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Research Article

Conflicts in passive building performance: Retrofit and regulation of informal neighbourhoods☆

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Abstract Urbanization growth in developing countries raises concerns regarding these countries' ability to consider slums, underdeveloped communities, and neighbourhoods in economic, health, and climatic goals. This research proposes a methodology that integrates algorithmic design and analysis strategies to define, study, and measure key parameters that affect the rehabilitation of these areas. Construction scenarios and design dimensions are analysed to establish design and comfort thresholds, and alternatives are simulated and tested to identify possible improvements. The methodology includes an optimisation step integrated in the workflow that maximizes thermal comfort, minimizes costs, and ensures fairness in the rehabilitation of large sets of buildings. This step identifies improvements in thermal comfort for different construction scenarios from which a two-staged rehabilitation plan is defined. The first stage comprises a sensitivity analysis to identify building materials regarding their improvement and cost of application, and the second defines the most suitable construction scenarios considering the results from the optimisation process for each building. Additionally, we research and document guidelines regarding the parameters tested for building design, revealing the existing conflicts between performance objectives, and the architect's role in their prioritization.

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1. Introduction

It is estimated that, by 2050, 66% of the world population will live in urban areas, 90% of which concentrated in Africa and Asia (United Nations, 2019). This suggests an urbanization growth in many underdeveloped countries, which raises concerns over the way housing and settlements fit in the economic, health, and climatic goals of affected countries (Haines et al., 2013). Currently, most of this expansion has no effective planning and populations are living in informal areas that often show poor living conditions, without clean water and with infrastructures of poor construction quality (Mottelson, 2019). The research here presented proposes a strategy to improve living conditions through affordable rehabilitation and retrofitting of existent passive constructions.

An example of enabling strategies for informal areas is provided by Mozambique, which approved a regulation and the corresponding procedures regarding *land use and appropriation rights*: DUAT *(Direito ao uso e aproveitamento de Terra)* (Conselho Municipal de Maputo and Direcção Municipal de Planeamento Urbano e Ambiente, 2018). DUAT's goals include having instruments for adequate soil management and neighbourhood improvement. DUAT is currently being applied in the HABITAT Project, located in Maputo's neighbourhood of Chamanculo C. The manual of procedures describes 11 stages towards adequate land management, including street regulation and assignment of land parcels to each owner. Alas, no consideration is given to architectural decisions and housing rehabilitation, despite the importance of improving living conditions through passive design using affordable and sustainable rehabilitation processes that follow the urban program applied in each land parce.

The application of retrofitting and rehabilitation solutions in such neighbourhoods is a common practice. However, it represents a complex problem since each building is affected by its climatical and topological context, as well as its adjacent infrastructures (Martinho et al., 2020). In addition, the building's performance reflects conflicting goals that are hard to manage (Khazaii, 2016; Shi et al., 2016), such as illuminance, thermal and construction costs. The integration of processes such as Algorithmic Design (AD), Building Performance Simulation (BPS), and optimisation can help identify and solve emerging performance conflicts for complex urban and architectural problems.

AD facilitates the creation of shapes through mathematical and logical concepts represented in algorithms (Caetano et al., 2020; Frazer, 1995; Terzidis, 2006), while BPS helps predict building performance when it is not feasible to test it empirically. AD and BPS tools can be combined to provide valuable insights in every design stage (Samuelson et al., 2016). Furthermore, by integrating optimisation processes in this workflow, it is possible to treat each building as a variable that ranges over different possible retrofitting solutions that provide the best performance levels at a minimum cost (Nguyen et al., 2014). Using available geographic information, weather files, and the implicit design rules of existing vernacular architecture, it is possible to algorithmically model an accurate representation of an urban area according to the chosen representational parameters. Additionally, we can automatically simulate and evaluate buildings' performance, which allows the development of sensitivity analyses that can improve existing conditions and proposed design solutions, as well as fine-tune optimisation models with the goal of helping the architect understand the existing performance conflicts and mitigate them in future constructions.

2. Integrated algorithmic processes

In this section we review and discuss the algorithmic processes integrated within this research, namely, (1) AD, (2) BPS, and (3) optimisation.

2.1. Algorithmic design

AD is described by Janssen (2006) as an assembly of processes, that can be associative, dataflow, and procedural. The author further illustrates AD as a method to achieve specified objectives that may, or may not define a design movement (Janssen and Stouffs, 2015). This definition supports earlier research, which described AD as a complete design system from inception to development, including optimisation and execution (Frazer, 1995). However, recent research argues that in AD practice, the algorithm which generates the proposed design must provide a certain degree of traceability between parts of the algorithm and the corresponding parts of the generated 3D model. Thus, AD does not include in its scope generative processes such as optimisation (Caetano et al., 2020).

AD practices and other generative processes are usually associated with expensive, cutting-edge projects. However, the possibility of generating what-if scenarios has a great potential in both vernacular architecture, city planning, and rehabilitation projects as well. Within the scope of this research, the main advantage of AD is the ability to effortlessly generate versatile models that describe different designs, including the corresponding building information. When combined with BPS and optimisation, it allows the architect to quickly overcome the complexity and conflictive nature of the urban and built environment while selecting the best alternatives both for urban and architectural scales.

2.2. Integrated building performance simulation

One of the applications of AD is the integration and automation of BPS tasks in the design process, which allow generating multiple design variations and assessing their performance in several stages of a project (Eltaweel and Su, 2017; Samuelson et al., 2016). By combining AD and BPS, it is possible to focus on building performance aspects, such as indoor air temperature, energy consumption, or illuminance to guide the development of architectural designs (Touloupaki and Theodosiou, 2017). However, given the need for a shared understanding between design and engineering disciplines, the use of such methods in early design stages is still recent. This understanding can be achieved through an integration between the AD and BPS processes that simplifies simulation inputs, making it easier for architects to grasp concepts regarding building physics (Toth et al., 2011).

