall ratio of 0.1 was used in each façade, and a height of 3 meters was set.

Table 1 – Construction scenarios to be tested in the neighborhood. Numbered layers go from the innermost to the outermost coating.

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	Air gap
	3	XPS
	4	Zinc

The heat flow between the ground and the 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 the used tool to simulate thermal comfort, even though most houses are built directly above the soil, it is advisable to use a slab-on-grade floor type [28].

The material properties were obtained from EnergyPlus' library for wall-air resistance. However, cement bricks and extruded polystyrene (XPS) show differences in their properties according to the manufacturing processes and their type. In this case, material thermal properties were retrieved from tables for common construction materials[i] (Table 2) except for their cost, which was an estimate of the local markets.

Simulation outputs include an adaptive chart indicating indoor and outdoor temperature distribution for the respective analysis period, and the percentage of time in which each house is in the comfort zone of the ASHRAE adaptive chart, a metric known as Thermal Autonomy (*TA*) [29]. This analysis was made for the summer period, from 10 am to 8 pm, as it comprises the warmest hours of the year. Furthermore, results were compared with the worst-performing scenario (W1+R1 - zinc cladding), to quantify and visualize the impact of each upgrade and evaluate the suitability of each scenario for each building.

Table 2 – Materials thermal properties

	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

After the material analysis, we investigated the impact of design parameters on TA. To this end, we implemented an iterative simulation with different values for the height and surface area. This quantifies the TA variation towards the establishment of design thresholds to regulate informal construction.

To complete the building performance simulations, the outdoor airflow is tested and discussed, and critical areas are mapped according to its wind speed and to the identified climatic context, while indoor airflow is discussed for the defined parameters.

These analyses aim to highlight the impact of using different passive design strategies, and local materials in non-conditioned environments towards rehabilitation and to correctly design a building according to illuminance and thermal comfort thresholds.

2.4 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 [17, 18]. 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 and minimum cost. However, given the extensive amount of computational resources and time required by each simulation [30], only one optimization process was applied in this research.

The urban area thermal comfort and their buildings' respective construction solutions were chosen to have a MOO process applied. Three objective functions were developed to optimize the thermal comfort in the studied urban area. This was done by shifting the parameters of construction solutions, defined in the case study, to minimize the rehabilitation 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 (σ) of TA between buildings, which guarantees fairness and equality of comfort among the building sample.

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

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

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

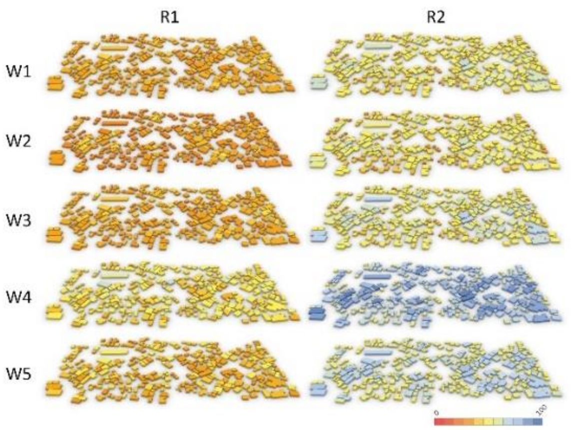
Within the AD tool, several optimization algorithms from vast open source libraries can be used with a complementary tool that is easily integrated into the AD geometric description [31]. In this thesis, the metaheuristic algorithm NSGAII [32] was tested and then used as a solver for the Random Forest Regressor model-based algorithm [33]. The solution samples 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. RESULTS 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, illuminance, and wind comfort. AD was integrated with BPS and optimization tools to perform several evaluations and thus quantify the impact of location, positioning, glazing ratio, material properties, and floor area in the design and planning of such building typologies. Considering the proposed workflow, the research outline and discussion are separated into two sub-sections: (1) Urban area rehabilitation and planning; (2) Architectural Planning.

