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 development of algorithmic design and analysis strategies to compose 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 surface area are analyzed to establish design and comfort thresholds. 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.
KEYWORDS: Informal Housing, Sustainable Development, Algorithmic Design, Software & Simulations

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 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 fast 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: 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].

House upgrading programs comprise rehabilitation strategies that enhance building performance at reduced costs. An example is shown by Bonaccorso, Martins, and Carrilho da Graça [7]. The authors applied three bioclimatic strategies in a full-scale prototype model and validated their thermal impact during summer through real-time measurements and simulations. The model was updated with a solar chimney, radiant insulation, and albedo. Results show different levels of impact on indoor temperature by these strategies. While the use of albedo did not show significant changes, the solar chimney and radiant insulation solutions successfully improved indoor comfort.

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 fluid shapes through mathematical and logical concepts represented in algorithms [8], while BPS helps to predict building performance when there is no possibility to test it empirically.

AD and BPS tools can be combined into a method known as performance-based design, which guides the design by focusing on building performance for goals like comfort, energy consumption, and structural performance [9].

In this context, Taleb and Musleh [10] seek to develop an urban parametric design and optimize design solutions dependent on environmental factors like wind speed, solar radiation, and energy consumption. The case study in UAE, composed of several simple houses, is optimized regarding height and volume, providing independent optimal solutions for each simulation. Results show improvements of 8% in cooling loads and 30% in wind speed

In line with the related work described above, 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 limitations pointed out by previous research [11] 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, and analysis tools, allowing a seamless flow between design and analysis [12].

2. WORKFLOW

We propose a three-phased workflow to structure data gathering, algorithmic processes, and sensitivity analysis (Fig.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 modelling the studied urban fabric from OpenStreetMap (OSM) data, it is possible to measure the impact on people's comfort of different (**a**) material scenarios and (**b**) 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.

Finally, phase three analyzes the thermal autonomy at different scales to understand how each scenario and design parameters impact indoor comfort.

2.1 Case study – Chamanculo C urban fabric and building typology.

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 [10]. 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 (Fig.2).

One of the most common self-made houses seen in the area is the "Ventoinha" house. Landowners add units incrementally according to the family needs and their financial availability (Fig.3). 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 [13].

Fig.2 - Chamanculo C satelite image and 3d model.

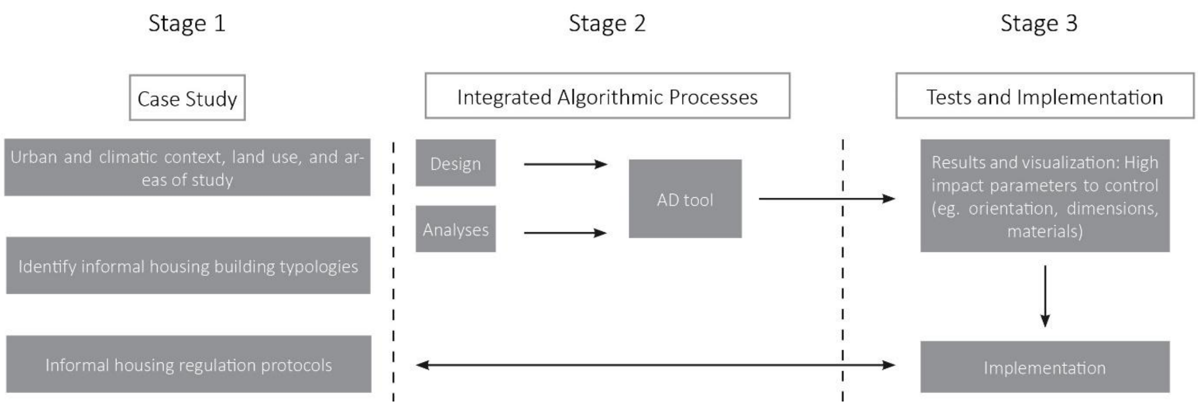

Fig.1 – Research workflow

Fig.3 – Ventoinha house typology

2.2 Algorithmic design description and parameters

When planning incremental informal housing in developing nations facing challenges related to housing provision, 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 related to the roof angle. To form a complete house, this starting unit is rotated four times around the center corner (Fig. 4).

