A framework for parametric multi-criteria decision analysis (P-MCDA) for building retrofits

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Abstract

Multi-Criteria-Decision-Analysis (MCDA) has been incorporated into retrofit decision-making to help obtain optimal strategies that can address a holistic objective criterion. However, MCDA for retrofit problems is often performed over two stages through pre-processing or post-processing of the simulation inputs/outputs which leads to detecting only a limited portion of the optimal (Pareto-Front) decisions available. This study proposes a parametric approach for MCDA, embedded into building performance simulation, that addresses many of the MCDA limitations highlighted and demonstrates how the parametric and area-weighted approach proposed can explore a bigger parameter space and be responsive to the various building geometries.

Highlights

- The pre-processed and post-processed simulation approaches incorporated into the existing MCDA frameworks could not identify 93-95% of the optimal (non-dominated) solutions obtained by the parametric MCDA (P-MCDA) framework.
- Through a python script that performs backend calculations for the score-based qualitative retrofit objectives, the EnergyPlus Energy Management System (EMS) can be used to define and report additional custom outputs for the score-based (non-simulated) retrofit objectives.
- While acknowledging the limitations to the attempts to formulate "objective" decisions for qualitative objectives, area-weighted MCDA calculations are one approach to decrease the subjectivity of the decision-making process.
- P-MCDA may improve MCDA efficiency in terms of the size of the investigated parameter space as it can benefit from the means of parametric building performance simulation and optimisation.
- Separate retrofit configurations for building fabric elements with different orientation could be derived using P-MCDA.

Introduction

The decision-making process for building retrofit is complex as multiple parameter options to configure retrofit measures can be investigated and multiple objectives of the retrofit performance criteria can be looked at (Lu et al., 2021; Ma et al., 2012; Pacific Northwest National Laboratory et al., 2011). Due to the difficulty of making retrofit decisions that account for the trade-offs for the often-competing retrofit objectives, parametric building performance simulation and algorithmic optimization have been deployed in multiple studies to automate the process of investigating a large pool of possible retrofit scenarios (Costa-Carrapiço et al., 2020; Evins, 2013; Hashempour et al., 2020). However, regardless of how efficient these methods can be at estimating measurable objectives such as energy, carbon, and thermal comfort, etc., building performance simulation (BPS) can be deemed insufficient to derive holistic and realistic retrofit decisions (Gleeson et al., 2011; Kimpian et al., 2021; Robinson, 2021). Choosing an optimal retrofit scenario can often be attributed to other important goals that cannot be evaluated through BPS methods, such as the applicability of the retrofit measures, the heritage concerns, the disruption to the occupants, and the labour skills required, etc. Multi-criteria-decision-analysis (MCDA, also called multi-criteria-decision-making or MCDM) has been utilized in the literature for retrofit decision makings to account for the non-simulated factors to broaden the optimality criteria and assure that the retrofit scenarios proposed are applicable and appealing to the different parties involved (Hopfe et al., 2013; Kimpian et al., 2021; Powell et al., 2015; Robinson, 2021).

Retrofit MCDA revolves around formulating quantitative scores that estimate the performance of the various retrofit measures against a holistic criterion that would often include a mixture of quantitative and qualitative objectives. For a retrofit scenario, a certain combination of retrofit measures is formulated. Objectives of the scenario are evaluated by summing the scores the selected retrofit measures would achieve (Ruggeri et al., 2020). The ranking of the scenarios proposed is based on aggregating the scores of each retrofit scenario across the different objectives. Different weights can be applied to the objectives scores before aggregation if the objectives are deemed of different relative importance. Objectives' weights direct the ranking of the scenarios to favour the measures that address the objectives with the higher weights (Kokaraki et al., 2019; Robinson, 2021; Ruggeri et al., 2020).

For retrofit decision-making, quantifying the qualitative features has been performed in the literature by consulting the relevant stakeholders (such as the occupants and the retrofit experts) to let them assign scores that indicate how the various retrofit measures perform at achieving a certain qualitative objective. Consulting ~~the~~ stakeholders has been deployed as well to help define the optimality criteria by distinguishing the objectives in the first place (Roberti et al., 2017) and assigning weights that represent how much a specific objective should be contributing to the overall decision .

