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Citation for published version:
Akin, S, İşeri, OK, Dino, IG & Erdogan, B 2020, An Exploratory Multi-objective Retrofit Decision-Making Process. in Proceedings of the International Symposium of Architecture, Technology and Innovation (ATI): “Smart Buildings, Smart Cities” . Yasar University, pp. 16-25, International Symposium of Architecture, Technology and Innovation, Izmir, Turkey, 27/08/20.

Published In:
Proceedings of the International Symposium of Architecture, Technology and Innovation (ATI): “Smart Buildings, Smart Cities”

Architecture, Technology and Innovation 2020
"Smart Buildings, Smart Cities"
27-30.04.2020, Izmir / Turkey
http://ati.yasar.edu.tr

An exploratory multi-objective retrofit decision-making process

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Abstract

The retrofit processes for buildings necessitates long-term planning and costly operations and requires a collaborative approach where a high number of alternative solutions should be explored by stakeholders. However, the evaluation of a range of retrofit solutions is a complex process wherein various design parameters and objectives are involved. The identification of the most effective solutions requires a collaborative evaluation in order to satisfy all stakeholders' expectations; however, during the decision-making process, stakeholders may generally have conflicting objectives. This paper discusses different user preference-based decision-making approaches for building retrofit that involves the collaborative evaluation of multiple design parameters and objectives simultaneously. For this purpose, we demonstrate a simulation-based approach for performative exploration for building retrofits, which may allow a broader consideration of alternative retrofit solutions to increase stakeholders' involvement over design decisions for improved building performance. In this regard, a hypothetical office building was selected, and a list of possible retrofit scenarios focusing on multiple objectives was determined. Following, energy simulations for each scenario combination were conducted. The simulation results were presented with a Parallel Coordinate Plot (PCP), which visualizes the entire solution set and allows stakeholders to filter the results gradually based on various preferences. The presented approach has the potential for well-informed retrofit decision-making through the visualization of two different but interrelated design and performance spaces simultaneously, where the relationship between these two spaces can be explicitly visualized. Using these visualizations, different means of evaluation were discussed according to various stakeholder types.

Keywords: Building retrofits, decision-making, performance-informed design visualization, multi-objective performative design, exploratory research.

Introduction and Literature Review

Rapid industrial and technological progress have adverse effects on the earth's climate system. The climate system is under threat than any point in human civilization history, and change in the climate is seen as the most significant global and longterm problem of the 21st century (Barros et al., 2014). Greenhouse gas emissions in the atmosphere have the most impactful factor in climate change (Intergovernmental Panel on Climate Change, 2014). The need for the implementation of effective mitigation strategies plays a critical role in reducing the harmful effects of climate change caused by greenhouse gas emissions.

The construction sector is responsible for 30% of carbon emissions and has more than 30% of the total energy consumption globally (International Energy Agency (IEA), 2018). These emissions are largely due to the existing building stock rather than the new constructions, which have a small share of the emissions per annum (Durmus-pedini & Ashuri, 2010). Besides, the operational CO_2 release in a building is almost 80% of its total life cycle carbon emissions (Ramesh, Prakash, & Shukla, 2010). Therefore, improving the performance of existing buildings in terms of energy and environmental impact is necessary to achieve low energy demand and low carbon emissions towards climate change mitigation and adaptation.

Building Retrofits

Building retrofits comprise of the refurbishment of building elements and systems with better performing alternatives (Güçyeter & Günaydin, 2012). Improvements in the existing buildings' performance can be achieved with well-planned retrofit actions, which are practical solutions to improve the buildings' as-is performance and reduce the energy demand and greenhouse gas emissions (Jagarajan et al., 2017). Various studies have highlighted the issue of building retrofits' significance in achieving four main performance criteria: (1) Energy efficiency (Paiho, Seppä, & Jimenez, 2015), (2) Environmental impact – life cycle assessment (Huang et al., 2017; Walker, Lowery, & Theobald, 2014), (3) Occupant comfort (Berardi & Manca, 2017; Park et al., 2020), (4) Architectural and functional quality (Mora, Cappelletti, Peron, Romagnoni, & Bauman, 2015).