3.1 Urban model analysis

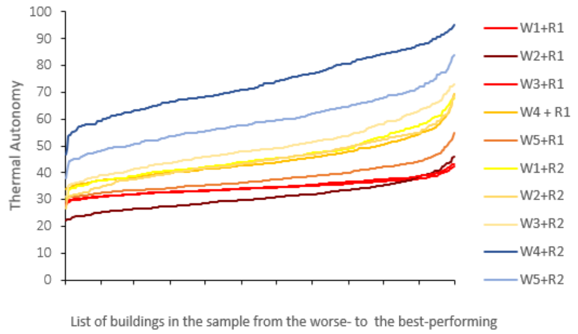
The results illustrated in *F7* show that walls W1, W2, and W3 have similar performance, and W4 and W5 have better performance. The same wall scenarios with roof R2 show greater improvements in every construction. Consequently, regardless of the wall construction, a roof upgrade emerges as the most viable option of slum upgrade. Moreover, houses in different areas of the neighborhood vary their TA according to both their surface area and their context and surroundings. Thus, it is possible to define different rehabilitation plans for neighborhood areas that require more urgent upgrades.



F7 - Thermal Autonomy per building in Chamanculo C for each construction scenario.

Regarding the overall comfort spectrum (*F8*), the best-performing scenario is W4+R2, a double pane of cement brick with a wall air gap and a roof composed of double zinc cladding with air space and 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 added advantage of being a better rehabilitation solution due to its adaptability to the identified building typologies in the area.

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



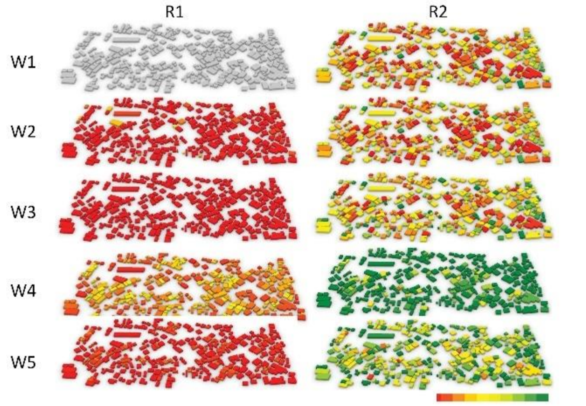
F8 - Line chart illustrating the range of comfort in the urban area for buildings with each construction scenario.

These improvements can be quantified by TA variation between buildings with scenario W1 and all the others with and without roof improvement. Table 3 shows the TA variation of each house with all the scenarios compared to the original one. Results show that some houses worsen their thermal comfort up to -40% but, on average, the variation ranges from -10% up to 114%, with a maximum increase in thermal performance reaching 218%. While scenarios W4 and W5 show the biggest improvements, some buildings show a neutral or negative impact from these and other upgrades, either because of sun exposure, building density, or surface area, which motivates a spatially contextualized analysis.

Table 3 –Thermal Autonomy variation in each building when upgraded from scenario 1.

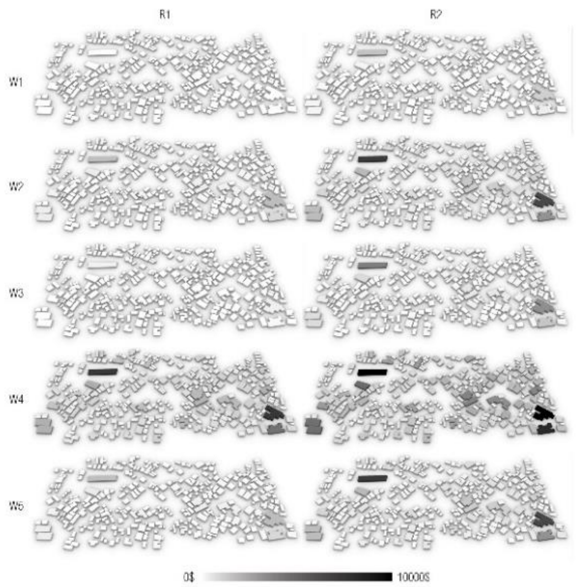
	AVG	MAX	MIN
W2+R1	-10%	52%	-41%
W3+R1	1%	4%	-5%
W4+R1	29%	70%	9%
W5+R1	9%	34%	-1%
W1+R2	34%	105%	-26%
W2+R2	31%	101%	-26%
W3+R2	45%	120%	-24%
W4+R2	114%	218%	21%
W5+R2	73%	156%	0%

F9 shows the results of the TA variation on a scale from 0% or below (in red) to 100% and above (in green). The performance of the wall scenarios is highly sensitive to roof constructions, which act as catalysts for comfort improvement. This is illustrated by scenarios W4 and W5, which provide 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. The wide range of viable design solutions and their corresponding impact factors can be difficult and time-consuming to analyze and control, highlighting the need for optimization regarding the cost and TA improvements of the whole urban model.