There are multiple methods found in the literature that can be used to aggregate the MCDA scores such as weighted sum, weighted product, analytic hierarchy process (AHP), and ELECTRE (Robinson, 2021; Wang & Rangaiah, 2017). However, regardless of the MCDA method used, MCDA tools can be deemed impractical at approaching some complex decision-making problems due to limitations such as:

1. The results of the MCDA objectives are often logged individually/manually. The number of scenarios explored through MCDA is limited or much less than what can be explored via parametric BPS. As a result, it would be difficult to investigate a large number of scenarios systematically via MCDA as the number of the investigated scenarios has to be narrowed down.
2. The score attributed to a certain retrofit measure is does not factor in the area of this intervention. The score would be a number that is attributed to retrofit measure regardless of how large the area of application is. It is unclear how the geometry of the building can change the overall scores.
3. Most importantly, retrofit MCDA often incorporates pre or post-processing of the simulation inputs or outputs due to limitations in the MCDA tools used to evaluate the various objectives (Robinson, 2021). Energy, carbon, and thermal comfort are often estimated using BPS while retrofit objectives of qualitative nature are often estimated using simple spreadsheet calculations. In simulation pre-processing, the best performing MCDA scenarios in terms of their qualitative features only will qualify for the simulation stage. In contrast, in simulation post-processing, a large number of scenarios can be simulated, but only the best performing scenarios at the simulated objectives will qualify for the assessment of the qualitative features to narrow down the parameter space within the computational limitations. This phased comparison of the objectives would mathematically make some of the optimal solutions go undetected.

To address these limitations, the study proposes a parametric approach for multi-criteria decision analysis, called hereafter P-MCDA that can be utilized to optimize building retrofits. The study presents a novel framework to support embedding the calculations of any user-defined (non-simulated) MCDA retrofit criteria into parametric BPS. P-MCDA can be characterised by the following aspects of novelty that address the MCDA limitations:

1. MCDA automation that enables the investigation of a larger parameter space using BPS tools.
2. Area-weighted MCDA scores that can imply the measure specific score as well as the area of the measure intervention. This enables the application of the same scores to buildings of different geometries (i.e. stock level decision making). Area-based calculations also help with evaluating complex scenarios where different retrofit measures are applied to the fabric elements positioned at different orientations.
3. Simultaneious pareto-front analysis to obtain optimal retrofit scenarios that can capture the tradeoffs of all the quantitative or quantitative objectives, instead of performing pre-processed or post-processed optimisations.

Automating MCDA has also permitted the incorporation of more features such as algorithmic optimisation, sensitivity analysis, and data clustering, but these features were beyond the scope of this paper as they were not considered to be the main drivers behind P-MCDA, but rather a by-product. The aspects of novelty in this study are to present the concept of simultaneous processing of the MCDA objectives to detect the optimal solutions and to demonstrate how an automated and area-weighted approach for MCDA calculations can make retrofit decision-making adaptive to the building geometry.

Methods

Through the application of alternative fabric retrofit configurations on models of different form factors, the study compares between the simultaneous optimization in P-MCDA against the existing phased optimization (pre-processing and post-processing MCDA) frameworks.

P-MCDA is a Python script to improve and automate the MCDA calculations that looks at a range of simulated (quantitative) and non-simulated (score-based or qualitative) decision-making objectives criteria. The script uses multiple modules such as NumPy, Pandas, Eppy to manipulate and run EnergyPlus files, Pymoo to detect the Pareto-Front, and K-means for data-clustering. The main steps for P-MCDA script, also illustrated in Figure 1, are to:

1. Read an EnergyPlus Input Data File (IDF) for a certain building.
2. Read an excel file that controls the MCDA input and output configuration. This file includes a database of the variant options for the retrofit measures investigated (parameters/inputs) as well as the objectives criteria elements that should be considred (outputs).
3. Manipulate and run the IDF file based on the Excel file configurations.
4. Implement backend calculations and report the non-simulated objective results back to the EnergyPlus outputs using an EMS script.
5. Perform analysis on the parameter and solution spaces using sensitivity correlation, data-clustering, and Pareto-Front analysis to understand which parameter configurations can be deemed optimal.