Buildings are made up of various complex systems, and the application of retrofits in any single system affects the overall performance of buildings (Giebeler et al., 2013). In retrofits, systems in a building can be intervened separately or at the same time to improve a building's performance, e.g., thermal comfort, visual comfort, acoustic comfort, environmental impact, energy efficiency, and indoor air quality through various interventions, depending on passive and active system renewals (Bernier, Fenner, & Ainger, 2010). Interventions may differ in scale according to the planned renovation rate and are classified in the literature as small, medium, and large scale retrofits (Hyde et al., 2019). For instance, while roof insulation material replacement from outside is considered as small; the interventions that make a huge impact in the outer shell, such as replacement of fenestration components or installment of air conditioning systems are accepted as medium scale; and lastly, the heating system and material replacement of an entire building are considered as large scale retrofits.

The prospective retrofit actions should be carried out within a planned process by focusing on more than one factor (Danny Harvey, 2012). Even though building retrofits directly aim at improving buildings' energy performance or environmental impact in general, there are other constraints related to economic (i.e., project delivery or management costs), cultural (i.e., heritage value, conservation concern), social (i.e., adaptation of users), legal (i.e., building regulations), functional (i.e., usability or maintenance), aesthetical and technology dimensions as well (Shen, Braham, Yi, & Eaton, 2019). Every constraint represents a performance objective to consider during the decision-making processes. These objectives' performances can change depending mainly on the use of different building parameters (e.g., changing exterior shading elements' dimensions, increasing the number of surrounding trees or insulation material thicknesses for the exterior walls).

Decision-Making in Retrofit Processes

According to Michalos et al., there is not a single solution to the design problems; instead, there is a set of solution clusters (Michalos & Simon, 1970). According to Akin (Akin, 2001), rather than focusing on a single solution in the design processes, finding a final solution by the repeated evaluation of the design alternatives in an extensive solution set is one of the most important factors that show the expertise of a designer. The larger the set with alternative solutions, the more likely it is that design problems can be solved effectively by eliminating other alternatives and achieving the final solution. There are many alternative approaches to meet with a particular performance objective or solving a design problem over different building parameters. Some building parameters may help decision-makers to reach similar performance objectives. For instance, in order to improve summertime indoor occupant comfort in a building, decision-makers can mount exterior shading elements, or they can achieve a similar solution by installing an air conditioning unit. Also, there might be conflicting interests between the impacts of building parameters on the performance objectives (Mora et al., 2015). Even though both of the solutions focus on occupant comfort, the use of air conditioning systems has more adverse effects on the energy consumption of a building compared to the exterior shading element installment. Therefore, the identification of possible building parameters and analysis of the parameters' performance are critical to preventing unexpected outcomes in retrofit processes.

There are several challenges in the decision-making process for retrofit actions. The application and planning phase of building retrofits are expertise required complex processes (Novikova et al., 2011), where designers, engineers, and many people from other professions have to work together (Gultekin, Anumba, & Leicht, 2013). Each stakeholder's involvement in retrofit processes adds a new layer to the design, making it increasingly difficult to complete the already complex decision-making process. Moreover, the selection of the most effective design parameters and identification of performance objectives among a vast amount of similarly performing alternatives and many parameter combinations is accepted as a confusing and labor-intensive process for decision-makers (Ruparathna, Hewage, & Sadiq, 2016) because each different building parameter and performance objective increases the number of possible solutions exponentially (Tresidder, Zhang, & Forrester, 2011). The conflict between stakeholders on their preferences for the identification of parameters and performance objectives is a commonly faced problem in retrofit processes since there is often a trade-off between the objectives (Radford & Gero, 1980). These kinds of challenges in decision-making processes between stakeholders may cause serious consequences, leading to prolongation or even cancellation of retrofit actions (Tuominen, Klobut, Tolman, Adjei, & De Best-Waldhober, 2012). These challenges can be overcome effectively for decision-makers to reach retrofit solutions reviewing many different design alternatives collaboratively. The success of retrofit actions is directly proportional to the designers, engineers, and customers' collaborative exploration of the most effective retrofit options (Liang, Peng, & Shen, 2016). These options should satisfy and be accepted by all involved stakeholders in retrofit processes for achieving a successful solution (Woo & Menassa, 2014).

Building Performance Simulation for Retrofits

Building performance simulation (BPS) provides effective results in quantifying the effect of planned refurbishment actions in existing buildings and in predicting the new buildings' performances before they are built (Hong, Langevin, & Sun, 2018). In order to facilitate the decision-making process, exploration, and evaluation of design alternatives, BPS is frequently used in the construction sector and academia (Crawley, Hand, Kummert, & Griffith, 2008). BPS facilitates decision-making processes by presenting an integrated approach for a better understanding of design parameters and their effects on performance objectives (Hensen & Lamberts, 2012). The discovery of relationships between building parameters can be achieved to meet particular performance objectives in the solution set (Dino, 2012). In BPS, depending on the size of the building, many parameters and objectives can be tested, and finding an effective solution from a vast amount of alternatives can be challenging (Wright, Nikolaidou, & Hopfe, 2016). However, evaluation and conduction of many design alternatives in a solution set require meticulous focus and plenty of time during the retrofit planning processes (Giannakis, Kontes, Korolija, & Rovas, 2017).

