EINDHOVEN
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Energy flexibility services from buildings by using adaptive comfort strategies

(EFComf)

Final report

Project details

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Project title:	Energy flexibility services from buildings by using adaptive comfort strategies
Main applicant:	Eindhoven University of Technology
Project partner:	BAM Energy Systems
Project period:	July 2021 – September 2023
Contact person:	dr.ir. P. Hoes

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Contents

1 Introduction

1.1 Background

Need for energy flexibility

The penetration of renewable energy sources (RES) is increasing, and many countries have set ambitious targets for integrating RES into their energy systems in the upcoming years. With the increase in RES, which have high variability and uncertainty, the controllability of electricity production decreases. This makes flexibility in both the supply and demand of electricity crucial for balancing purposes.

Providing energy flexibility as a service to balance the (local) electricity grid offers interesting (business) opportunities to building owners. For example, a building can offer/sell its energy flexibility to an aggregator on the market, thus reducing its operational costs. The aggregator can group the flexibility of multiple buildings to generate enough flexibility volume for the market.

Thermal comfort, thermal mass and energy flexibility

The energy demand of a building can be influenced in various ways using demand response strategies, such as shifting thermal (heating and cooling) loads by leveraging the building's thermal mass. Of course, providing thermal comfort is of key importance in (office) buildings and should never be compromised when using demand response strategies. Nonetheless, it is expected that some flexibility exists within the acceptable comfort bandwidth. This was also investigated in the NWO iCare-project (Personalised Climate and Ambience Control for zero-Energy buildings[1]); both EFComf-project partners BAM and the TU/e BP research group were also involved in the iCare-project.

One of the aims of the iCare-project was to investigate the thermal demand flexibility that can be offered by ‘occupant comfort flexibility,’ in other words, the flexibility offered by occupant adaptation to the thermal environment and the gradually developing thermal perception of occupants. The iCare project showed that adaptive comfort control strategies can be used to create flexibility in building energy demand without compromising thermal comfort[2]. The amount of flexibility that can be offered by using the adaptive comfort control strategies depends on several building characteristics, e.g., window-to-wall ratio, Rc-values, and the building’s thermal mass. The thermal mass is one of the key influential parameters affecting the available flexibility. As the thermal mass of (existing) buildings is available at zero additional cost, it is of great interest to analyze the possibility of storing/conserving heat and cold in the thermal mass during Demand Response (DR) events.

Building energy flexibility assessment tool

In the iCare-project, the TU/e (BP research group) and BAM developed a simulation-based tool that helps building designers create buildings with high energy flexibility (based on adaptive comfort control strategies)[3]. The tool is based on a large database with simulated results of more than 800,000 variations of a Dutch office building. The tool provides suggestions to building designers concerning various building design parameters (e.g., window-to-wall ratio, thermal mass, Rc-value) to achieve higher energy flexibility. These suggestions, among other performance indicators, are based on a simplified energy flexibility characterization method. However, the characterization method is not able to quantify the energy flexibility that can be offered under realistic operational conditions of a building, making it difficult to translate the results to real-life applications.

In the EFComf-project, the existing iCare tool has been expanded to provide predictions of the actual building energy flexibility that can be expected by using adaptive comfort control strategies through the inclusion of user behavior and weather conditions. This expanded tool indicates and compares the available energy flexibility generated with the comfort control strategies to other energy flexibility sources in the building, such as electrical batteries and heat pumps. As such, the expanded tool provides valuable information to understand the business case related to the building’s energy flexibility.

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[1] https://www.nwo.nl/en/research-and-results/research-projects/i/01/6701.html

[2] Mishra, A. K., Loomans, M. G. L. C., & Hensen, J. L. M. (2016). Thermal comfort of heterogeneous and dynamic indoor conditions - An overview. Building and Environment, 2016(109), 82-100. DOI: 10.1016/j.buildenv.2016.09.016

[3] https://research.tue.nl/en/publications/designing-a-decision-support-tool-for-high-performance-office-bui

1.2 Objective

The goal of this project is to develop a tool that predicts the available energy flexibility of a specific office building, while taking into account user behavior and weather conditions. It focuses on exploiting the energy flexibility provided by adaptive comfort control strategies (without compromising thermal comfort) and the building's thermal mass. Other flexibility sources in the building, such as electrical batteries and heat pumps, are also included in the analysis. The business case associated with the predicted building energy flexibility will be investigated, showing if the energy flexibility provided by the building is of interest to an aggregator on the energy market.

2 Project approach and structure

2.1 General approach

The tool developed in the EFComf-project is based on a detailed high-resolution dynamic building performance prediction model, which makes it possible to analyze the thermal comfort and energy flows in the building in detail. This is different from several other building energy flexibility projects which make use of lower resolution building models, which do not allow to study the resulting thermal comfort in detail.