Regarding the decision-making parameters, variable discrete configurations for wall insulation, floor insulation, roof insulation, window glass, window frames, and window shading have been defined. P-MCDA is not limited to the parameters defined in this study as it can handle many more building retrofit measure variables such as external shading, window to wall ratio, lighting power, HVAC system template, HVAC operation strategy, and options for photovoltaics.

Four MCDA objectives have been defined as retrofit criteria in this study: operational energy use intensity (kWh/m^2), retrofit embodied carbon (kCO$_2$/m^2), building disruption (unitless), and heritage concerns (unitless). The energy and carbon objectives are both examples for quantitative simulation-based metrics, while the disruption and heritage are examples for qualitative objectives that are converted into score-based calculations. P-MCDA is not limited to the objectives considered by this study as any user-defined score-based objectives can be added to the objectives criteria by the decision maker.

A measure-specific score was assigned for each retrofit measure against the non-simulated objectives defined. The scores were arbitrarily, but sensibly, assumed by the authors to test P-MCDA. Actual scores should be obtained through feedback from retrofit stakeholders in a certain building or context. The calculation of a non-simulated objective $(S_{objective})$ is area weighted according to Equation 1. The objective result is the aggregated sum of the of scores assumed for each retrofit measure ($S_{measure}$) multiplied by the area of application of the measure ($A_{measure}$), divided by the total (gross) floor area of the building (GFA).

$$S_{objective} = \frac{\sum(S_{measure} * A_{measure})}{GFA} \qquad (1)$$

To test a large pool of retrofit scenarios, iterative EnergyPlus simulations have been automated in Eppy in Python. A random sample of 500 iterative simulations for each IDF file has been carried out. A random option for the retrofit each retrofit measure was assigned for each iteration. Eppy was used to capture the areas of intervention for each retrofit measure in every iteration and Python built-in maths operations have been used to calculate the final scores for the non-simulated objectives.

In terms of reporting the objective results back to the EnergyPlus ecosystem, a Python script that deploys the Energy Management System (EMS, a scripting tool used to manipulate EnergyPlus IDF files during the simulation) was used to log the final scores of the objectives criteria into the EnergyPlus standard outputs. This has been carried out by creating EMS “global variables” that would be a placeholder for the calculated values. The values calculated using Equation 1 in Python were logged into the global variables using an EMS program. The EMS global variables were then reported in the EnergyPlus output files as regular output variables.

For the analysis of the results, P-MCDA deploys K-means data clustering to establish performance-driven clusters (group the retrofit scenarios that lead to similar results together). This method is used to group the similar retrofit scenarios in terms of their outcomes rather than their inputs. Data clustering was applied to the entire solution space as well as the optimal solutions to identify if certain clusters are found to have more optimal solutions. The parameters representation in each cluster was derived for the entire solution spaces as well as for the Pareto-Front.

To recap the workflow, shown in Figure 1, Python was used to manipulate and run the EnergyPlus files iteratively based on an input/output configuration set in an excel file. In the background, Python was used to perform the model-based and area-weighted score calculations, and an EMS script was added to report the calculations back to the IDF file to enable finding the results among the standard EnergyPlus outputs. Python was used after the simulation to analyse the solution space and to obtain the parameters that can be deemed optimal.

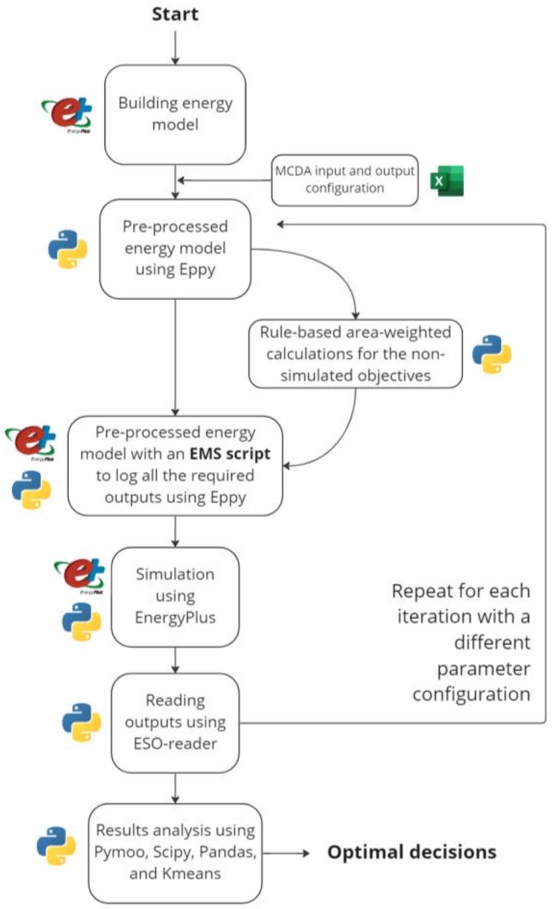

Figure 1: P-MCDA workflow.