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 analyses of sets of design variations in two case studies, testing their structural and lighting performance. The proposed workflow is compared with a traditional analysis workflow, highlighting the time and resources saved by the former, and errors resulting from the latter. Additional work has been developed towards integrating this approach to illustrate the impact of buildings in the adjacent urban fabric and vice-versa, showing how it can help improve the general performance of the urban area or even prevent future damage resulting from poor design decisions (Martinho et al., 2020).

2.3. Optimisation

When both design generation and evaluation processes are automated, the potential to integrate optimisation processes in design workflows emerges, which facilitates the search for optimal solutions within design variations (Belém and Leitão, 2018). Optimisation is mathematically defined as the process of finding the best solution from a set of variables that affect the resulting outcome, which can have a single, or multiple objectives. 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 et al., 2014). When dealing with complex architectural systems, an architect must typically address multiple objectives such as costs, thermal, illuminance, and more (Khazaii, 2016). Consequently, the optimisation problem becomes increasingly complex, particularly when a large number of parameters and conflicting objectives are found (e.g., less energy consumption usually entails higher costs) (Wortmann et al., 2015).

The adequacy of optimisation algorithms is another important aspect to consider, as their performance varies with the optimisation problem they are addressing. As an example, Pereira et al. (2019) explored two open-source libraries of optimisation algorithms (Belém, 2019) and compared 6 metaheuristics and 4 model-based optimisation algorithms in two multi-objective optimisation case studies (Pereira et al., 2020): (1) maximizing the Spatial Useful Daylight Illuminance (sUDI) provided by an exhibition space's skylight while minimizing its costs, and (2) minimizing the structural displacement of a complex shape while minimizing costs. From the tested algorithms, the particle swarm optimisation group of algorithms (Kiranyaz, 2014; Nebro et al., 2009) revealed the best results in the structural problem, and the worse in the illuminance problem, while the Random Forest Regressor (RFR) algorithms (Pavlov, 2019) revealed the opposite. Additionally, model-based algorithms were complemented with the tested evolutionary algorithm Non-Dominated Sorting Genetic Algorithm II (NSGAII) (Deb et al., 2002) which seemed to be the most consistent in both cases. These studies confirm the importance of testing multiple algorithms within the same optimisation problem (Wolpert and Macready, 1997).

3. Methods

The main goal of this research is to provide a robust methodology to help the architect identify the complexity and solve existing conflicts in existing urban and built environment. Additionally, this research demonstrates the impact of design solutions and materiality in complex urban regeneration problems by maximizing thermal performance and fairness, while minimizing material costs. This methodology is applied in a case study of an informal neighbourhood and comprises three different phases (see Fig. 1). The first phase comprises the required input generation. This includes the area weather file and the definition of the case study's context by algorithmically modelling (1) its respective urban fabric from OpenStreetMap (OSM) data, and (2) its respective building typology using Khepri, an AD tool capable of integrating multiple CAD, BIM, and BPS platforms (Martinho et al., 2020). Phase two includes model generation and performance simulations to measure the impact of different factors on building performance, namely (1) material scenarios, (2) design dimensions (e.g., floor area), and (3) Window-to-Wall Ratio (WWR). The latter is easily applied in the field and regulated, while the former two are suitable for modular rehabilitation processes and future constructions. The performance simulations use EnergyPlus (Crawley et al., 2001) for thermal performance and Radiance (Ward, 1994) for illuminance, both integrated in Ladybug tools for data visualization (Roudsari and Pak, 2013). Finally, the third phase explores the existing conflicts in building performance at urban and architectural scales. The urban scale is studied by applying a Multi-Objective Optimisation (MOO) process to a set of buildings in the area, to maximize both thermal comfort and fairness of the solution, while minimizing material costs. At the architectural scale, we evaluate the impact of the design parameters in the performance simulations, highlighting the architect's role in objective and performance prioritization.

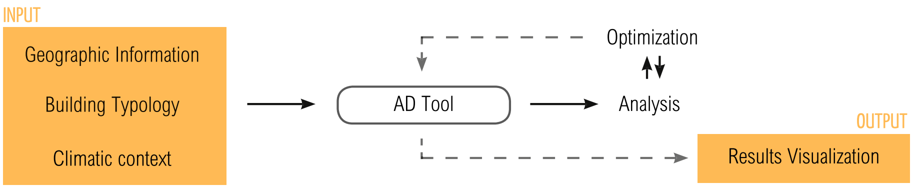

Fig. 1 Conceptual diagram for the proposed methodology.

Considering the three integrated computational processes - AD, BPS, and optimisation - this section is organized in three sub-sections. The first describes the case study's urban/housing typologies and the respective AD processes used to represent the existing vernacular architecture in the area, the second specifies the simulation inputs and outputs for both urban and architectural analysis, and the third describes the objectives and algorithms employed in the optimisation process.

3.1. Case study — Chamanculo C

Chamanculo C is a neighbourhood in the city of Maputo, district of Nhlamankulu, characterized as an old suburb of type A (Henriques and Ribeiro, 2005). These neighbourhood types are mainly described as basic infrastructures composed of zinc cladding and/or cement bricks, heavily distributed in non-delimited areas and showing high population density in narrow public spaces. To represent the urban fabric, we used OSM data to generate 3D models of the corresponding houses that match the urban landscape with a WWR of 0.1, 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 (see Fig. 2).

