Decision Support Tool for Energy Flexible Office Buildings

			
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We present a tool that helps building designers design office buildings with high energy flexibility. The tool provides them with information they need in order to choose building and system parameters to achieve the highest amount of energy flexibility possible and satisfy the comfort of the occupants.

Keywords: Office building, energy flexibility, productivity loss, decision support tool, building design, self-consumption, building performance simulation

Background

When stepping forward as a society, any move towards a greener future should include buildings as a main focus. The growing need of decarbonizing our energy, calls for the integration of more renewable energy sources (RES) such as solar and wind. Many RES has a stochastic nature. This results in fluctuations in the electricity production by RES and this increases the risk of discrepancies between energy supply and demand. One way to deal with this mismatch is by using demand side management. The so-called energy flexibility of buildings can be used for this purpose. The energy flexibility of a building is the ability of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements [1]. An example of energy flexibility is utilizing the thermal mass of the building and use pre-heating and pre-cooling methods to achieve load shifting when energy demand is high. Energy flexibility is also one of the pillars in defining the smartness of a building and a vital factor in supporting future energy systems. To exploit and utilize an energy flexible building, its full potential should be known along with how other indicators such as cost and comfort are affected by exploiting this potential.

Design Tool for Building Energy Flexibility

In this article we present a tool that helps building engineers in the design process. The tool supports designers in every step of the design process when choosing building parameter values and thermal comfort strategies. The tool is developed in corporation with BAM; a major construction company with its headquarters in the Netherlands. The tool is focused on office buildings in the Dutch market and targets both new office buildings and renovation offices. By just a few clicks, the designer can select the design parameters that are fixed already and he can leave open the ones that they want to explore. Subsequently the decision support tool presents the best available design solutions. These solutions score the highest on both energy flexibility and productivity/comfort, but also show the lowest energy consumption and cost (investment and operational). Using the tool, designers can quickly and easily get vital information about the performance of the building design and receive support on how to optimize the design in order to arrive at a high-performance office building. The tool focuses on comparing building design variations and how their performance compares with each other. Note that the tool does not provide predictions on the actual energy or comfort performance during operation. A fully functional version of the tool with the appropriate user-friendly designed interface is not available yet, but is work in progress.

Development of the tool

The tool is based on a database which contains simulation results of 839.808 office building variations. Each database entry contains scores on several relevant performance indicators. A building performance simulation software (EnergyPlus) and machine learning are used in order to develop the database. The database is filled with cases that are simulated and cases whose results are predicted through surrogate models developed by classification algorithms. The predicted results from the machine learning algorithms are validated to be sufficiently accurate for this study [2].

Interviews with the potential users of the tool were performed in order to identify the requirements of the tool, the relevant performance indicators and the design parameter variations that needed to be included in the database.

Performance Indicators

The following performance indicators are selected based on the interviews.

- Cost: Divided in operational and investment cost

- Yearly energy consumption: in electricity assuming a heat pump connecting to the delivery system with a COP of 3.
- Productivity loss: Productivity loss is based on and calculated through thermal comfort and indoor climate. Using PMV values and air temperature along with freshness and CO_2 concentration in the offices, productivity loss in the cases that the tool investigates, is calculated based on the average loss according to several studies that have been presented in literature [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13]. More information on the calculation can be found in [14].
- Energy flexibility: Quantifying the energy flexibility that each design variation potentially can offer is implemented through two different assessments and their corresponding indicators: the characterization assessment and self-consumption assessment.

Energy flexibility characterization

Energy flexibility characterization is included in this project by utilizing the suggestions of [15]. Grønborg et al. suggest that a static building can be characterized based on its flexibility potential and introduces a novel methodology, the Flexibility Function. The Flexibility Function assumes a building in a steady state for every time step and a penalty signal that is given by the controller (price, CO_2 etc.). The signal aims to control the demand. Before the signal, the building is operated in the highest (in winter) or lower (in summer) breach of the temperature range that is acceptable. When the signal is received from the building, the terminal system is either shut down or lowers its setpoint to save on operational cost (as seen in **Figure 1** that the setpoint is lowered). The terminal system starts to consume energy again when the comfort or temperature values fall outside the accepted range of values. (e.g. when PMV<-0.7 or >0.7, or Top<20 or Top>25).