The following general steps are defined:

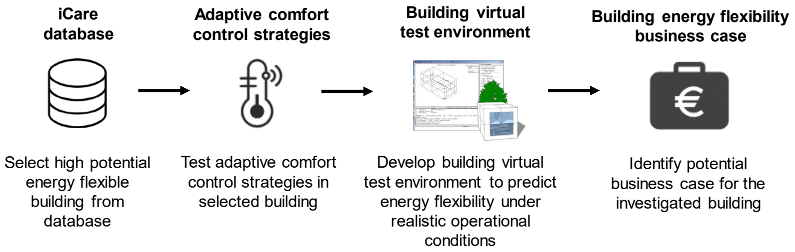

Figure 1: General overview of project steps.

This project tested various adaptive comfort control strategies in two office buildings on the BAM campus in Bunnik and two other offices buildings. The strategies were evaluated by measuring relevant IEQ parameters in the building and by using surveys to understand the perceived thermal comfort of the office workers. This provided knowledge about the acceptance of the adaptive comfort control strategies by the office workers and insight into the actual energy flexibility that could be generated using these strategies.

The measured energy flexibility depends on the thermal state of the building (e.g. the stored energy in the thermal mass). Consequently the adaptive comfort control strategies will only generate the same energy flexibility when the building is in the exact same thermal state as during the measurements. The thermal state of the building is influenced by many (uncontrollable) factors, such as weather conditions and occupant behavior. It was only possible to perform the measurements for a limited number of thermal states, while many more thermal states will occur during the year. Therefore, it is not possible to generalize the measurement results for the whole year.

To understand the flexibility that could be offered throughout the year (for various thermal states), we developed a building model validated using the measurements. The building and building energy system were modeled in the whole building energy simulation program EnergyPlus. The validated building model was able to predict the flexibility that could be offered by the adaptive comfort control strategies for any thermal state of the building. The EnergyPlus model was embedded in a virtual test environment. This virtual test environment provided a realistic prediction of the expected energy flexibility for a full year. The building virtual test environment uses a model-based controller that selects the control strategy offering the most energy flexibility for a certain optimization horizon (e.g., the following day) under uncertainty of weather conditions and occupant behavior.

2.2 Overview of work packages

The figure below provides an overview of the work packages in this project. The work packages (WPs) are described in more detail below.

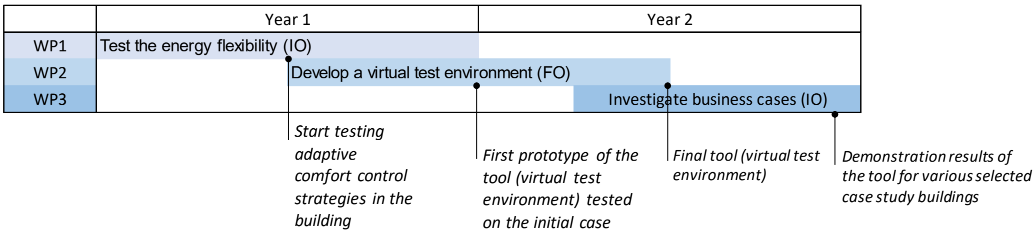

Figure 2: Overview of the project work packages.

WP 1: Test the energy flexibility provided by the operational strategies

Activities:

- Select an office building from the BAM campus that provides high energy flexibility according to the tool developed in the iCare project.
- Create an overview of the available and suitable iCare operational strategies for the selected office building.
- Test the operational strategies on the selected building. Testing includes onsite measurements of parameters relevant to energy and to thermal comfort and surveys on the perceived the thermal comfort by the building occupants.

WP 2: Develop a building virtual test environment with a model-based controller that predicts the available building energy flexibility

Activities:

- Investigate the influence of the most important uncertain boundary conditions on the building energy flexibility, e.g., weather conditions and occupant behavior.
- Create an overview of the available modeling approaches for the model-based controller.
- Select the most suitable modeling approach and model complexity for the building model and the model-based controller.
- Develop the model-based controller and validate the model using the measurements from WP1.
- Develop a building virtual test environment which makes use of the model-based controller.
- Investigate and quantify the expected energy flexibility using the building virtual test environment.

WP3: Investigate business cases

Activities:

- Create an overview of the possible energy and service markets with their associated requirements regarding possible flexibility services from office buildings.
- Select various case study buildings from the (extended) iCare database.
- Perform simulations using the building virtual test environment and quantify the energy flexibility of the selected building designs.
- Benchmark the flexibility service offered by the building thermal mass with other flexibility sources.
- Assess the potential business case for the selected buildings.