For facilitating the decision-making process even further, in recent years, various optimization techniques were introduced in BPS (Nguyen, Reiter, & Rigo, 2014). Optimization techniques in BPS help designers to manage large solution sets and reduce a vast amount of design alternatives to a more manageable size by eliminating the least favored alternatives according to the selected objectives. Optimization can help decision-makers in finding the optimum building parameter values for meeting a particular objective or an optimum solution between multiple or single objectives. According to Evins (Evins, 2013), the algorithms used in optimization techniques are divided into three groups: namely, hybrid algorithms, direct search algorithms, and heuristic algorithms. Evolutionary algorithms are the most often used algorithms with the BPS simulations that have a share of about 60% (Si et al., 2018). The most common types of evolutionary algorithms include the genetic algorithms (GA) (Michalos & Simon, 1970) and its derivatives, e.g., non-dominated sorting genetic algorithm II (NSGA-II) (Deb, Pratap, Agarwal, & Meyarivan, 2002).

On the other hand, the optimization results are presented in Pareto-based charts and diagrams in point-based solutions, where the relationship between design parameters and performance objectives cannot be established easily. Moreover, optimization algorithms cannot guarantee that the optimal solution will be delivered to the decision-makers. Selection and elimination processes in optimizations may omit several good alternatives that could have been preferred by some decision-makers. Even though the optimal solution could be found in the optimization studies, there is no assurance that the final optimum solution will satisfy stakeholders' preferences on performance objectives. According to Bradner (Bradner, Iorio, & Davis, 2014), the computed optimum solution generally serves as a starting point for the design instead of the final solution. Stouffs et al. (Stouffs & Rafiq, 2015) assert that the exploration in design processes should be aimed, and designers should not directly apply the solutions delivered by optimizations. The computational optimization algorithms are helpful to guide decision-makers in finding effective design solutions and can change one's way of thinking. However, their results should not be accepted as the ultimate or the best design solution because the delivered results might be limiting and generally miss several good alternatives.

An integrated evaluation of design alternatives, their performances, and relationships between each other is still required. These should be presented to decision-makers for retrofit planning processes in a collaborative environment that can facilitate the decision-making processes by allowing exploration and selection of useful solutions together. In this study, a user preference-based decision-making approach for building retrofit processes, and the benefits of the processing of multiple design parameters and objectives simultaneously for alternative retrofit solutions from multiple points of view are discussed. In this regard, a hypothetical office building is selected, and an energy model is developed with various design parameters and objectives. All possible design combinations' simulations were conducted and visualized in a single diagram in an interactive and integrated way. The diagram was divided into interrelated two spaces, design and performance space, for a broader exploration of alternative retrofit solutions to increase stakeholders' control over design decisions for improved building performance.