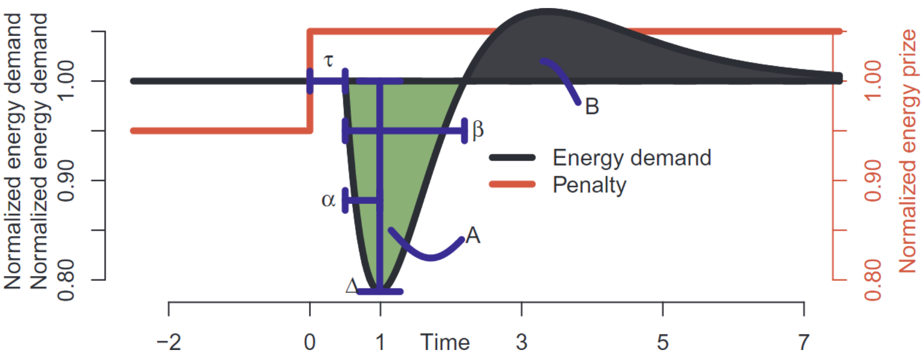

Figure 1. Building response to a penalty signal [15]

That way, as seen in **Figure 1**, the area labelled as A is considered as the amount of energy that can be shifted and it can give an indication of the potential of energy flexibility a building design can provide. In the simulations for the energy flexibility characterization, a weather file with constant temperature and no irradiation is used, which eliminates the effect of weather conditions. This allows us to compare different building design variations and to suggest which one has the ability to shift a greater amount of energy. Note that by eliminating the influence of the climate, the building orientation does not play a role in the comparison of different building design variations.

With respect to acknowledging the effect that the weather can have on the ability of a building design to offer energy flexibility, and to inspect the self-consumption of each design, a second set of indicators is used. Note that per building variation another simulation (including a realistic weather file) is necessary to assess these indicators.

Self-Consumption
The On-site Energy Matching (OEM) and On-site Energy Fraction (OEF) can help the user to identify the matching of generation and demand for each design. OEM represents the percentage of the energy generation on-site that is used to cover the demand of the model, while OEF represents the percentage of the energy demand of the building that is covered by its generation [16].

Building design variations

The building variations that are investigated in this project were agreed with BAM engineers in order to ensure that typical Dutch office parameters are included and that expectations are met. Different envelope parameters are studied such as external wall Rc value (e.g. Rc value of 3.5 to 9 m^2K/W), room dimensions and orientation. Moreover, the layout type (open plan or cellular) of the office building was investigated along with the thermal capacity (e.g. heavyweight, lightweight), glazing parameters such as U value (e.g. 0.8 to 3 W/m^2K), g value, Window to Wall Ratio (e.g. from 0.4 to 1), thermal comfort control strategies (e.g. different setpoints), different heat/cold delivery systems, occupancy scenarios and internal heat gains.

Thermal Comfort Control Strategies

Thermal comfort requirements form one of the main boundary conditions for energy use in buildings. With that they set criteria for the heating and cooling demand. Considering thermal comfort control strategies, the typical strategies that are normally applied in Dutch offices are considered and furthermore, different strategies that were the outcome of field thermal comfort control studies at TU/e through the iCARE project are included [17].

Loomans and Misha suggest that occupants have a connection with the outside temperature for at least 20 min, and a diurnal variation of 3°C is not noticeable in an office environment. Finally, they suggest that a transitional space can have 2°C difference in the setpoint without jeopardizing the comfort of the occupants. All observations of the iCARE research and their combinations are implemented in this project as parameter values in the thermal comfort control strategies. One more extreme value for each strategy proposed by iCARE is also included to explore the effect it could have on the indicators chosen. In total, 27 thermal comfort control strategies are investigated in this project.

More information on the assumptions and design parameters can be found in [14].

Filtering the database – A case study

This section gives an example of a case study building and the possible design variations that can be found using the developed database.

Step 1: Building design exploration

The case study building that is used to showcase the tool is a building in need of renovation. The case study building resembles the BAM building D in Bunnik. Assumptions are made for the fixed parameters and for the parameters which are still open to investigate. The tool-user is assumed to be a designer who is mainly concerned about the operational cost of the office building. **Figure 2** shows the input page of the tool. The parameters that the user can input are depicted. If a parameter is decided, the user can "lock" it; only the results with the locked parameters are presented in the results tab. The unlocked cells, which include a dash instead of a parameter value, represent the undecided parameters; the designer wants to explore various values for these parameters.