3 WP1: Test the energy flexibility provided by the operational strategies

3.1 Overview of experimental campaign

The main goal of the experimental campaign in WP1 was to test if adaptive comfort strategies in real office environments can be used to generate energy flexibility while ensuring the comfort of the office workers. The campaign aimed to test various adaptive comfort strategies by adjusting heating setpoint schedules from the reference case during workdays of the heating season. The adaptive comfort strategies were tested in two office buildings on the BAM campus in Bunnik, as outlined in the TKI project plan. Additionally, the strategies were tested in two office buildings, one in Breda and one in Amsterdam.

The adaptive comfort strategies were evaluated by measuring relevant Indoor Environmental Quality (IEQ) parameters using specific sensors, along with utilizing questionnaires (surveys) to gauge the perceived thermal comfort of the office workers. Consequently, statistical analysis was performed to verify that there was no significant difference between the Experiment Days and the Reference Days when the normal settings of the heating systems were applied.

3.1.1 Buildings in experimental campaign

The experimental campaign has been performed in total in four office buildings located in the Netherlands:

- The first two buildings are Royal BAM n.v. buildings located in Bunnik. These two buildings (2511 m^2 and 2255 m^2) are both built during the 80s. The buildings are 3 stories buildings equipped with gas boilers and air-coil units. The experiment for these two buildings took place in February 2022 and April 2022.
- The third building is an office building in Amsterdam, built in 2018, it has 4 floors with a total area of 9000 m^2, although just the third floor was used in the experiment. It is equipped with fan coil units fed by an aquifer. The experiment in this building took place in April 2022.
- The fourth building is an office building in Breda, built in the 90s, it has 2 floors with a total area of 1500 m^2. It is equipped with gas boilers and radiator units, a humidifier, and a balanced ventilation system. The experiment in this building took place in April 2022.

The buildings' differences are important for a better understanding of the energy flexibility potential and thermal comfort that the same adaptive comfort strategy can provide during the heating season. Further details of the investigated buildings are described in the EngD thesis of Peluso (2023)[4].

3.1.2 Adaptive comfort strategies

Two main different kinds of adaptive comfort strategies have been implemented. The first group aims to identify the thermal comfort limit of the users and gain energy flexibility as a consequence. Typically, there is a first heat-up during unoccupied hours in the first part of the day, followed by a second timeslot where the heating system is switched off. During this timeslot, the goal is to understand the comfort limits in terms of acceptability of the temperature and thermal comfort level for the users, before a second heat-up usually before lunchtime till the closure of the office. An example of such an adaptive comfort strategy is shown in Figure 3. The second group of adaptive comfort strategies aims to maintain thermal comfort conditions but change the temperature more dynamically. Its goal is to exploit energy flexibility and observe how the heating systems react to understand potential dynamic settings.

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[4] Peluso, U. (2023). BE-FLEX: a tool to evaluate energy flexibility in office buildings through adaptive comfort strategies. EngD thesis, Eindhoven University of Technology.

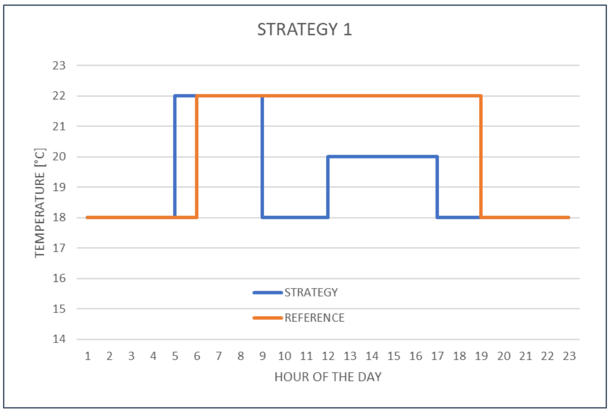

Figure 3: Strategy 1 of the experimental campaign. In orange is the reference setpoint schedule for Building F, and in blue is the adaptive comfort strategy setpoint

These two groups of strategies have been developed by assessing different inputs. In the NWO iCare Project (Mishra A. K., et al., 2017)[5], the air temperature limit ranging between 20°C and 24°C during the heating season was assessed as comfortable conditions and taken into account. Secondly, regarding the exploitation of flexibility services to the grid, the strategies are shaped according to an analysis of the EPEX electricity prices for 2021 (the year before the experiment). Furthermore, the connection between the low energy prices of the dynamic market and the high percentage of RES production (and low energy demand) has been assessed (Aščerić, A., et al., 2021)[6], to ensure an indirect CO2 emission reduction when flexibility services are applied. Readers can find more information regarding the measurements in the EngD thesis of Peluso (2023)[7].

To gain insights into thermal comfort levels and energy flexibility through the adaptive comfort strategies, two main data sources are used: data retrieved from sensors and data collected via questionnaires.