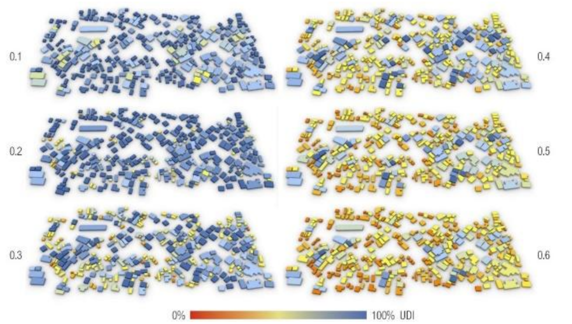
*F*9 – Heatmap illustrating the percentage of thermal autonomy improvements compared with the original scenario (Top left corner).

If the levels of TA improvement for each scenario are compared with their respective cost per building (*F*10), it is possible to grasp that the original with only a roof upgrade would cost as much as rehabilitating with any better wall scenario, while yielding similar and, in some cases, even better results. Additionally, this comparison reflects the conflicting nature of TA and costs. However, with the integration of these optimization processes, it might be possible to determine a good solution, with lower costs, by applying higher cost materials only in critical buildings according to the comfort results.

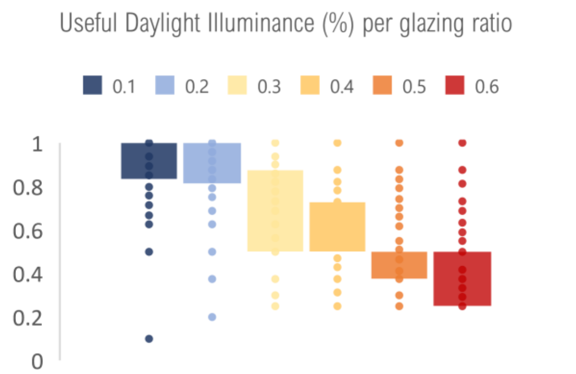


*F*10 - Heatmaps of the cost per building for each construction solution.

For the illuminance analysis, results from the urban area analysis are illustrated in a heatmap of each building's UDI (*F*11) and show lower values of glazing ratio having better results. Additionally, areas that might be able to support higher glazing ratios are easily visible in the heatmap and allow to determine thresholds for each building or cluster of buildings. By looking at the box plot illustrated in *F*12, the distribution of buildings and their respective UDI can be seen. Thus, glazing ratios show most buildings having values between 80% and 90% for both 0.1 and 0.2; 50% and 85% for 0.3, 50% and 70% for 0.4, 40% and 50% for 0.5 and 20% and 50% for 0.6. Given these results, it is advisable that, independently of the window and building design, but dependent on the location and positioning, the glazing to wall ratio should be between 0.1 and 0.3. 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 the 334 buildings. This creates a very large number of 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.



*F*11 - UDI heatmaps of each building for selected glazing ratios.