In this example, the decided parameters are:

- Heavyweight construction
- 4.5 meters façade
- 6 meters office depth
- WWR 0.7
- Adjacent temperature the same as the offices and corridor
- Air based heating and cooling system

Undecided parameters:

- U-value glazing
- G-value glazing
- Type of offices
- Occupancy scenario
- Thermal comfort control strategies

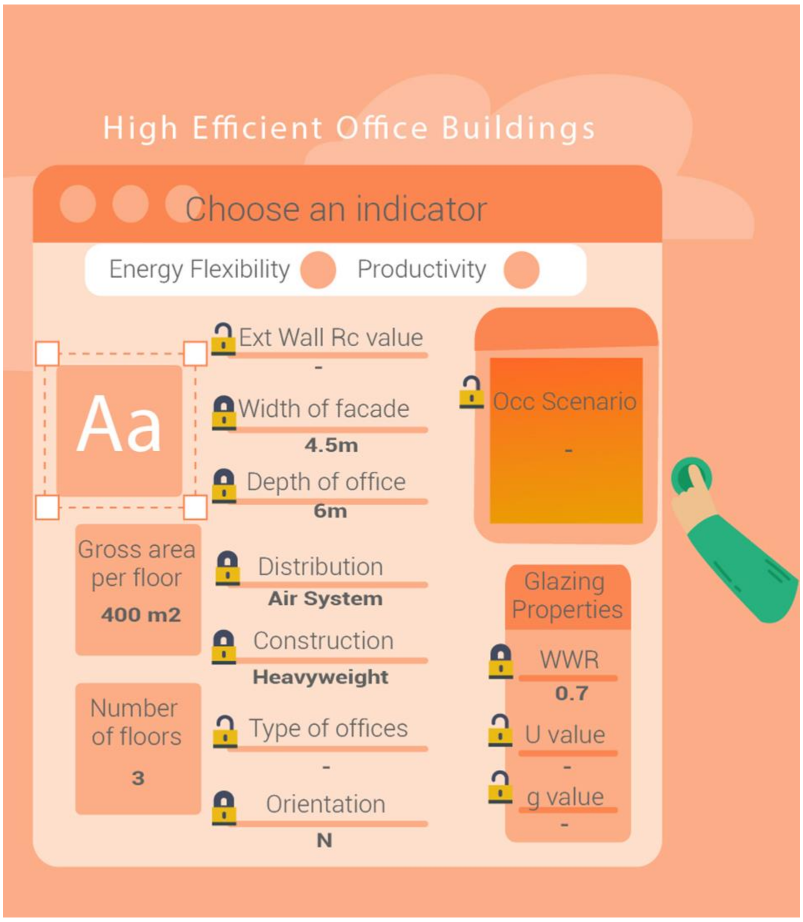

Figure 2. Mock Up of the input page of the product.

Presenting the results in a simple list, can obscure valuable information to the designer, while a more complicated approach such as a 3d graph can overwhelm the user and either confuse him or discourage him to use the tool. Interviews and literature review is used to identify the most valuable way to depict the results. In order to provide the most information without confusing the user, a 2d scatter plot is used. In order to decide which indicators will be taken into account in each graph, the conflicting indicators are considered. In every graph, the users can choose one of the design solutions on the graph and get all the information on that solution (building parameters, indicators' results, etc.).

Filtering of the database returns 5800 possible design variations. These design variations and their KPIs are presented in **Figure 3**. The figure shows all 5 800 designs on 2 axes. Normalized Investment Cost is on the x axis and Normalized shiftable energy on the y axis in the left graph, while on the right graph Yearly Energy Consumption and Productivity Loss related to the levels of thermal comfort and indoor climate are included. Each dot/bubble represents one building design solution. There are 5800 dots on each of the graphs. Shiftable energy based on the characterization method does not include the effect of the weather and occupants, which results in a lot of cases performing the same. These dots show overlap in the figure. The size of the bubble though represents the annual consumption and the colour represents OEF, so there are a few dots that score the same on the shiftable energy but have different annual consumption (size) and different OEF (colour).