Methodology

Exploratory Decision-Making Process

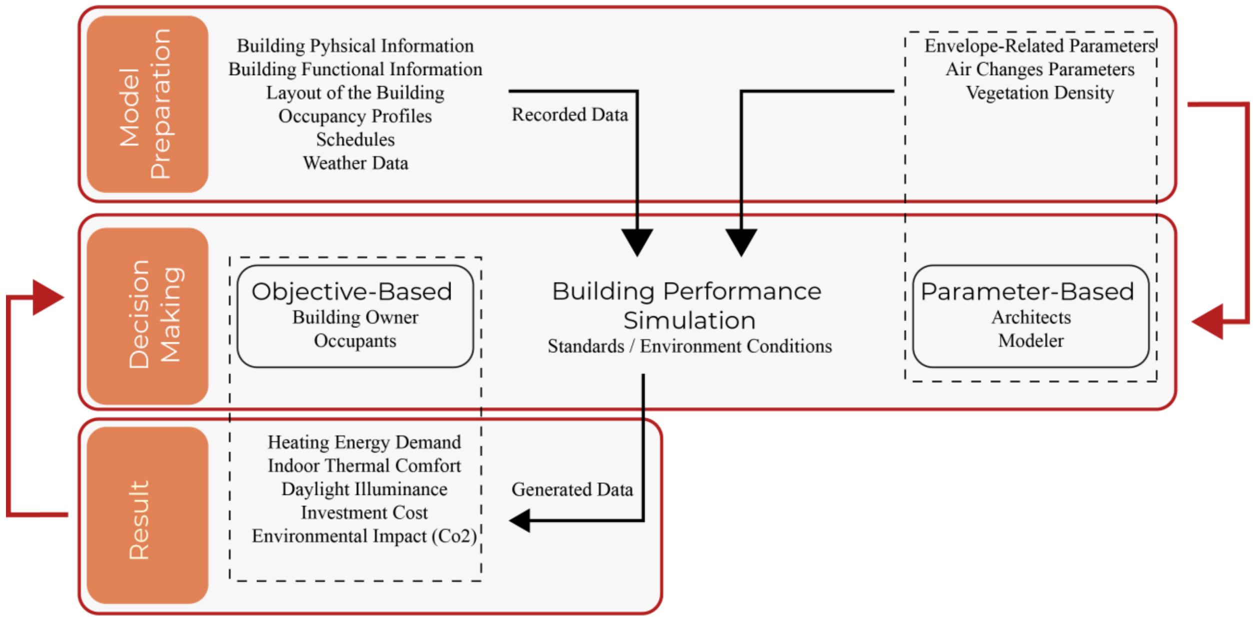

Figure 1. The boundaries of the study

During the planning phase of retrofit processes, decision-makers are autonomous agents in design exploration when they are provided with a well-ordered solution set. In exploratory decision-making processes, the broader the solution set is higher the chance of finding an effective design solution. In this regard, seeing and evaluating all of the design solutions may lead to giving better decisions. The instrumentalization of BPS in retrofit processes can be reached its full potential by collaborative design exploration conducted by decision-makers from different professions with as many alternatives possible.

This study points out the necessity of the involvement of different decision-makers in the building parameter and performance objective exploration during retrofit processes informed by BPS. Consequently, a hypothetical exploratory decision-making process is presented and discussed over a case study building. In the discussed approach, an energy model was first generated by employing different building parameters (i.e., infiltration rate, thermal properties of building envelope elements), and recorded data (i.e., occupancy profiles, schedules). The generated energy model, along with its parameter combinations, were simulated. Then the whole solution set was visualized in an interactive diagram. The diagram was divided into two parts, including parameter-based design space and objective-based performance space. Over the diagram, different means of evaluations were discussed according to the stakeholders' priorities.

Hypothetical Digital Energy Modelling Process

In order to discuss the exploratory decision-making process, several retrofit simulations were performed over a case study, which is a hypothetical office building (Figure 2-a). The main aim of the model is the presentation of the algorithmic process for decision-makers. All of the recorded energy modeling data inputs (i.e., occupant profiles, schedules) were defined in the analysis model. Various building parameters that have the potential to expand the solution set by complex relationships (i.e., parameters that may work similarly or oppositely) with each other or the performance objectives were added to the analysis model to test the discussed decision-making process. The total simulated area is equal to 300 m^2. The simulation model consists of 3 thermal zones, including open office, conference, and corridor (e.g., entrance) spaces. The location is selected as Ankara, which has a dry continental climate with hot-dry summers and cold winters. Also, occupancy, heating, and lighting period schedules are different for each zone to represent ideal daily occupant activity in the analysis model. Ideal loads that are representative of a theoretical HVAC system are calculated (US Department of Energy, 2010). For the building energy simulations, EnergyPlus (US Department of Energy, 2010) was selected. Due to the computational capacity and the algorithmic model design, Honeybee/Ladybug building energy assessment tools (Roudsari & Pak, 2013), which have a visual-coding interface, were used.