One of the most common vernacular houses seen in the area is the "Ventoinha" (fan) house (see Fig. 3), that landowners can extend by incrementally adding units according to the family's needs and the 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 (Lizancos et al., 2014).

Planning incremental informal housing in developing nations that face housing-provision challenges represents a policy-making model that must consider the existing vernacular architecture typologies and cultural context in these settlements (Jenkins et al., 2006). This, in addition to the modular qualities of available construction materials in these countries make it useful to model these building typologies parametrically where such rules can be applied pre-emptively. To this end, we started from one cuboid unit 2.25 m tall, variable length (l), and width (w), and a triangular prism with the same dimensions and a height of 0.75 m. To form a complete house, this starting unit is rotated four times around the unit's corner, and windows are centred according to a variable WWR (see Fig. 4).

3.2. Simulations, inputs, and outputs

Considering the described building and urban typology, five scenarios for wall, and two scenarios for roof solutions were tested in the urban model (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. The defaults for our study were based in the building survey performed in the area (see Fig. 3). Therefore, a WWR of 0.1 was used in each façade, and a height of 3 m was set (see Fig. 4).

Fig. 2 Chamanculo C satellite image and model.

Fig. 3 "Ventoinha" houses in the area.

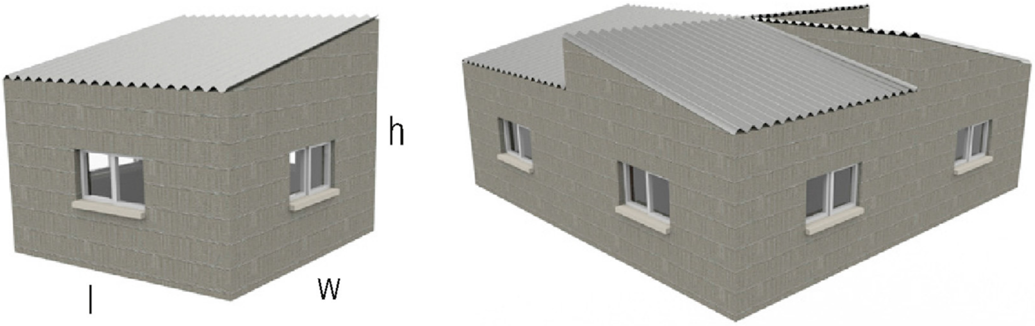

Fig. 4 Algorithmically modelled "Ventoinha" house with 0.1 window to wall ratio.

Properties from the local chosen materials 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[1] (Tables 2 and 3) except for their cost, which was an estimate from the local markets.

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 EnergyPlus, 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 (Costa et al., 2017).

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*) (Levitt et al., 2013). This analysis was made from January to March, from 10 a.m. to 8 p.m., 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 the buildings in the area. The materials construction cost are also contrasted with their respective thermal comfort results, identifying existing conflicts in urban rehabilitation.

After the material analysis, we investigated the impact of design parameters on a single building's thermal and illuminance performance. To this end, we implemented an iterative simulation of the "Ventoinha" house with values for the floor area ranging from 12.5 m^2 to 200 m^2, and WWR from 0.1 to 0.4. Additionally, we tested two types of window design and their illuminance performance for the different areas and WWR, one with a single centred window in each unit's façade, and other with equally distributed windows with a sill height of 1m, and a window height of 1.2 m (see Fig. 5). The illuminance simulation comprised a climate-based sky from 6 a.m. to 6 p.m., for the summer

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[1] Available online at: https://www.engineeringtoolbox.com/.

Table 1 Tested construction scenarios.

Item	Scenario	Layer	Material	U-value (W/m^2·K)
Wall	W1	1	Zinc	5.88
	W2	1	Cement brick	3.44
	W3	1	Zinc	3.12
		2	0.15 m Air gap	
		3	Zinc	
	W4	1	Cement brick	1.78
		2	0.15 m Air gap	
		3	Cement brick	
	W5	1	Zinc	2.27
		2	0.15 m Air Gap	
		3	Cement Brick	
Roof	R1	1	Zinc	5.88
	R2	1	Zinc	0.52
		2	0.15 m Air Gap	
		3	XPS	
		4	Zinc	
Window	Window 1	1	Glass	1.70
		2	0.013 m Air Gap	
		3	Glass	

Table 2 Opaque 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/m^3)	1442	20.8	2085
Specific heat (J/kg·K)	380	1131	900
Absorptance	0.25	0.7	0.9
Cost (€/m^2)	6	4	12

Table 3 Glass Material thermal properties.

	Glass
Thickness (m)	0.003
Solar Transmittance	0.837
Solar reflectance	0.075
Visible Transmittance	0.898
Visible Reflectance	0.081
Front emissivity	0.84
Back emissivity	0.84
Conductivity (W/m·K)	0.9

solstice day and an analysis grid at 1.5 m height with a cell size of 1 m. All these design variations yielded TA and Useful Daylight Illuminance (UDI) (Nabil and Mardaljevic, 2005) results which allowed the establishment of design thresholds to regulate informal construction. Additionally, they aim to highlight the conflicting nature of the performance goals in building design and provide insights regarding design dimensions for future architectural planning and design in the area.

3.3. Multi-Objective optimisation

Extensive research has been made depicting the advantages optimisation brings to the architectural field, in particular, to address problems comprising objectives of a conflicting nature (Khazaii, 2016; Wortmann et al., 2015). The third phase of this workflow, which encompasses an optimisation process, is directly related to BPS as it uses the analysed parameters as inputs (material scenarios, WWR, and floor area) and returns acceptable combinations that better address the proposed objectives. Within this research, optimisation processes available in the AD tool can be applied in both illuminance and thermal performance for the minimum cost. However, given the extensive computational resources and time required by each simulation (Pereira and Leitão, 2020), the optimisation process is demonstrated only for the thermal comfort and in a sample of the buildings.