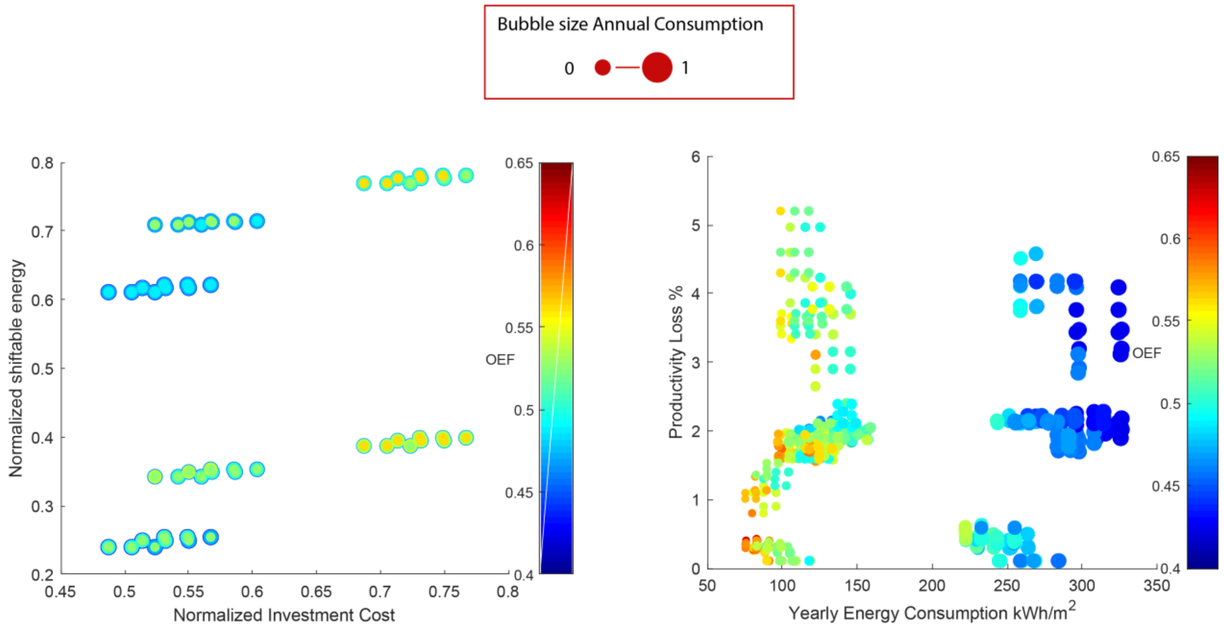

Figure 3. Results from filtering the database based on example 2.3 - All results.

Depicting all results on a graph might be confusing, so **Figure 4** includes only the Pareto solutions of the filtered results. That way, the designer can choose from the best ranking solutions. Again, the size of the bubble represents annual consumption, while the colour represents self-consumption (OEF).

Pareto efficiency is a state of allocation of resources from which it is impossible to reallocate so as to make any one individual or preference criterion better off without making at least one individual or preference criterion worse off. The tool-user can stop at this stage, choose the solution he finds more satisfactory and do not spend more time on the tool. However, if needed, the user can dive deeper in the results and get even more information.