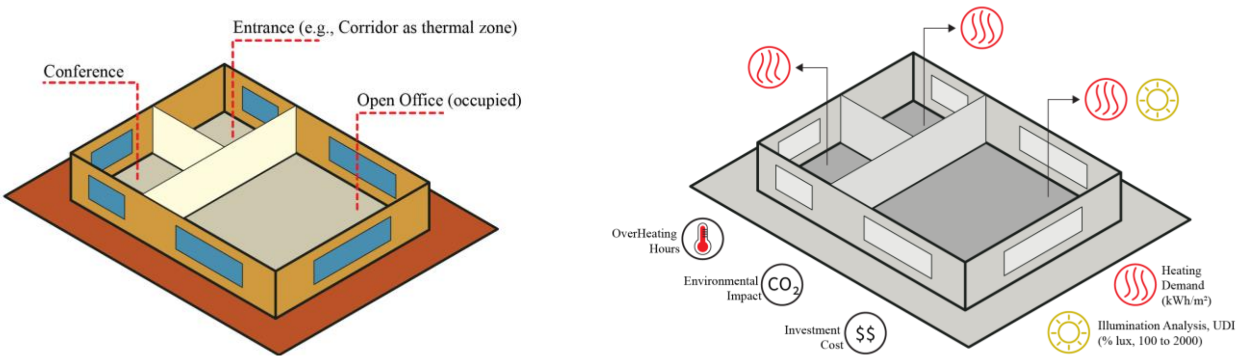

Figure 2. (a) Digital Building Model; (b) Analysis types in the thermal zones

Table 1 shows the building parameters and performance objectives of the analysis model. All parameters were selected as discrete values to reduce the computational cost. Several different building parameters that focus on building envelope, its landscape, indoor zone characteristics were defined in the analysis model (Figure 3). Besides, there are five different objectives for the simulation process. The zone-based objectives consist of heating, overheating hours, and useful daylight illumination (UDI) demands, and the building-related objectives are defined as overheating hours, environmental impact, and investment cost (Figure 2-b). UDI consist of the total percentage of the annual values between 100 – 2000 lux, which measures sufficient daylight for indoor activities.

Table 1. Design parameters and objectives defined in the analysis model

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
Selected Retrofit Scenarios	Lighting Density	Ventilation per Person	Infiltration Rate	Glazing Opening Ratio	Glazing Type	Shading Types, Interior	Roof Insulation	Wall Insulation	Floor Insulation	Surrounding Trees
Unit	W/m^2	m^3/s-person	m^3/s per m^2 facade	%	U value, SHGC	Reflectance, Transmittance	w/m^{2}K	w/m^{2}K	w/m^{2}K	% Density
Range	Discrete									

	Y_1	Y_2	Y_3	Y_4	Y_5
Selected Objective	CO_2 (ppm)	Heating Energy Demand (kWh/m^2)	Useful Daylight Illumination 100 lux to 2000 lux (UDI)	Cost ($)	Overheating Degree-Hours according to ASHRAE (ASHRAE, 2004)

The simulations were run for four weeks for different seasons. Relatedly, the design parameter value range discretized to reduce the size of the solution space. The overheating degree hours objective calculation is the cumulative summation of all the indoor temperature values passes the 28°C threshold value. This objective is essential to calculate the design parameters' impact in the summer period when the heating system is not actively used. As an environmental impact indicator, CO_2 emissions are implemented in the analysis model. The calculation method of the $C0_2$ objective comprises the cumulative calculation of the indoor zone's CO_2 particles, which are higher than 1000 per million, as suggested in ASHRAE (ANSI, 2007). The cost objective is calculated by assigning each design parameter a monetary value. It is important to state that the cost for the existing conditions of the building is assumed as equal to zero, and the cost objective for the design alternatives are calculated by aggregating the monetary values.

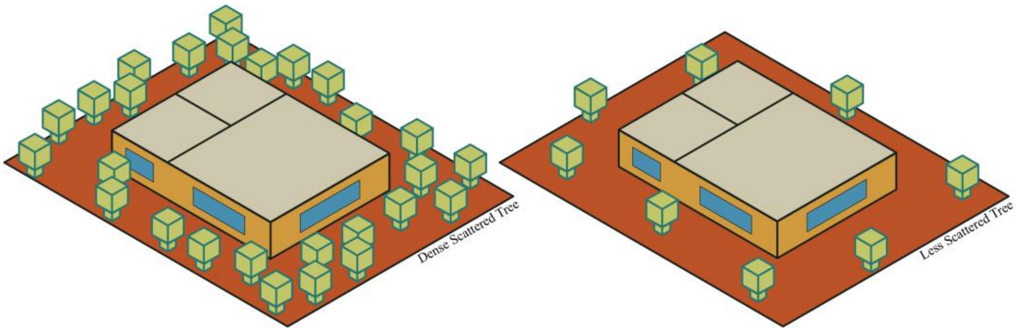

Figure 3. Design parameter example

Visualization of the Simulation Results

Interactive and integrated data visualization transforms crude information or complex data sets into a more apprehensible form as decision support for decision-makers (Janvrin, Raschke, & Dilla, 2014). With a clear understanding of the variation between all design options and their impact on building performance, the complex relationship between design goals, constraints, and effective design solutions can be revealed through effective visualizations in exploratory design. In this way, stakeholders can be more engaged in a dynamic decision-making process and contribute to it with their points of view.