EnergyPlus single and multi-floor shoebox models with 12 m x 18 m footprint generated in DesignBuilder have been used to test the P-MCDA framework as shown in Figure 2. The floor(s) height for the tested models was 3 m. The EnergyPlus weather file for Cairo International Airport in Egypt was used to load the weather data as this study is a by-product of a larger research project that looks at devising retrofit strategies in the context of Cairo.

Three buildings with different form factors (FF) have been studied to investigate how the proportional changes in the areas of the building fabric elements can make changes to what retrofit measures will be optimal. Three configurations for the same building were tested: a single floor model (3 m high, FF = 0.94), a three-floor model (9 m high, FF = 0.5), and a five-floor model (15 m high, FF = 0.41). It has been found that increasing the number of floors to be more than three floors would have a negligible effect on the form factor. The form factors mentioned were calculated by dividing the overall surface area including the ground floor area by the building volume. Form factors might also be calculated by dividing the overall surface area by the gross floor area (GFA). In that case, the form factors will be 2.83, 1.5, and 1.23 for the single, three, and five floor models respectively.

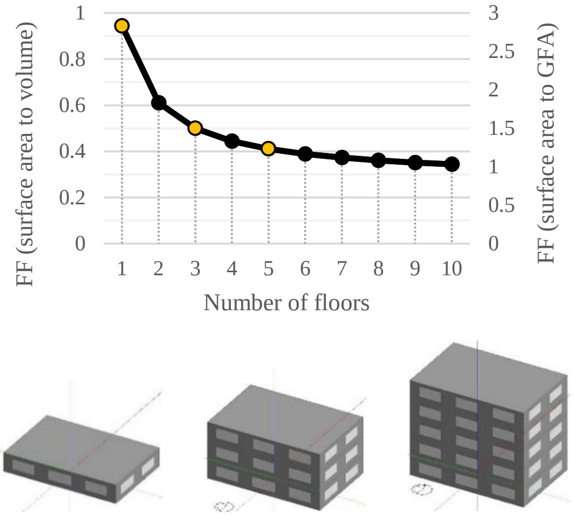

Figure 2: Three buildings with different form factors tested.

A brief for the retrofit measures options and their scores can be found in Table 2 in the Appendix. The rationale behind the study assumptions was to make a complex decision-making problem where several trade-offs will be arising for the competing objectives. For example, adding the same amount of a certain insulation material to the external walls externally or internally will result in external walls with the same U-Values and the same embodied carbon (unless unintended thermal bridging occurring at the building junctions is accounted for). Hence, the disruption and the impact on the heritage significance will be the decisive objectives that will direct the decision.

For instance, internal wall insulation would result in more disruption and less heritage concerns, while external wall insulation would have an opposing impact. High disruption scores and low heritage concerns have been presumed for the retrofit measures that deploy internal insulation, with the scores slightly varying to account for the different insulation thickness. In contrast, lower heritage concerns scores and high disruption scores have been assigned to the retrofit measures that would deploy internal insulation.

Moreover, P-MCDA was designed to enable assigning different retrofit measures for the fabric elements at different orientations. All fabric measures can have a scope of application where the decision-maker can choose whether to unify or separate the retrofit measure configurations based on the orientation. For this study, all the fabric retrofit measures were applied through separating the configuration of the north facing elements from the rest of the building. If needed, one of the following configurations can be assigned for each measure:

- Unified retrofit measure for the different orientations
- Separate north, and unify east, west, and south facing configuration.
- Separate north, separate south, and unify east and west facing configurations.
- Separate measure configuration for each orientation.