Three objective functions were developed to optimize the thermal comfort in the studied urban area. This was done by changing the parameters of construction solutions, defined in the case study, to minimize the rehabilitation cost while maintaining a fair level of comfort between the analysed 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 promotes fairness by seeking the same level of comfort among the building sample.

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

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

$$(c)\min h(x_1, x_2, \ldots, x_n) = \sigma(\text{Thermal Autonomy}(x_i))$$

Previous research evaluated the performance of different optimisation algorithms to different optimisation problems (Pereira et al., 2020; Waibel et al., 2019; Wortmann, 2017) and concluded that no single algorithm can outperform all others on all problems (Wolpert and Macready, 1997). Taking this into account, in this research, the metaheuristic algorithms NSGAII (Deb et al., 2002) and SPEA2 (Zitzler et al., 2009) were tested and then used as solvers for the model-based algorithms Random Forest Regressor (Pavlov, 2019), and Gaussian Process Regressor (Quiñonero-Candela and Rasmussen, 2005), from which the best performing ones are selected, shown, and discussed. In the next section, the solution samples provided by the algorithms are showcased and discussed, and their adequacy to solve the identified problems is compared against the obtained results in the sensitivity analysis phase.

4. Results

Results and their respective discussion will be shown initially at an urban scale. The sensitivity analysis of the thermal

Fig. 5 Window design 1 and 2 with 0.1 (top) and 0.3 WWR (bottom).

performance will highlight the complexity that emerges from an urban retrofitting solution as well as the existing conflicts between cost and performance. Additionally, this analysis will lead to the correct modelling of the optimisation problem, allowing to choose the construction solutions that yield the best results at acceptable costs. Finally, at an architectural scale, results will be analysed and discussed regarding the "Ventoinha" house typology's thermal and illuminance performance, particularly, by assessing the house's TA and UDI with increasing floor area and WWR.

4.1. Urban analysis

The results illustrated in Fig. 6 show that walls (described in Table 1) 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 for the slum upgrade. Moreover, houses in different areas of the neighbourhood vary their TA according to both their floor area and their context and surroundings. Thus, it is possible to define different rehabilitation plans for different areas.

Regarding the overall comfort spectrum (see Fig. 7), 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. This scenario has the added advantage of being a better rehabilitation solution due to its adaptability to the building typologies in the area.

A larger performance discrepancy 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.

These improvements can be quantified by TA variation between buildings with scenario W1 and all the others with and without roof improvement. Table 4 shows overall urban results for TA variation with all the scenarios compared to the original (W1+R1).

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. This variation can be caused by multiple factors, including the buildings' solar exposure, density, or floor area, which motivates a spatially contextualized analysis. This analysis helps understand how different buildings respond to each construction scenarios.

Fig. 8 shows the results of the TA variation on a scale from −40% (red) to 220% (green) in an urban model

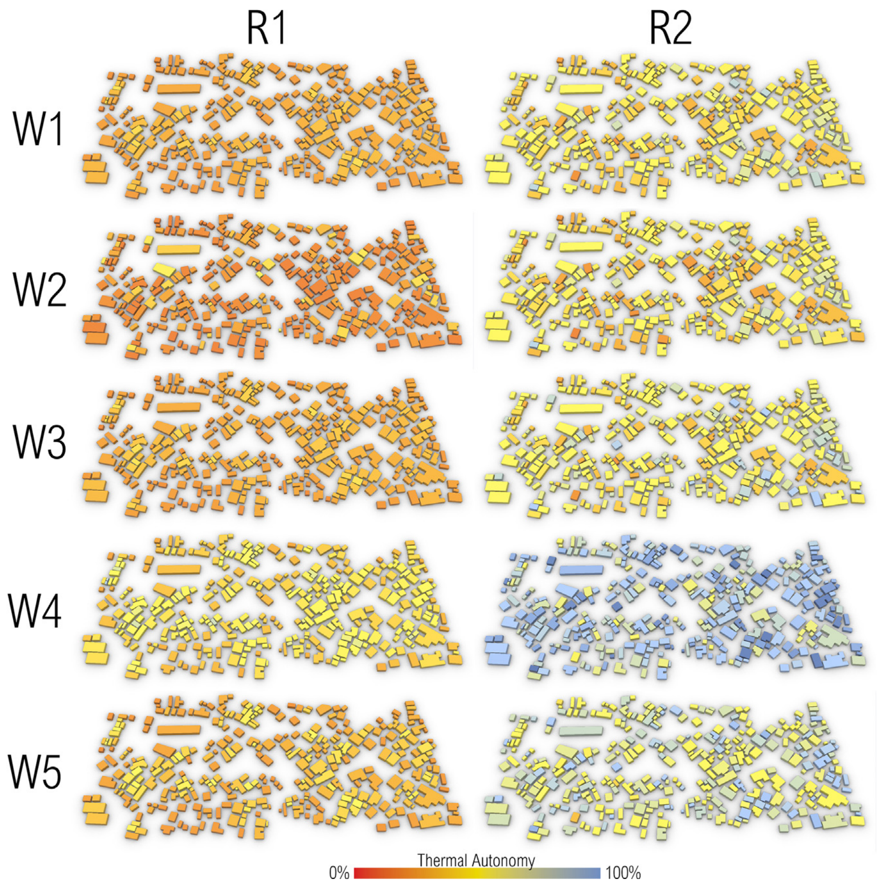

Fig. 6 Thermal Autonomy per building in Chamanculo C for each construction scenario.