In this study, Parallel Coordinate Plot (PCP) is selected as the primary visualization method. PCP was generated by using Design Explorer 2.0, a web-based interactive visualization tool to visualize and label all the simulation results (Thornton Tomasetti, 2020). Stakeholders can use this interactive visualization technique and can explore a vast amount of alternative design solutions that were not easy to be spotted in conventional visualization methods, e.g., bar or line based charts. PCP may allow stakeholders, including designers, engineers, users, and building owners, to observe all design alternatives in a single diagram. The employed PCP visualization can offer to filter the solution set in order to focus on some areas on the diagram and can provide direct feedback to decision-makers. However, using the whole diagram with many stakeholders may still cause problems and lead to conflicts in the selection of effective solutions. In this regard, two different but interrelated spaces, e.g., objective-based performance and parameter-based design spaces (Figure 4), are recommended to be focused by decision-makers according to their priorities.

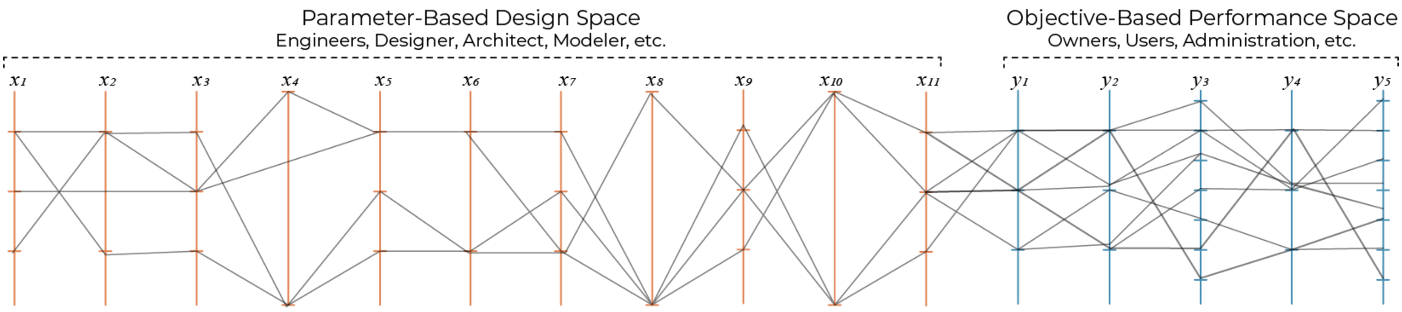

Figure 4. PCP representation of the simulation results

A distinct space for parameter exploration, namely, design space, can be accessed by all stakeholders. These stakeholders can simultaneously switch between these parameters and observe the changes in the performance space. In this way, the connection between parameters and performance can be established more visibly. In this study, the design space consists of different variables for building parameters (i.e., U-values for envelope materials or ventilation rates), including the values specific to the existing building's current condition (baseline scenario). According to the preferences of these stakeholders in the design space, satisfying design solutions can be re-evaluated in the performance space.

On the other hand, the performance space comprises of different objectives, criteria, and targets of stakeholders. It is presumed that owners, occupants, and administrative stakeholders may tend to focus on performance space rather than the technical aspects of the design parameters. These stakeholders can focus on the final results which arise from the implementation of various design parameters. In this study, heating demands, overheating hours, investment costs, useful daylighting illumination, and operational CO2 were defined as the primary performance objectives. These stakeholders can define the maximum and minimum limits in the defined objective values and can evaluate the various retrofit solutions which satisfy their criteria.

Results and Discussion

An exploratory research process with performative simulations was completed with 2048 design alternatives, which consist of 10 design parameters and their combinations. Five performance objectives were defined to evaluate the parameters' impact on the overall building performance. All of the simulation results were visualized by using PCP. The exploratory multi-objective retrofit decision-making process discussed in this paper focuses on the alternative ways of evaluation using the results of the case study.

The discussed approach in this study can be evaluated by stakeholders in three alternative ways, including the design parameter-based, performance objective-based, and the hybrid evaluation process. Figure 5 shows an example that points out the parameter-based evaluation processes. In the upper part of Figure 5, a group of technical designers/engineers may apply filtering for a design-parameter, which is the indoor shading design of the building. The corresponding parameter is discrete and has two options. The stakeholder group can select a variable among them and can see all alternative solutions where the selected variable is involved. However, most of the retrofit applications focus on multiple objectives and design parameters, and filtering for one design parameter does not yield a clear solution set to evaluate. In this regard, the stakeholders can apply filtering for multiple design parameters as well, as it is seen at the bottom of Figure 5. The implementation of filtering for multiple design-parameters decreases the number of alternative solutions in the performance space. Then, the remaining design solutions can be re-evaluated according to their performances in the selected objectives and the priorities of all stakeholders. For instance, the remaining alternatives can be ranked according to the amount of the total CO_2 emissions if it has a high priority for stakeholders; then, they may select the best performing retrofit solutions accordingly.