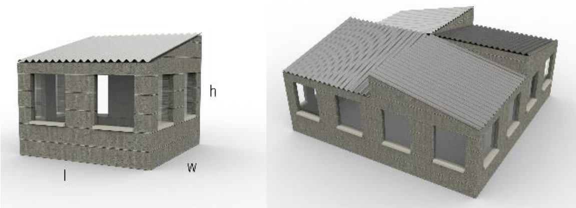

Fig. 4 – Unit parameters (left) and n = 4 units (right).

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.

The heat flow between ground and ground 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 are built directly above the soil, it is advisable to use a slab-on-grade floor type [14].

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 material properties were obtained from EnergyPlus' library for wall-air resistance. However, cement bricks and extruded polystyrene 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).

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*) [13]. 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

After the material analysis, we investigated the impact of design parameters on the thermal performance. 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.

3. RESULTS AND DISCUSSION

The urban analysis results are presented through 3D model heatmaps for the TA of each building (Fig. 5), allowing the identification of areas that might benefit from modular upgrades, as well as line charts with the TA range of each construction (Fig. 6), providing a more detailed view of the performance of each construction scenario.

3.1 Urban model analysis

The results illustrated in Fig. 5 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.

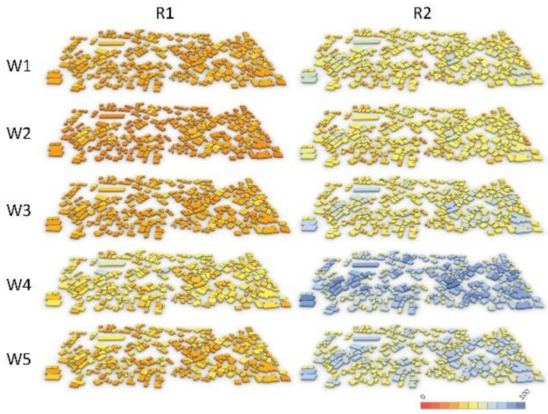

Fig. 5 – Chamanculo C thermal autonomy 3d model heatmap for the different construction scenarios

Regarding the overall comfort spectrum (Fig. 6), 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.

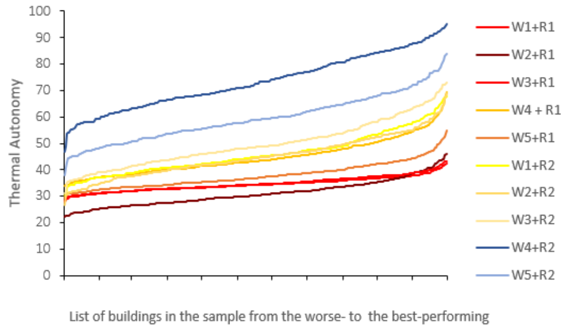

Fig. 6 – Thermal Autonomy from worse to best performing house for each construction scenario (comfort spectrum).

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.

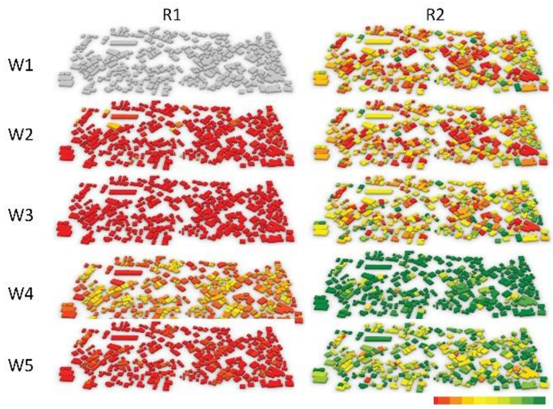

Fig. 7 – Heatmap of increase in thermal autonomy (%), compared to the zinc scenario and roof 1 (in grey).

Fig. 7 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 sensible to the roof construction, which acts as a catalyst 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 corresponding impact factors can be difficult and time-consuming to analyze and control, highlighting the need for optimization processes regarding the cost and TA improvements of the whole urban model.

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%

If the levels of TA improvement for each scenario are compared with their respective cost per building (Fig. 8), 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.