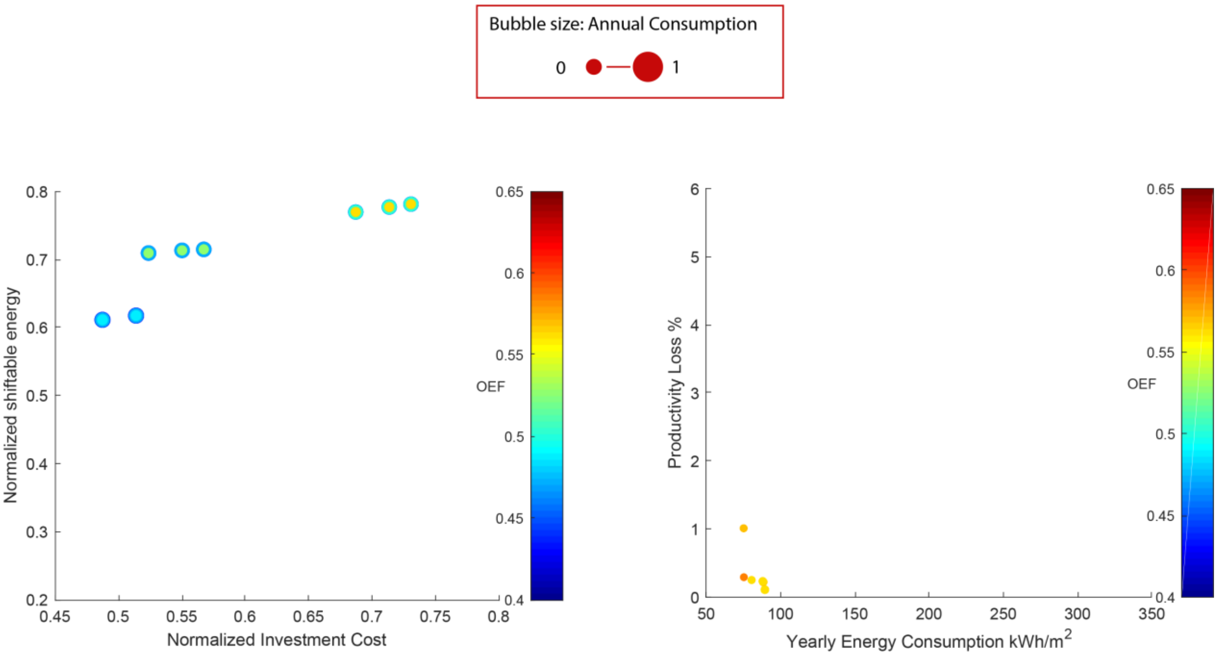

Figure 4. Results from filtering the database based on example – Pareto solutions.

Step 2: Detailed information per building design

As a second step, the option is given to choose a specific design parameter in order for the user to receive more information about how different design parameters affect the performance. The user will still see the same Pareto solutions, however the parameter values of the selected design parameters are presented through the colours of the bubbles.

For example **Figure 5 and Figure 6** still show the same performance indicators as in the previous figures, but the colours of the bubbles represent the Rc-values of the exterior wall and U-value of the glazing.

By examining **Figure 5**, the designer can extract information on how Rc-values and U-values affect productivity loss and potential shiftable energy. These figures show that the external wall Rc-value is not that dominant as all three investigated Rc-values are present on the Pareto front, while also low Rc-value cases offer high potential shiftable energy. On the other hand, even though all three investigated U-values are also part of the Pareto front solutions, it is clear that lower U-values offer higher shiftable energy potential.

Regarding the productivity loss in **Figure 6**, it shows again that the Rc-value does have an important effect, while the U-value seems to be more important. The cases that are included in the Pareto front for productivity loss and yearly energy consumption only include the lowest U-value investigated.