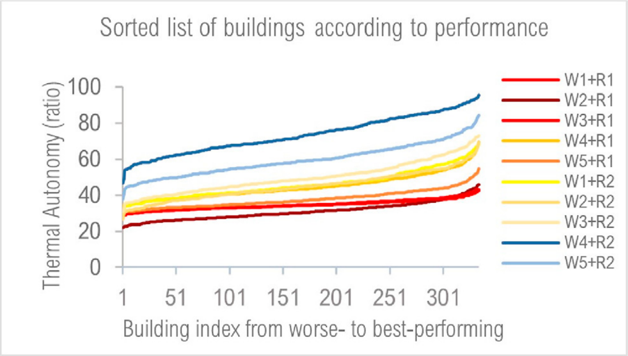

Fig. 7 Line chart illustrating the range of comfort in the urban area for buildings with each construction scenario.

Table 4 Thermal Autonomy variation in the buildings when upgraded from scenario W1+R1.

		Average (%)	Maximum (%)	Minimum (%)
R1	**W1**	0	0	0
	W2	−10	52	−41
	W3	1	4	−5
	W4	29	70	9
	W5	9	34	−1
R2	**W1**	34	105	−26
	W2	31	101	−26
	W3	45	120	−24
	W4	114	218	21
	W5	73	156	0

heatmap, which provides a spatial context for the results. As seen, the performance of 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. Despite the usefulness of specific scenario analyses for each building unit, the wide range of viable design solutions can be difficult and time-consuming to analyse and control, highlighting the need for optimisation regarding the cost and TA improvements of the whole urban model.

Assuming that the same construction scenario is adopted for all building units, by comparing the levels of TA improvement for each scenario with their respective cost per building (see Fig. 9), it is possible to conclude that a roof upgrade is less expensive than any wall upgrade, while yielding similar and, in some cases, even better results. It is also possible to see that different houses need different upgrades, and it is therefore important to find a set of upgrades that gives good TA improvements at the lowest

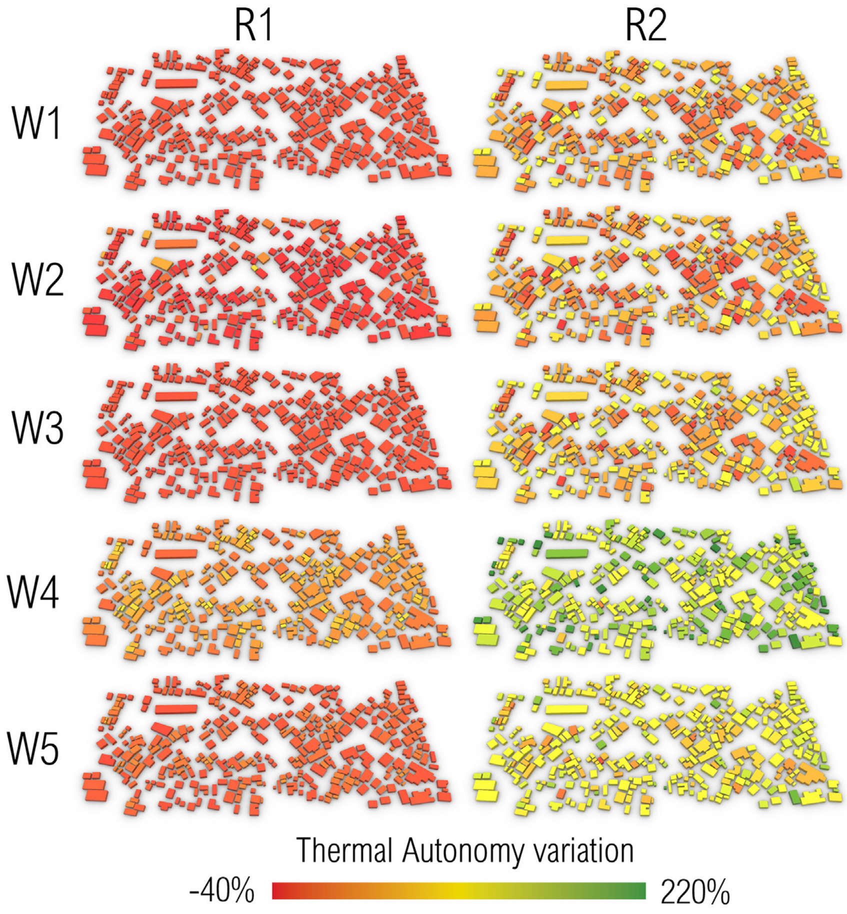

Fig. 8 Heatmap illustrating the percentage of thermal autonomy improvements compared with the original scenario (W1+R1 corner).

costs by applying higher-cost materials only in critical buildings.

To find the best upgrades that consider the conflicting nature of TA and costs, we used a Multi-Objective Optimisation (MOO) process. However, taking into account that we are considering 10 possible construction solutions, an urban area comprising 334 building units entails a solution space of 10^{334} possibilities. Executing this optimisation process regarding the entire solution space would require a large number of simulations, which can be unfeasible in commodity hardware. To evaluate the proposed methodology in a reasonable amount of computing time (3 days in a mid-range laptop), a sample of 20 houses from the Chamanculo C Urban area was chosen to be optimized regarding comfort, cost, and fairness (measured by the standard deviation, as explained in Section 3.3). It is noteworthy that this sample still comprises an enormous solution space, which would require many evaluations before the optimisation algorithm yields an acceptable range of optimal solutions. Fortunately, from the sensitivity analyses made 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 W4+R2, W5+R2, and W1+R2 (see Fig. 10). The latter does not show the best comfort results but rather represents the cheapest solution with acceptable results, which acts as a threshold when comparing optimal solutions.