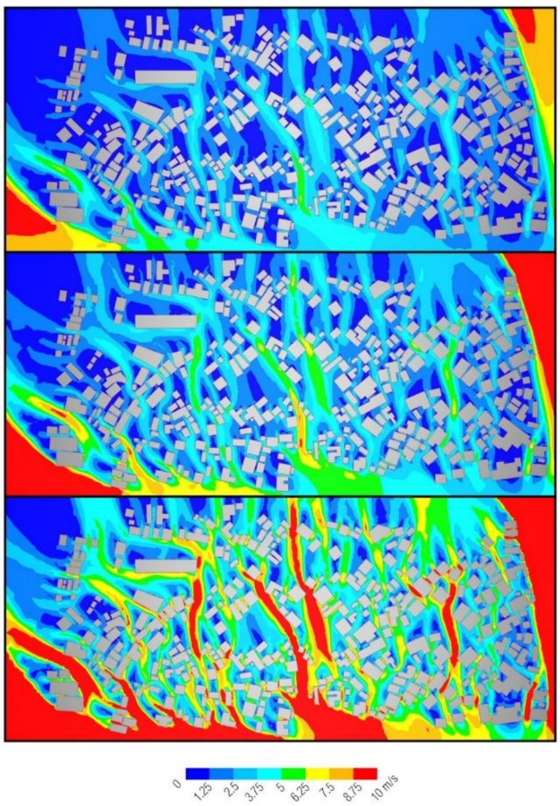


*F*12 - Box plot of UDI distribution for each building in the urban model, for selected glazing ratios.

To map critical areas in the neighborhood regarding airflow and windspeed, Lawson's Wind comfort criteria [34] was chosen to identify areas that are comfortable based on the velocity magnitude in the area, for certain activities, and the Isyumov and Davenport's criteria [35] to assess which areas are uncomfortable. This is then applied in the urban model of Chamanculo C.

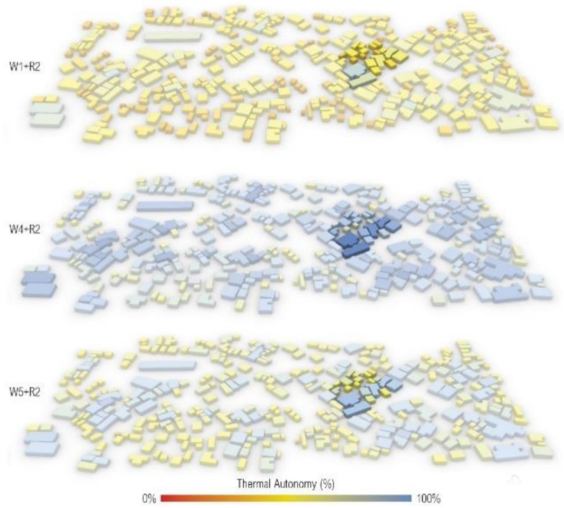
Through the climatic context, it is possible to determine two main wind directions (South and East), and their wind speed frequency. In this case, during the year, Maputo had winds up to 19 m/s, and for roughly 60% of the year, the wind did not exceed 7.5 m/s. Three wind tunnel tests were made in Chamanculo 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.

Results are illustrated according to the selected comfort criteria (*F*13) and show that a southern wind of 3.5 m/s creates some corridors of speeds up to 6.25 m/s, which is considered by 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.



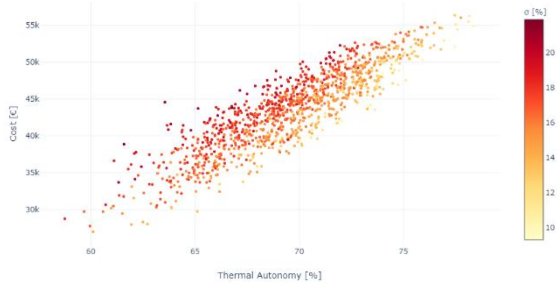
*F*13 - Wind speed magnitude heatmap for southern wind speeds of 3.5, 5, and 9 m/s (from top to bottom).

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, a sample of 20 houses from the Chamanculo C Urban area was chosen to be optimized 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) (*F*14). 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.



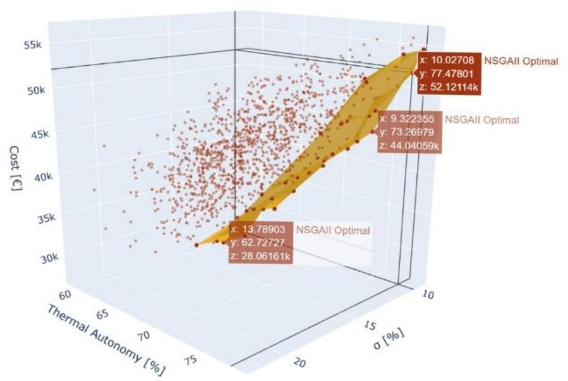
*F*14 – Thermal Autonomy per building in Chamanculo for the three selected construction solutions. The optimization sample is highlighted.