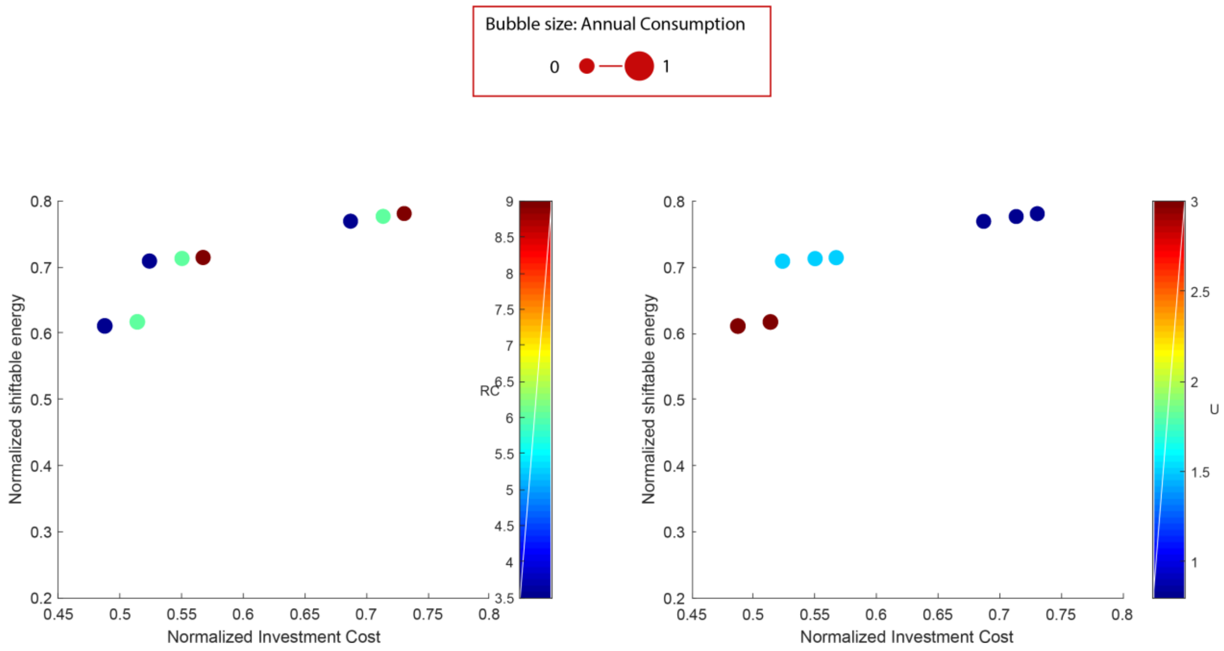

Figure 5. Results from filtering the database based on example - Pareto solutions -Energy Flexibility -Design Parameters.

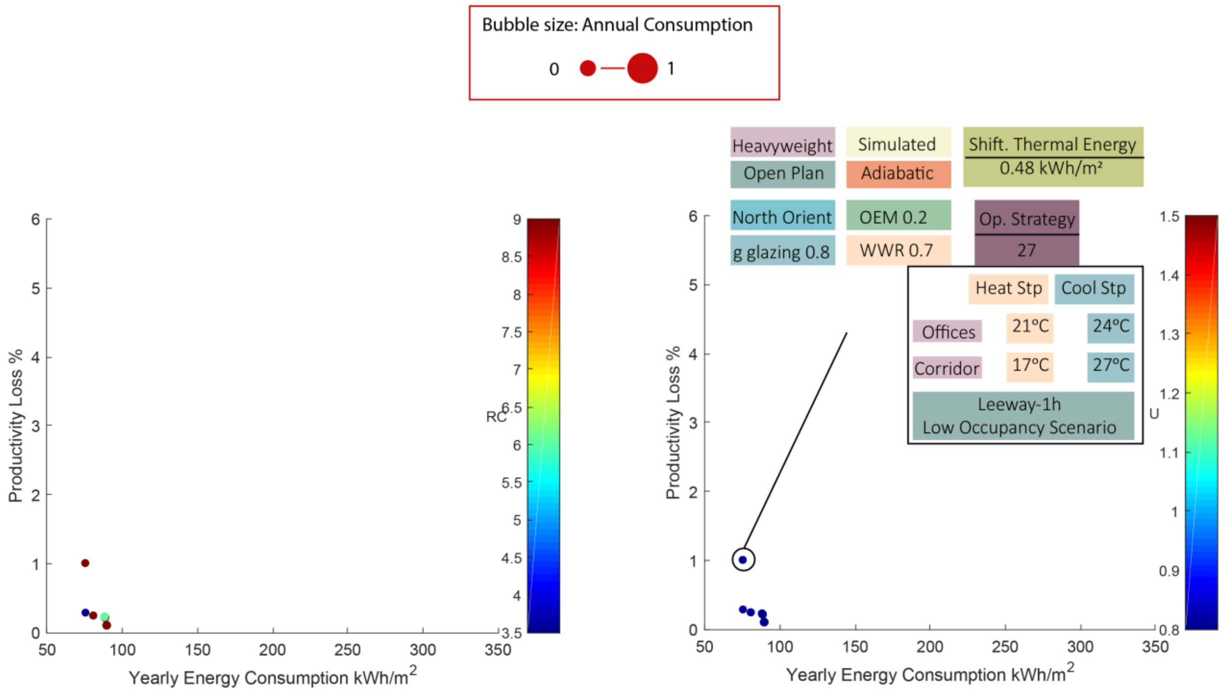

Figure 6. Results from filtering the database based on example- Pareto Front Results - Productivity Loss - Design Parameters.

Each building design variation can be studied thoroughly through all their parameters and results. For this case study building, operational cost is assumed to be the most important performance indicator. If the user selects the solution depicted on the productivity loss graph with the lowest operational cost, he/she can see all the building parameter values of that solution. The productivity loss, even though it is higher than of the other solutions, is still a percentage of 1%. Each bubble represents a building design variations and by clicking on it, the user can see its specific parameter combination and its result on different Performance Indicators as seen in **Figure 6**. By examining all the results of this building variation, it can be seen that the shiftable energy that a building envelope like this can offer is not in the range of the Pareto front solutions but it is also not in the lower part of the spectrum. So this solution is believed to be one of the fitter ones for this renovation case.