The number of options for the parameters of walls, roofs, floors, window glazing, window frames, and window shading were 21, 13, 13, 17, 10, and 2 respectively. This has initially resulted in more than 400 thousand possible combinations of the retrofit measures (scenarios) that can be investigated via P-MCDA. Since north facing elements have been configured to be separate, the parameter space size has increased to more than 1.3 billion possible retrofit scenarios. This denotes how computationally expensive it is to consider various retrofit configurations for the various orientations.

The retrofit measures options have been developed for the context of an office building in Egypt, but any other score assumptions could be tested. The scope of this paper is to validate the framework rather than the scores assumed.

Results

From the 500 simulations run by P-MCDA, 49, 47, and 40 optimal (non-dominated) solutions were identified for the one, three, and five floor buildings respectively. As shown in Figure 3, the study found that phased processing (pre and post processing) for the three models would lead to obtaining only a maximum of 3 optimal solutions. This denotes that the largest portion of optimal solutions (from 93% to 95%) will remain undetected when phased processing to the MCDA scores is used. The simple reason for that is that phased processing can only obtain the intersection of two Pareto Front: the solutions that are concurrently optimal in the simulated and the non-simulated objectives' space.

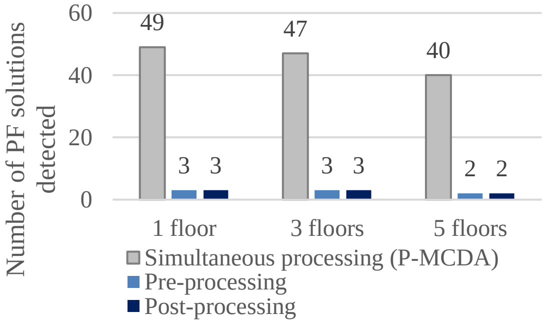

Figure 3: Solutions obtained out of 500 runs for the three buildings tested using different MCDA approaches.

In other words, phased optimisation only detects the scenarios that are non-dominated in terms of their simulated objectives and non-dominated in terms of their non-simulated objectives. However, normal simultaneous processing gives many more options to achieve optimality as it detects the solutions that are non-dominated across all objectives even if they are dominated by other solutions if only the simulated objective space or the non-simulated objectives' spaces are looked at.

Figures 4 and 5 show how the Pareto-Front (PF) solutions across all objectives is dispersed across the solution space. This is the main reason why phased optimisation could not detect all the optimal solutions. For instance, post-processed simulation in MCDA will fail to obtain those highlighted PF solutions that cause relatively high energy consumption and embodied carbon shown in Figure 4, while pre-processed simulation will prematurely filter out those highlighted PF solutions that might cause relatively high disruption and heritage concerns shown in Figure 5.

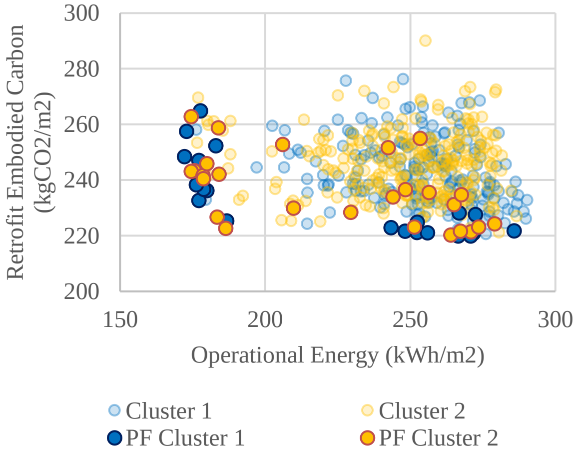

Figure 4: The objective result space for the simulated objectives for the one floor building

Figure 5: The objective result space for the non-simulated objectives for the one floor building

It was obvious that changing the building geometry has not only affected the number of solutions in the Pareto-Front, but also has made some impact on some of the retrofit measures that were present most frequently in the Pareto-Front, as shown in Table 1. By shortlisting the three options of measures that appeared the most in the Pareto-Front for the buildings studied, it can be observed that some parameter options for a specific building (form factor) have changed in rank or have disappeared from the top three shortlist in the other two buildings. For example, business as usual wall retrofit (BAU) has become more optimal as the form factor decreased in the three and five floor buildings. This shows that P-MCDA is responsive to the building geometry as accounting for the relative areas of the building fabric elements would change the scores of the objectives, hence the optimal solutions obtained. It is also shown that separating the configuration of the retrofit measures based on the building element orientation has managed to derive orientation-specific measures that can better suit the optimality criteria, another feature that will be challenging to do using manual MCDA.