The solutions tested by the NSGAII [32] are illustrated in a heatmap of a scatter plot (*F*15), 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.



*F*15 – Heatmap scatter plot of all the tested solutions cost, thermal autonomy, and standard deviation.

The scatter-plot can also be visualized with three axes according to the three defined objectives, and through its Pareto front [36][37], a surface containing 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 (*F*16).



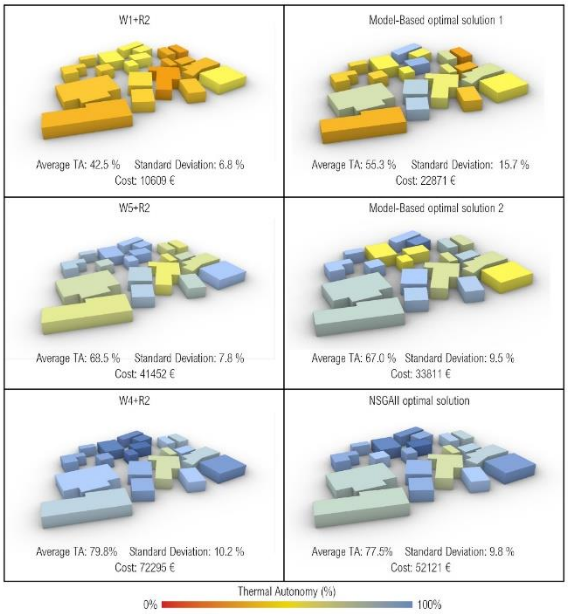
*F*16 - 3D scatter plot of all tested solutions results, and a 3D Surface generated from the respective Pareto front.

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 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 (*F*17).

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.

Considering the presented results, we can suggest three steps towards slum rehabilitation in this area:

- Identify critical buildings and areas.
- Apply MOO processes regarding lighting and thermal comfort in selected clusters
- Integrate open space regeneration plans in critical areas for high wind speeds.

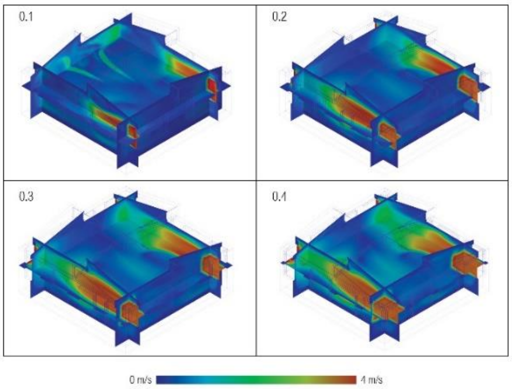


*F*17 - Comparison between cost, comfort, and deviation of the 20 buildings with each selected construction, and the optimal combinations of constructions found by the optimization process.

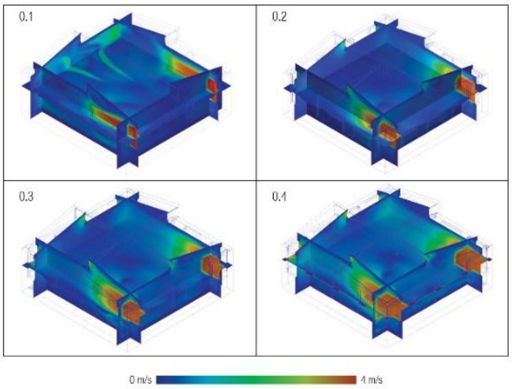
3.2 Housing typology

These analyses focused on one of the most famous houses seen in the area, the "Ventoinha" house design. Parameters tested in these analyses include glazing ratio, surface area, material properties, and design variations for the illuminance and ventilation. These were analyzed and compared to understand how each parameter impacts 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 the wind speed (*F*18, *F*19). 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.



*F*18 - Wind speed inside “Ventoinha” house with 3.5 m/s south inlets for different glazing ratios, no roof windows.



*F*19 - Wind speed inside “Ventoinha” house with 3.5 m/s inlets for different glazing ratios, and roof windows as outlets.