The solutions tested by the best-performing optimisation algorithms (NSGAII, and the model-based RFR) are illustrated in a scatter plot where we can find solutions that best reconcile the three objectives, namely, maximum TA, minimum costs, and minimum standard deviation (σ) (see Fig. 11). The NSGAII performed 1200 evaluations, while the RFR fine-tuned NSGAII's results with 600 additional evaluations. Each evaluation represents a combination of constructions for the 20 buildings. Solutions were found in a range from 22 000€ to 56 000€ for the full rehabilitation cost of these buildings, with an average TA between 50% and 78%, and σ varying from 9.3% to 22%. Additionally, the plot helps us identify the trade-offs between TA, costs, and σ. As expected, solutions with the best fairness and TA are also the most expensive. To balance the three optimisation goals, the architect can consider the available budget and use it to filter the set of solutions that have the best performance and fairness.

Three optimal solutions were chosen according to different costs and compared with the previous results of

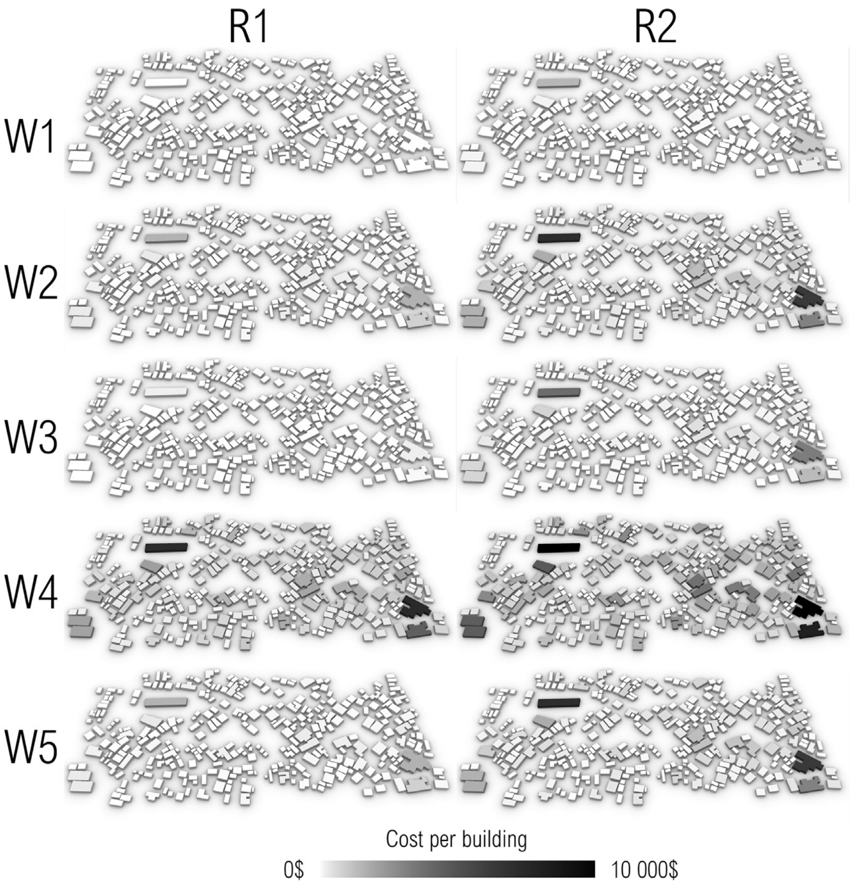

Fig. 9 Heatmaps of the cost per building for each construction solution.

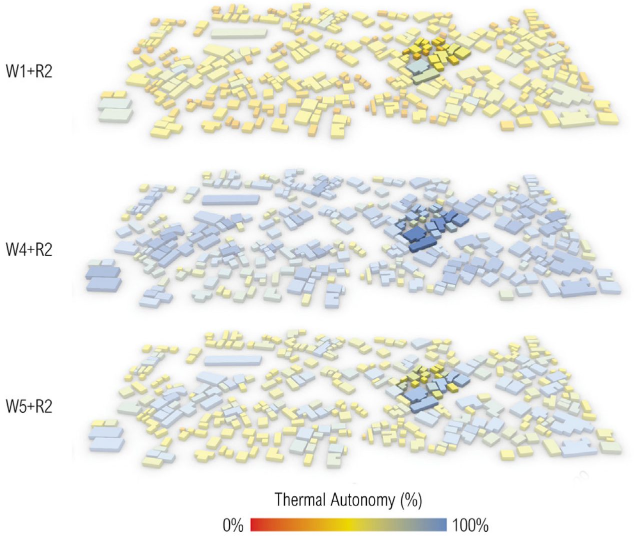

Fig. 10 Thermal Autonomy per building in Chamanculo for the three selected construction solutions. The optimisation sample is highlighted.

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 (see Fig. 12).

In the sensitivity analysis, we identified scenario W4+R2 as the best solution regarding comfort performance, but also as the costliest. Rehabilitating all the 20 buildings with this solution would have an average TA of 79.8%, with a standard deviation of 10.2%, for a cost of 72 295€. On the other hand, the optimal solution found by the NSGAII algorithm shows similar results for the average TA (77.5%), and standard deviation (9.8%), but a significantly lower cost (52 121€).