Discussion

Phased processing was found to be incapable of considering the trade-offs between the simulated and non-simulated objectives. As shown earlier in Figure 3, phased processing gets the solutions that are either lowest in terms of their quantitative (simulated) objectives criteria scores or their qualitative (calculated/ non-simulated) objectives criteria scores. It fails to capture a huge grey zone of retrofit solutions that might not be the best in terms of the qualitative nor the quantitative objectives separately, but they remain optimal as they are not dominated by other solutions (those scenarios that could achieve higher scores in all objectives criteria). In fact, this missing grey zone offers a significantly larger variety of optimal retrofit scenarios where a sweet spot between the competing objectives might be found.

Limitations

Some limitations can underpin the notion of transforming the qualitative objectives into measurable values/scores. It is difficult to convert people’s feelings and perceptions into scores and consider numbers to be a true representation that can be generalised for a larger group of people. However, while acknowledging the conceptual limitations, decision-making for accountable policy making often requires some quantification for the qualitative factors in order to reach definite, transparent, and justified decisions through a systematic process. Score-based decision making enables the participation of the multiple stakeholders and creates a basis for a “less subjective” process. This has become a normalised practice to establish tangible evidence on people’s feedback, either in the form of a simple feedback form that to measure customers’ satisfaction, or through sophisticated algorithms embedded into applications that tailor the service provided to the users based on complex metrics that measure the user preferences.

Furthermore, rigorous formulation of measure-based scores that are derived from stake-holders feedback will remain an ongoing limitation until more validated scores roll out as more retrofit post-occupancy evaluations are carried out.

However, even if the scores are validated, it might not be accurate to consider that the final score for a qualitative objective should only consider the measure-specific score multiplied by the area of each. In fact, the scores could change with more factors considered. For example, a disruption caused by adding internal wall insulation in a building will differ if a kitchen or a built-in storage is installed against the wall and will have to be removed to install the measure. The heritage concern score attributed to an external wall insulation might differ depending on the orientation of the wall or how difficult it is to maintain the outer appearance of the wall after adding the insulation. However, these missing factors can be programmed into P-MCDA by multiplying the scores of the measures by multipliers that account for these additional considerations.

Unless it is developed further, P-MCDA will hardly be considered a universal solution that can tackle all the different considerations in retrofit decision-making systematically. The scores for an individual measure should be seen in tandem with the whole-building retrofit approach. For example, replacing the windows alone can be disruptive, but it might not be as disruptive if the walls are insulated or if the window sizes are to be changed as part of a building conversion or adaptive re-use. Score amendments by the stakeholders might be performed to account for all these considerations. Finally, one last limitation is the simulated outputs that cannot be modelled by EnergyPlus such as the thermal bridging that occurs when internal insulation is used, cannot be considered in P-MCDA.

However, the limitations discussed are either concerns that can be addressed or systemic limitations that are attributed to the complexity of retrofit decision-making and not to P-MCDA alone. The same limitations would also exist in the various MCDA and optimisation frameworks. Hence, P-MCDA can be a step towards a more robust decision-making, but it can still be improved to achieve systematic and transparent retrofit decisions that consider a holistic objective criterion.

Conclusion

P-MCDA is a framework that can be used to automate MCDA and achieve simultaneous optimisation for the various objectives in retrofit decision-making. The Simultaneous processing for the simulated and non-simulated objectives into one optimisation step could significantly increase the number of options obtained for optimal solutions in comparison to the existing MCDA methods that deploy phased optimisation (pre and post-processed simulation). Evidence in this study showed that phased MCDA could obtain 5-7% of the optimal solutions generated for 500 randomly sampled iterative simulations conducted on three EnergyPlus input files.

The proposed framework can be used to help decision makers add any user-defined score-based objectives to be included in the decision-making process such as disruption, practicality, heritage concerns, skilled labour required, etc. Every retrofit measure can have a particular score for the custom objectives added, and the overall score for each objective would be the aggregated area-weighted sums of all the measures combined. Following an area-weighted approach is of particular importance since P-MCDA retrofit measures applied to the building envelope can have various configurations based on their orientations. This approach supports scaling up retrofit decision-making at building stock level as it makes the initial scores assumed for the retrofit measures are independent of the building geometry.