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. However, the impact of the glazing ratio and floor area in a building’s UDI was the most relevant parameters in its impact (*F*200). This analysis allowed us to identify area thresholds 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% at 100 m^2. The same behavior is visible with glazing ratios of 0.2, 0.3, and 0.4, which have 100% UDI up to 36, 49, and 64 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 simulations for the “Ventoinha” house analyzed the impact of several design parameters in the building’s TA, particularly, height, surface area, glazing ratio, and materials. In this case, building height and surface area have demonstrated little impact with areas up to 16 m^2. However, further analyses comparing the influence of higher surface areas for different materials in the house’s thermal comfort revealed different area thresholds for the maximum comfort obtained by different constructions (*F*211). Additionally, different glazing ratios were tested with variable surface 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 surface 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 UDI and TA heatmaps of the glazing ratio per surface area, 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.

Useful Daylight Illuminance

Glazing Ratio \ Surface Area	9	16	25	36	49	64	81	100
0.1	1.00	1.00	0.80	0.67	0.53	0.50	0.38	0.39
0.2	1.00	1.00	1.00	1.00	0.84	0.75	0.69	0.64
0.3	1.00	1.00	1.00	1.00	0.98	0.92	0.80	0.70
0.4	1.00	1.00	1.00	1.00	1.00	0.97	0.89	0.84
0.5	0.56	0.81	0.92	1.00	1.00	1.00	0.99	0.91
0.6	0.56	0.75	0.84	0.89	0.92	0.94	0.95	0.96

*F*200 - Useful Daylight illuminance heatmap of ‘Ventoinha’ house with different areas and glazing ratios.

Thermal Autonomy

Glazing Ratio \ Surface Area	9	16	25	36	49	64	81	100
0.1	0.77	0.81	0.87	0.91	0.93	0.95	0.97	0.98
0.2	0.52	0.58	0.64	0.68	0.73	0.76	0.80	0.84
0.3	0.33	0.39	0.43	0.47	0.53	0.57	0.61	0.65
0.4	0.20	0.25	0.28	0.32	0.36	0.41	0.46	0.50
0.5	0.15	0.17	0.20	0.22	0.26	0.28	0.31	0.35
0.6	0.10	0.12	0.15	0.17	0.19	0.21	0.23	0.26

*F*211 - Thermal Autonomy heatmap of ‘Ventoinha’ house with different areas and glazing ratios.

4. CONCLUSIONS

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

Results are outlined in two sections regarding urban model analysis and housing typology. Both revealed that the impact of different construction solutions, glazing ratios, and surface area are co-dependent, and demonstrate the conflictive nature of the objectives studied. To solve this problem, an optimization process was successfully employed in the urban area rehabilitation that identified fair combinations of construction solutions in buildings that, in some cases, performed as well as the best-identified construction solution, but almost 30% cheaper.

Although weather data and other input sources may be a cause for model uncertainty, the integration of algorithmic processes in a 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.

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 us to test and identify an otherwise impossible number of combinations of material solutions for an urban area, revealing less costly and fairer combinations that achieve better comfort results.

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" [27]. These processes are usually associated with expensive, high-performant, and cutting-edge projects. However, the possibility of analyzing, improving, and preventing what-if scenarios that otherwise would take much more time to assess have great applicability in vernacular architecture. By integrating these processes in informal architectural and urban practices, it is possible to adapt design solutions to fit comfort and utility criteria, 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.

5. 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 using a series of representation methods that were considered adequate for their interpretation. Despite the methodology's 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.

AD, integrated BPS, result visualization, and MOO algorithms, all comprise algorithmic processes applied in this methodology. However, the used tool for airflow analysis is still not fully integrated. This results in time-consuming simulations for different parameters and presents itself as a barrier to 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 resources- and time-consuming. To address this issue, promising work is being developed in task parallelization, allowing several computers to perform different simulations, or even optimizations, simultaneously [30].

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 workflow 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.

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.

ACKNOWLEDGEMENTS

This work was supported by national funds through Fundação para a Ciência e a Tecnologia (FCT) with references UIDB/50021/2020, and PTDC/ART-DAQ/31061/2017.

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