4.2. Architectural analysis

These analyses focused on the "Ventoinha" house design, particularly, to understand how WWR and floor area impact the thermal and illuminance performance of the house (see Fig. 13). Thus, they allowed us to identify thresholds where the specified window ratios start causing performance decay. At a natural lighting level (see Fig. 13 left), this decay can happen for areas that are too bright or too dark, according to the UDI definition (Nabil and Mardaljevic, 2005). Specifically, a house composed of W5+R2 with 12.5 m^2 and 0.1 WWR has 0.83 UDI, which goes down to 0.3 UDI at 200 m^2, indicating that the house gets darker with larger areas. The remaining WWR values show better performance for larger floor areas up to a point when it starts to decay. Consequently, we can see that, for the summer solstice in Maputo, for an area of up to 25 m^2, the best-performant

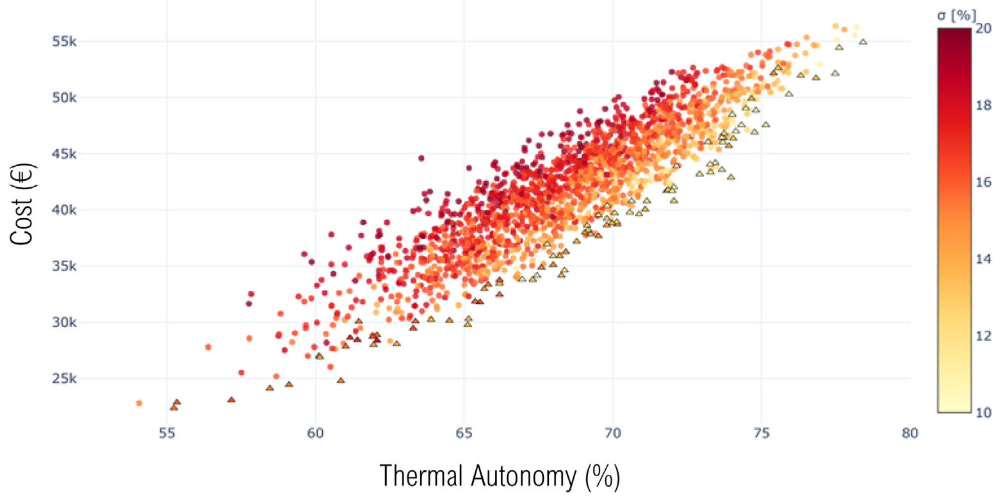

Fig. 11 Scatter plot of the tested solutions by the NSGAII and RFR algorithms — Optimal solutions represented as triangles.

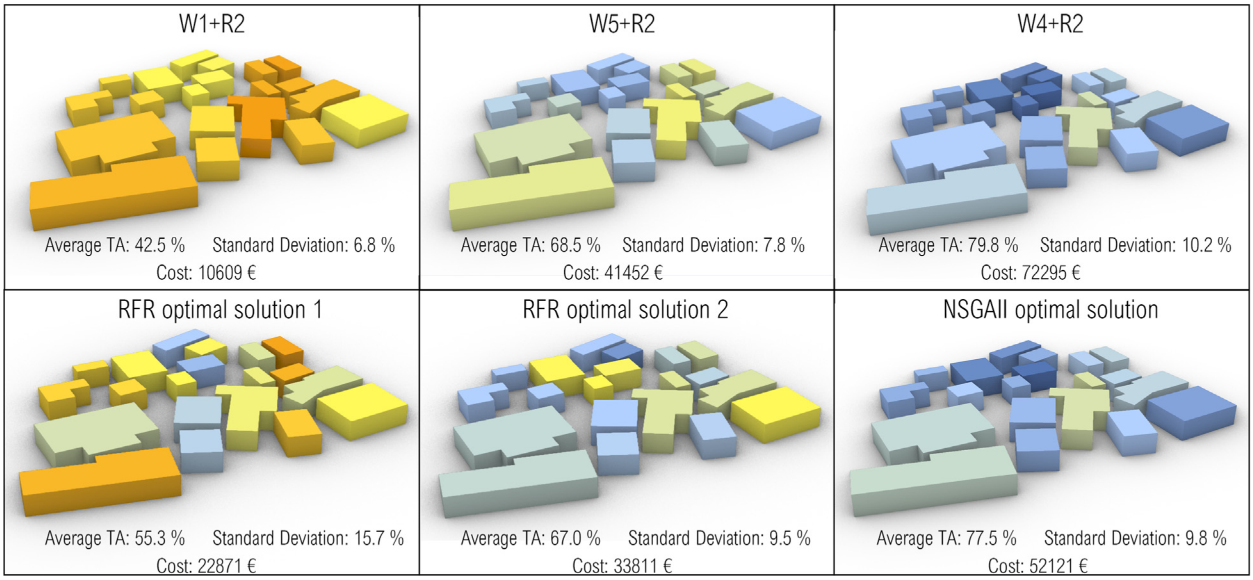

Fig. 12 Comparison between cost, comfort, and deviation of the 20 buildings with each selected construction, and the optimal combinations of constructions found by the optimisation process.

solution has a WWR of 0.1; from 25 m^2 to 112 m^2, a WWR of 0.2; from 112.5 m^2 to 162.5 m^2, 0.3; and from 162.5 m^2 onwards, 0.4.

Thermal comfort results for the same house show high discrepancies between glazing ratios for smaller floor areas, which ultimately converge to better performances as the area increases (see Fig. 13 right). If the illuminance and thermal comfort results are cross-referenced between their common analyses, we can infer a similar increase in performance for all WWRs' for thermal and illuminance performance except for 0.1 WWR, which performs better in the thermal analysis, but quickly declines in illuminance performance with larger areas. However, the performance decay of each WWR shows an inverse rate of change as the floor area grows, with higher window ratios showing better performances with a smaller decay.