Table 1: Frequencies of the retrofit measures that appeared the most in the Pareto-Front

	One floor (PF size= 49)		**Three floors** (PF size= 47)		**Five floors** (PF size= 20)	
Walls	IWI MW 50mm	8	BAU	20	BAU	14
	EWI EPS 50mm	7	IWI EPS 100mm	5	IWI EPS 100mm	5
	BAU	7	EWI EPS 100mm	3	IWI MW 50mm	3
N- Walls	IWI EPS 50mm	7	IWI MW 100mm	7	EWI EPS 50mm	7
	IWI EPS 100mm	6	IWI MW 50mm	6	IWI EPS 100mm	5
	BAU	5	IWI EPS 150mm	6	IWI MW 200mm	5
Roof	Roof Baseline	11	BAU EPS 50mm	6	MW 50mm	6
	BAU EPS 50mm	6	MW 100mm	5	AC 100mm	5
	MW 50mm	6	MW 200mm	5	BAU EPS 50mm	5
Floor	Floor Baseline	23	Floor Baseline	24	Floor Baseline	13
	EPS 50mm	8	AC 150mm	4	AC 100mm	5
	AC 150mm	4	MW 100mm	3	MW 200mm	4
Windows	Double Clear Argon 3/8/3	9	Triple Grey Air 3/8/3/8/3	9	Triple Grey Argon 6/13/6/13/6	6
	Double Clear Air 6/13/6 Triple	6	Double Grey Air 6/13/6 Triple	5	Double Grey Argon 6/13/6	6
	Clear Air 6/13/6/13/6	4	Grey Air 6/13/6/13/6	4	Triple Grey Air 6/13/6/13/6	5
N- Windows	Triple Grey Air 3/8/3/8/3	6	Double Grey Air 6/13/6	6	Triple Grey Argon 3/8/3/8/3	6
	Double Grey Air 6/13/6 Triple	6	Double Grey Argon 3/8/3 Triple	5	Double Grey Argon 6/13/6	5
	Grey Argon 6/13/6/13/6	5	Grey Argon 6/13/6/13/6	5	Triple Clear Air 6/13/6/13/6	5
Window Frames	Double Ins UPVC	9	Double Ins Aluminum	8	Double Ins UPVC	8
	Double Aluminium	8	Double Aluminum	8	Triple UPVC	6
	Double Ins Aluminium	7	Triple Ins Aluminum	7	Double Ins Aluminum	5
N- Window Frames	Triple Ins Aluminium	7	Double Ins Aluminum	8	Triple Ins Aluminum	8
	Double Aluminium	7	Double UPVC	7	Triple Aluminum	8
	Double Ins Aluminium	7	Triple Aluminum	7	Triple UPVC	5
Local Shading	Blind Slat30mm 45deg	29	Blind Slat30mm 45deg	29	Blind Slat30mm 45deg	25
	No Shading	20	No Shading	18	No Shading	15
N- Local Shading	No Shading	27	No Shading	31	No Shading	20
	Blind Slat 30mm 45deg	22	Blind Slat 30mm 45deg	16	Blind Slat 30mm 45deg	20

Guides on formulating a consistent score system for the various retrofit measures would be preferred if P-MCDA is used. Although P-MCDA normalises the scores, there won't be a mathematical problem if one objective is estimated with scores at scale from 1 to 5, and another on scale of 1 to 100. However, for a matter of consistency, a single system or range for all scores will be more viable and will help the stakeholders get more familiar with the scoring system and let them assign scores that are more representative of their perceptions.

P-MCDA can be developed further to account for more complex considerations that would have an impact on the retrofit measures scores such as having building facades that are of different degree of heritage significance or conducting moisture analysis for the building fabric to constrain the optimality criteria to filter out build-ups that are prone to interstitial condensation. However, while acknowledging the limitations found in P-MCDA in terms of how inclusive this method can be to the various retrofit considerations and how "objective" it is to convert a qualitative goal into a score-based metric, this study could address many of the challenges found in retrofit decision-making such that integrating the qualitative and the quantitative objectives into the decision-making process could be performed using the framework proposed. Additionally, automating the MCDA process helped with investigating a larger number of retrofit scenarios and deriving optimal orientation-specific retrofit measure configuration that can better suit the decision-making criteria.