Step 3: Sensitivity analysis

As a third step the user can get more detailed information about a specific design solution. When the user chooses a specific solution, along with the specifics of the parameter combination, box plots appear. The box plots show how one design parameter affects the performance indicators (**Figure 7, Figure 8**). To showcase an example: if the user chooses one of the design solutions from the decision space in **Figure 3, Figure 4, Figure 5** or **Figure 6,** the box plots show how this specific building solution reacts to changing one parameter at a time. **Figure 7** and **Figure 8** depict the case study showcased in **Figure 6** and how the building reacts to keeping all the other parameters constant and changing the exterior wall Rc-values etc. in regards to the annual energy consumption and the flexibility potential from the characterization assessment.

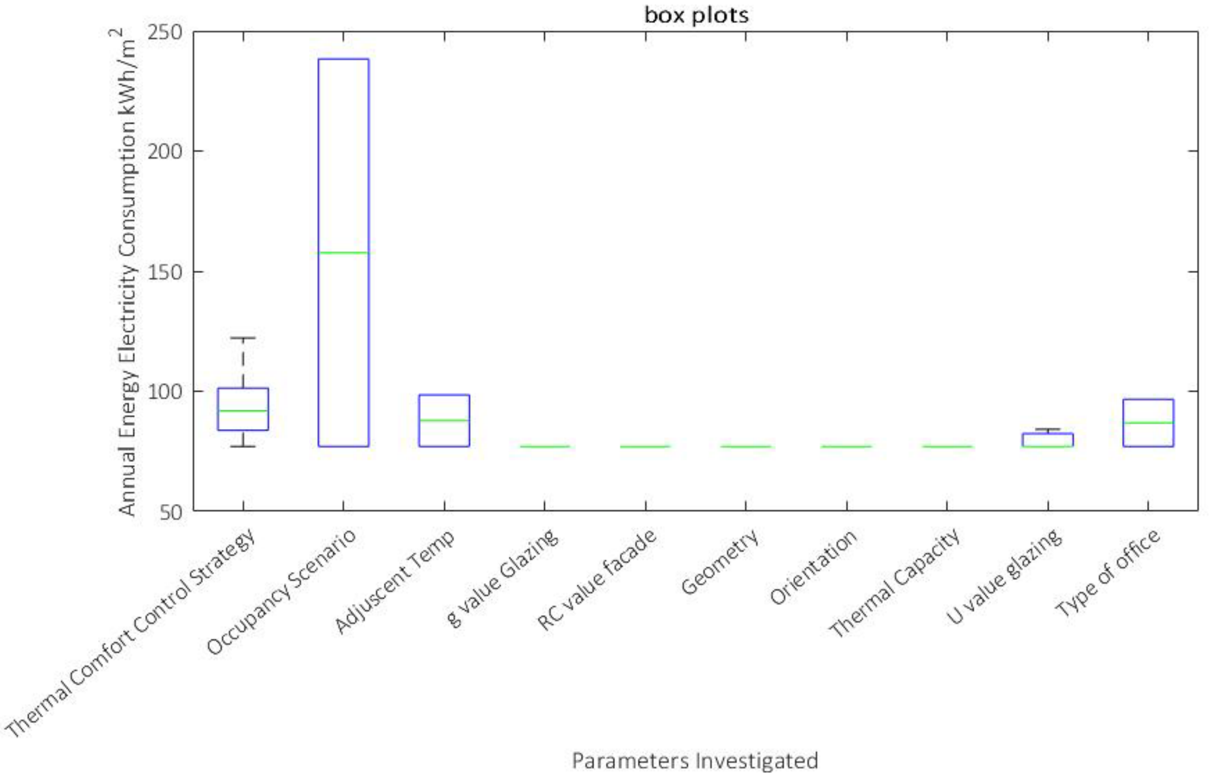

Figure 7. Box plots for each building variation investigated; each box shows the performance variation that is expected when changing the corresponding building parameter within defined ranges - Annual Energy Electricity Consumption.