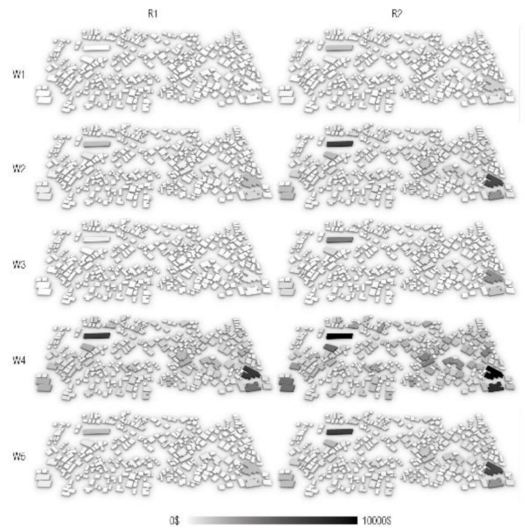

Fig. 8 – Cost per building for each construction solution.

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

- Identify buildings that critically benefit from the upgrade.
- Upgrade roof by adding a layer of insulation and zinc.
- Upgrade walls in stages, starting with the buildings that, after the roof upgrade, still have a margin to improve TA.

3.2 Housing typology dimensions

The next analysis focuses on the impact of surface area and building height on TA. The simulated model comprises a single house with scenario W5+R2, a height between 2.25m to 3.5m, a unit surface area from 6.25 m^2 to 16 m^2, and a natural ventilation schedule from an outdoor temperature of 16°C to 28°C. Results show a decrease of up to 4% as the height increases and an improvement of 4% to 7% as the area increases (Fig. 8).

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%

Fig. 8 – Thermal Autonomy with different heights and areas.

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

Fig. 9 shows that TA increases in larger proportional 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. 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 surface area.

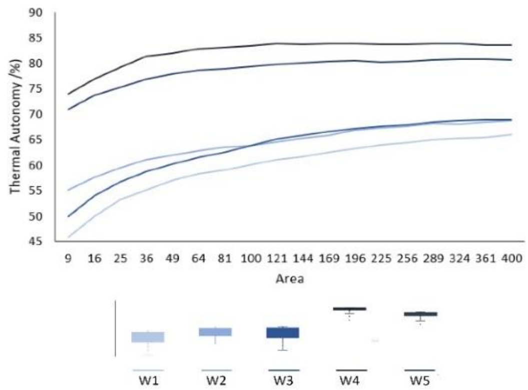

Fig. 9 – Thermal Autonomy variation with area increase.

CONCLUSIONS AND FUTURE WORK

Around the world, projects, such as Africa HABITAT, target the improvement of people's living conditions, particularly in slums. In Mozambique, DUAT (*Land use and appropriation rights)* is positively improving land use but fails to address important topics such as architectural decisions and housing rehabilitation materials regarding comfort and well-being. Additionally, these projects can act as vessels for the practical application of architectural research, contributing to a more affordable and climate-friendly approach towards a comfortable and healthy environment.

This research highlights the integration of algorithmic processes in informal architectural and urban practices, to identify how different construction scenarios and design parameters affect the buildings' thermal autonomy (TA) within the neighborhood. Results show that the impact of different wall solutions can be increased through the application of alternative roof solutions. However, while some construction scenarios return little to no improvements in the building's thermal performance, others might show significant improvements. To help make this distinction, we use a heat map comparing the TA variation between the studied neighborhood and rehabilitation scenarios, facilitating the recognition of critical areas.

To phase the slum rehabilitation and reduce its cost, it is necessary to define strategies that address the most important cases first and identify the least costly upgrades that obtain acceptable levels of comfort for each building. In the presented case study, height and surface area were analyzed in detail for selected scenarios, and the area thresholds with maximum TA were documented. We also conducted a sensitivity analysis to understand the impact of different design parameters in a specific climatic context. 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 impact of the developed project solutions.

Future work will comprise cost analysis of the identified upgrades so that their costs-efficiency in the urban neighborhood can be evaluated as a whole. We also plan to develop new algorithmic methods to integrate multi-objective optimization in rehabilitation. Finally, it would be worthwhile to do an on-site validation of the simulation results.

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