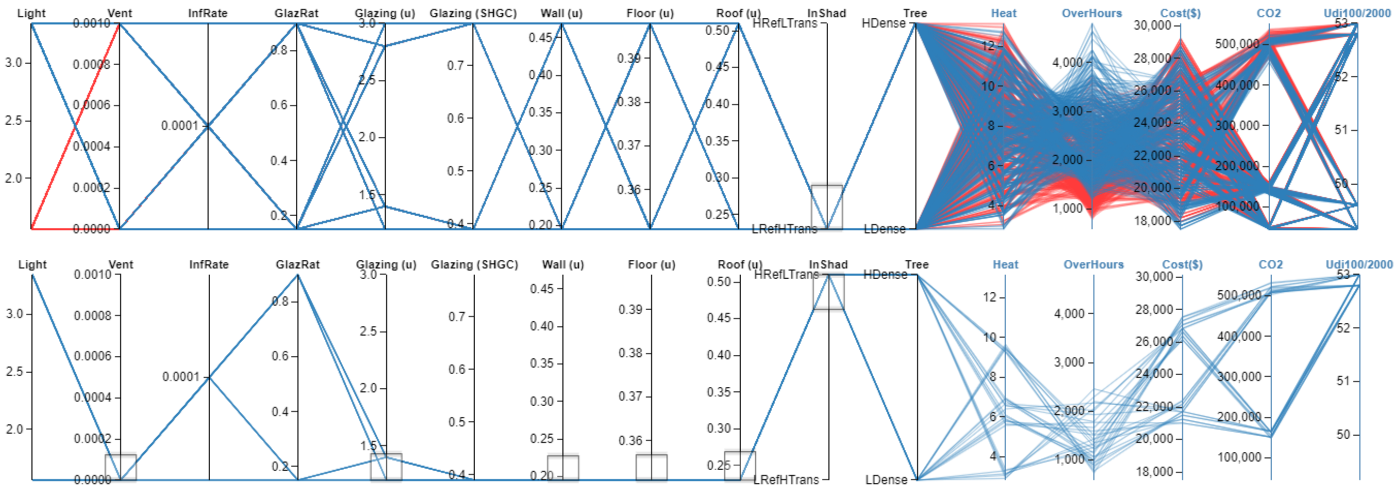

Figure 5. Design-parameter based interpretation of the results

As an alternative way to parameter-based alternative evaluation processes, the performance objective-based process can also be used in the presented approach. This evaluation process is assumed to be more common in non-technical stakeholders because they are more concerned with the final results rather than the used products, systems, or design parameters. In the scope of the study, several objectives that can reflect the different stakeholders' concerns were defined in the analysis model. For instance, monetary values of the planned retrofit actions are one of the top concerns of building owners or administrative staff who generally aim to decrease the cost of investment and maintenance of buildings. As another example, building's comfort performance more typically related to the occupants because the other objectives, such as cost or heating energy performance, may not directly affecting them. Also, there are several mandatory standards to be met for the application of retrofit processes in terms of operational carbon emissions. In Figure 6, the case study's solution set was evaluated by following a performative objective-based process. In the above part of Figure 6, filtering was applied for the heating demand of the building. This filtering on a single objective decreases the number of solutions, but still, it does not propose a clear explanation for the alternative comparisons. At the bottom part, filtering was applied for each performance objective by selecting the areas where the best performing alternatives are populated. Then the remaining results can be re-evaluated by checking the design space. According to the stakeholders' priority on the performance objectives, design parameters can be selected. However, there might be some uncertainties for some design-parameters. For instance, even though filtering was applied, there are similarly performing alternatives for the surface U-values. In this case, technical stakeholders can involve the process for helping to achieve a final decision.