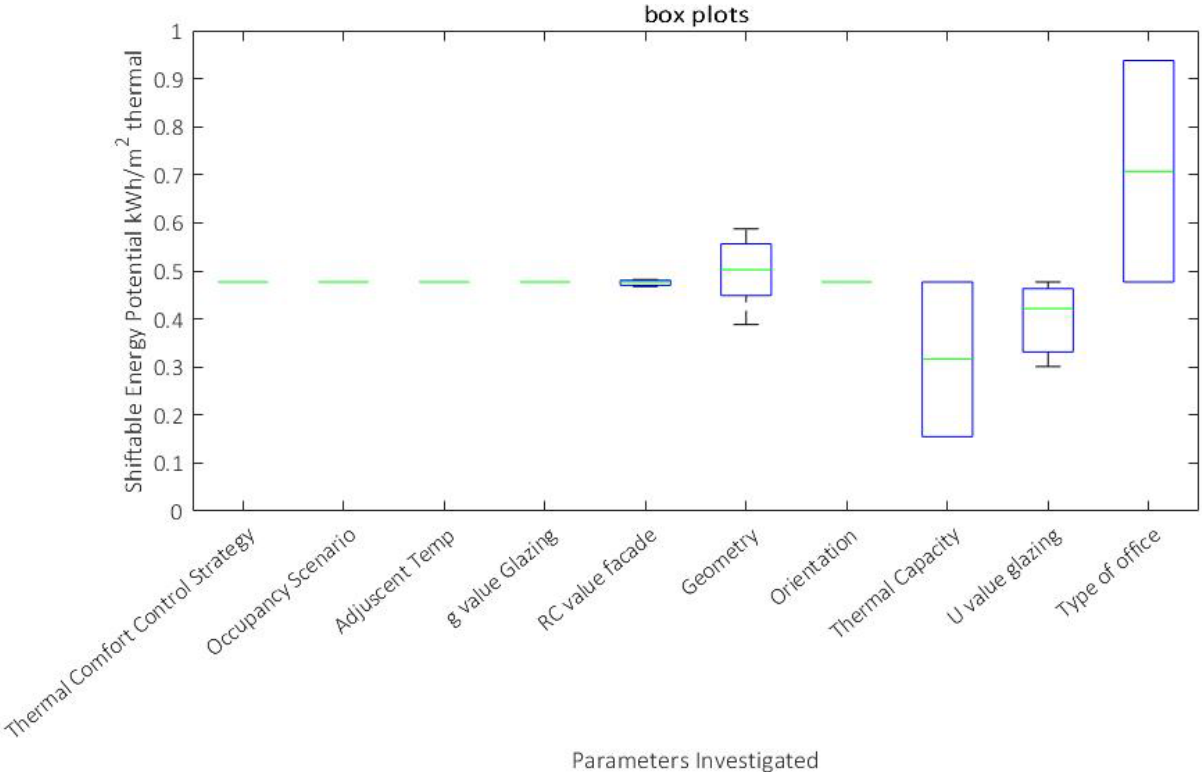

Figure 8. Box plots for each building variation investigated; each box shows the performance variation that is expected when changing the corresponding building parameter within defined ranges – Shiftable Energy Potential.

There are cases where the different variations investigated in this database do not return different results. E.g. for the specific case we chose, the annual energy consumption is the same no matter which Rc-value of the façade, the g value of the glazing or the geometry. Moreover, as the shiftable energy (flexibility potential) is based on the characterization assessment that exclude weather and occupant effects, the different control scenario, occupancy scenarios or orientation make no difference in the results.

More box plots based on other KPI's can also be presented. That way, the user can get a more complete overview of the way each parameter affects each KPI and they can make more informed decisions on their final design.

By using one or all three steps of the visualization process depending on the time and effort the designer wants to invest, they can receive valuable information about the building, make informative decisions and decide to use the best parameters based on the important indicators at the time.

Wrap Up

Thermal mass can be potentially important for energy shifting and it should be taken into account when investigating the shifting potential of a building, note that utilizing the thermal mass of a building does not include extra costs.

Using the tool takes no more than a few minutes, does not require special training or knowledge and returns valuable information and suggestions on how to get the most out of the building's abilities. The tool can also be used to investigate the flexibility that an already existing building can offer. It can also be used to assess the energy flexibility that a portfolio of buildings can offer, or a tool to investigate the influence of various thermal comfort control strategies on the Performance Indicators. The tool aims to contribute to the design of more flexible office buildings and help to assess the potential value of offices as active members of the energy infrastructure.

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