Acknowledgement

This research is a result of a doctoral research project on retrofit strategies for public buildings in Egypt. The project is funded by Newton-Musharafa, a joint fund supported by the Missions Sector of the Ministry of Higher Education in Egypt and the British Council.

Nomenclature

AC	Aerated concrete
AHP	Analytic hierarchy process
BAU	Business as usual
BPS	Building performance simulation
ELECTRE	Elimination and Choice Translating Reality
EMS	Energy Management System
EPS	Expanded polystyrene
EWI	External wall insulation
FF	Form factor
GFA	Gross floor area
HVAC	Heating, ventilation, and air-conditioning
Ins	Insulated
IWI	Internal wall insulation
MCDA	Multi-criteria-decision-analysis
MCDM	Multi-criteria-decision-making
MW	Mineral wool
PF	Pareto-Front
P-MCDA	Parametric multi-criteria-decision-analysis

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Appendix

Table 2: Options for retrofit measures and their scores assumed for the qualitative-based criteria.

Wall Construction	Name	BAU	EWI EPS 50mm	EWI EPS 100mm	EWI EPS 150mm	EWI EPS 200mm	EWI EPS 250mm	IWI EPS 50mm	IWI EPS 100mm	IWI EPS 150mm	IWI EPS 200mm	IWI EPS 250mm	EWI MW 50mm	EWI MW 100mm	EWI MW 150mm	EWI MW 200mm	EWI MW 250mm	IWI MW 50mm	IWI MW 100mm	IWI MW 150mm	IWI MW 200mm	IWI MW 250mm
	Disruption	1	2	2	3	3	3	9	10	12	14	16	3	3	3	4	4	12	14	16	16	17
	Heritage	1	7	7	8	9	9	1	1	2	3	3	6	6	7	7	1	1	1	2	3	3

Roof Construction	Name	Roof Baseline	BAU EPS 50mm	EPS 100mm	EPS 150mm	EPS 200mm	AC 100mm	AC 100mm	AC 150mm	AC 200mm	MW 50mm	MW 100mm	MW 150mm	MW 200mm
	Disruption	0	2	2	3	3	2	2	3	3	2	2	3	3
	Heritage	1	1	1	1	1	1	1	1	1	1	1	1	1

Floor Construction	Name	Floor Baseline	EPS 50mm	EPS 100mm	EPS 150mm	EPS 200mm	AC 50mm	AC 100mm	AC 150mm	AC 200mm	MW 50mm	MW 100mm	MW 150mm	MW 200mm
	Disruption	0	30	32	34	36	35	37	39	41	30	32	34	36
	Heritage	1	1	1	1	1	1	1	1	1	1	1	1	1

Glazing Construction	Name	Baseline	Double Grey Air 3/8/3	Double Grey Air 6/13/6	Double Clear Air 3/8/3	Double Clear Air 6/13/6	Double Grey Argon 3/8/3	Double Grey Argon 6/13/6	Double Clear Argon 3/8/3	Double Clear Argon 6/13/6	Triple Grey Air 3/8/3/8/3	Triple Grey Air 6/13/6/13/6	Triple Clear Air 3/8/3/8/3	Triple Clear Air 6/13/6/13/6	Triple Grey Argon 3/8/3/8/3	Triple Grey Argon 6/13/6/13/6	Triple Clear Argon 3/8/3/8/3	Triple Clear Argon 6/13/6/13/6
	Disruption	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Heritage	0	5	7	2	4	5	7	2	4	7	9	4	6	7	9	4	6

Window frames	Name	Single Aluminium	Single UPVC	Double Aluminium	Double UPVC	Triple Aluminium	Triple UPVC	Double Ins Aluminium	Double Ins UPVC	Triple Ins Aluminium	Triple Ins UPVC
	Disruption	5	5	5	5	5	5	5	5	5	5
	Heritage	1	1	2	2	3	3	2	2	4	4

Window Local Shading	Name	Blind Slat 30mm 45deg	No Shading
	Disruption	1	0
	Heritage	0	0