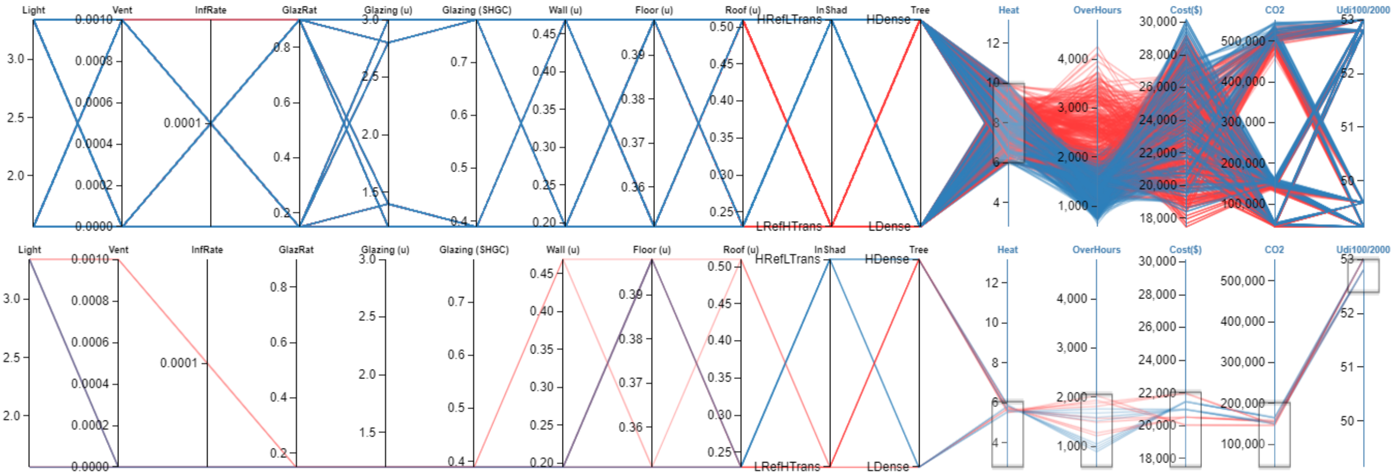

Figure 6. Performance-objective based interpretation of the results

Apart from the previous evaluation processes, the solution set can be evaluated by employing a hybrid way where both parameters and objectives can be used in filtering. In this case, while technical stakeholders can apply filtering for a few parameters that they consider necessary to them, likewise, non-technical stakeholders can also select their desired values among several high priority objectives. Then the remaining alternatives can be eliminated with all the stakeholders until reaching a satisfactory retrofit solution.

Consequently, in all of the discussed means of evaluation, there should be a compromise between all stakeholders for effective performance-based decision-making processes. The communication between stakeholders is an essential part of these complex processes, and it can be enhanced by effective and integrated visualization techniques. The discussed visualization method may prevent stakeholder conflicts by leaving a space where all stakeholders can review all results in light of their expertise and consult each other to reach a final retrofit solution. At the same time, these interrelated spaces, namely performance and design space, can promote collaboration between stakeholders by understanding each other's concerns and aims. Stakeholders can come together to decide several performance targets and try to reach their specific goals by selecting the related design parameters (Figure 6). Alternatively, they can choose design parameters first and then try to select the best performing design options by checking the performance space (Figure 5). Also, they can focus on both of the spaces and try to approach the selection process by reviewing the whole diagram. Finding a solution that redresses the balance between performance space and design space may satisfy all stakeholders and lead to achieving the most robust retrofit solutions for their buildings.

Conclusion

In this study, a decision-making approach is discussed, which may allow stakeholders to explore the parameters and objectives to be used in retrofit studies according to their priorities and expertise. Within the scope of this study, a typical office building was modeled with various design parameters and multiple performance objectives in a BPS tool; for the exploratory design process, simulations with different parameters and all possible combinations were conducted and visualized via a PCP in an interactive and integrated way. The discussed approach in this study can be evaluated by stakeholders in three different but similar ways, including the design parameter-based, performance objective-based, and the hybrid evaluation process. With PCP visualization, both design space with all the involved design parameters and performance space with all the employed multi-objective performance criteria can be presented to the decision-makers. The study points out that during retrofit planning processes, decision-makers can reach effective retrofit decisions by narrowing the alternative solution set through exploring these two different spaces. With an interactive PCP, sub-optimal design alternatives can be filtered interactively, and all stakeholders can take an active role in retrofit planning processes by evaluating the simulation results simultaneously. All stakeholders can declare their concerns or requirements, and the possible retrofit solutions can be decided over the interactive PCP by collaborative decision-making. For a better understanding of the suggested approach's limitations and potentials in decision-making processes, it is suggested as further studies are undertaken, where stakeholders actively engage in the decision-making of retrofit actions in an actual setup.

Acknowledgments

This research was supported by the Newton – Katip Celebi Fund, Grant No. 217M519, by the Scientific and Technological Research Council of Turkey (TUBITAK) and British Council, UK.

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