Regarding the analysis of the different window designs (see Fig. 5), their illuminance analysis show different performance levels (see Fig. 14 left). In a direct comparison, for a WWR of 0.1, design 1 (solid line) is consistently better than design 2 (dashed line). However, for a WWR of 0.2, design 2 is preferable to design 1 for areas up to 70 m^2. The same situation occurs for a WWR of 0.3 and areas up to 110 m^2. Finally, for a WWR of 0.4 both designs show similar performance. The thermal analysis (see Fig. 14 right) show only minor deviations in the performance of the different window designs.

The results also show that better performances tend to require larger areas. However, with the constant growth in population and urbanization, particularly in underdeveloped countries, the need to construct upwards and not sideways (i.e., smaller floor/area ratio) emerges.

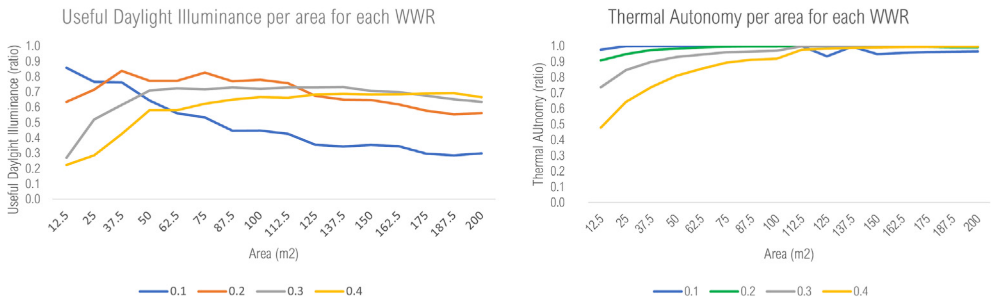

Fig. 13 Useful Daylight Illuminance (left) and Thermal Autonomy (right) per area for each Window to Wall Ratio.

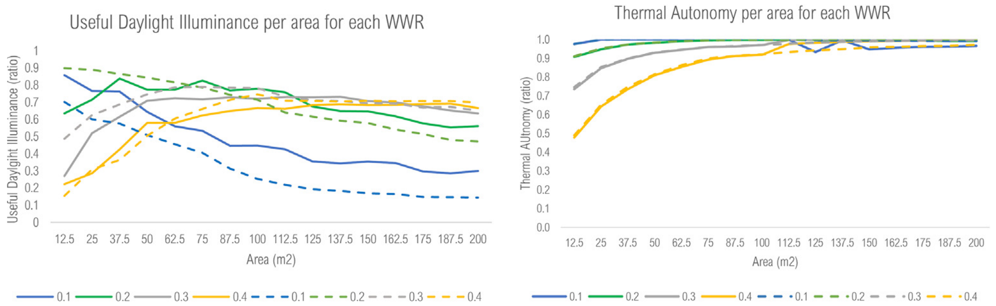

Fig. 14 Useful Daylight Illuminance (left) and Thermal Autonomy (right) per area for each Window to Wall Ratio for window design 1 (solid line) and 2 (dashed line).

Consequently, the architect plays an important role in the decision-making process regarding building performance and respective design parameters, particularly in resolving conflicting performance goals both in the built and urban environment.

5. Conclusions and future work

This research applies algorithmic processes in informal architectural and urban planning to reveal how different construction scenarios and design parameters affect building performance levels. By using Algorithmic Design (AD) to perform sets of design iterations, it was possible to automatically test and optimize different design parameters.

Results were outlined in two sections regarding urban model analysis and architectural analysis. The former revealed the performance of different construction solutions and their costs, while the latter showed Window to Wall Ratio (WWR) and floor areas have conflicting impacts on the thermal and illuminance performances, making it difficult to choose the best combinations. To solve this problem, an optimisation process was successfully employed in the urban area rehabilitation that identified fair combinations of construction solutions that, in some cases, performed as well as the best-identified solution, but were significantly cheaper.

Notwithstanding the existing vast application of AD and Building Performance Simulation (BPS) to expensive, high-performant, and cutting-edge projects, little exploration of this subject is being done for the "architecture where the other 90% live" (Lizancos et al., 2014). However, the possibility of analysing, 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 find design solutions that fit comfort and utility criteria with lower costs and/or usage of resources.

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. This research also shows that the application of AD, Multi-Objective Optimisation (MOO), and BPS has a positive effect on the time and labour required to perform the numerous simulations needed. Particularly, it allowed to effortlessly generate a parametric 3D urban model from recorded geospatial data and variations of typical vernacular architecture in the studied area.

Despite the methodology's success in achieving the proposed objectives, policymakers might want to explore different analysis and evaluation outputs. To that end, we plan to further improve the variety of algorithmic processes, building performance analyses, and evaluation methods, as well as improve their accuracy, visualization, and interpretation. Currently, with the integration of new and existing tools, the methodology's potential is being improved regarding air flow, structural, thermal, and illuminance analyses.

Given that simulations tend to be resource- and time-consuming, to obtain results in a reasonable amount of time, in this research we only optimized a subset of the buildings. To deal with larger sets of buildings we are currently working on task distribution and parallelization, which allows to simultaneously perform different simulations and optimisations, dramatically reducing the required computation time (Pereira and Leitão, 2020).

New developments in algorithmic processes such as AD, BPS, and MOO, demand new methodologies to accommodate these changes. This research demonstrated one such methodology capable of addressing the sustainable retrofit of informal neighbourhoods.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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