3.1.3 Data acquisition through BMS

The Building Management System (BMS) was utilized to collect data regarding air temperature, occupancy, and gas/electricity consumption for heating purposes. Furthermore, for the buildings of the BAM campus, additional measurement stations were installed to collect air temperature data in different locations of the buildings and to validate the BMS data (see Figure 4 and 5). Further information on the sensors' locations and characteristics is provided in (Peluso, 2023).

Figure 4: One of the BAM office buildings.

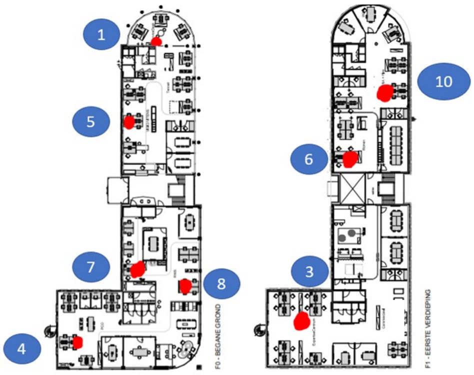

Figure 5: Temperature sensor locations in one of the office buildings.

3.1.4 Data acquisition through comfort questionnaires

The second source of data is through questionnaires for the workers, aimed at collecting information regarding the thermal comfort conditions. During the experimental campaign, daily questionnaires (surveys) were sent to

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[5] Mishra A. K., Loomans M. G. L. C., B. P. Group, and U. B. Physics, "Project iCare Report on the work done in TU / e, 2015-17," no. September 2017.
[6] Aščerić, A., Pantoš, M., & Čepin, M. (2021, June). Correlation of Day-Ahead Electric Energy Market Price with Renewable Energy Sources Generation and Load Forecast. In International Symposium on Innovative and Interdisciplinary Applications of Advanced Technologies (pp. 99-109). Springer, Cham.
[7] Peluso, U. (2023). BE-FLEX: a tool to evaluate energy flexibility in office buildings through adaptive comfort strategies. EngD thesis, Eindhoven University of Technology.

the office workers by mail and then collected (see Figure 7). In the BAM buildings, banners were also placed around the building to provide access to the survey via a QR code (see Figure 6). This allowed individuals in different locations from their usual workplace in the building to fill in the survey.
The purpose of the survey was to ask generic questions, ensure the anonymity of participants, and focus on thermal comfort. The questions covered the identification of the worker, location, time of arrival and departure, perceived thermal sensation, air quality perceived by the users, and a better understanding of the participant's location in their respective offices. A full copy of the questions and the answer options are presented in the EngD thesis of Peluso.

TROEF SHARING ENERGY

TKI URBAN ENERGY Topsector Energy

EXPERIMENTAL CAMPAIGN
BAM campus – Gebouw L

De juiste energie op het juiste moment

Slim sturen van het gebouw

In dit experiment worden verschillende - zogenaamde - comfort strategieën getest in de praktijk. Deze strategieën zijn gericht op het flexibel en efficiënt inzetten van energie. Het gebouw wordt bijvoorbeeld verwarmd op de momenten dat de sterk fluctuerende energieprijs laag is en de verwarmingsinstallatie wordt vervolgens uitgeschakeld op de momenten dat de energieprijs hoog is. Op deze momenten dient de thermische schil van het gebouw als buffer waardoor een goed comfort gegarandeerd blijft.

Volgens onderzoek hebben deze strategieën een positief effect op de comfort beleving, het energieverbruik (CO2-uitstoot) en de energiekosten van het gebouw.

Dit is precies wat we willen onderzoeken en bewijzen met dit experiment.

Wat merk jij hier van?
Wanneer jij werkt of op bezoek bent in gebouw L zul je zien dat op verschillende werkplekken in het gebouw deze flyers en enkele sensoren zijn geplaatst.

Daarnaast kan mogelijk een wisselend comfort ervaren worden, in totaal worden 7 verschillende strategieën getest over een periode van 4 weken.

Hoe kun je helpen?
Jouw mening over het comfort is belangrijk in dit onderzoek! Het zou dus erg helpen als je regelmatig de enquête invult. Dit kan door het scannen van de QR-code:

Scan de QR-code en vul de enquête in.
Iedere keer als je in Bunnik bent.

Heb je vragen of opmerkingen over dit experiment? Neem dan gerust contact op met Umberto Peluso:
Umberto.peluso@bam.com

Figure 6: Banner used in the BAM buildings to announce the experiment.

1. Before you proceed with the survey, I kindly request you create a random 4-digit code. Please use this code each time you fill in the survey.
2. Please fill in which floor you are currently situated on
3. Please fill in which zone you are currently situated in
4. How do you experience thermal comfort at the moment? [acceptable, neutral, not acceptable]
5. How are you feeling right now? [very cold, cold, slightly cold, ok, slightly warm, warm, hot]
6. How would you prefer your thermal environment to be? [much warmer, warmer, slightly warmer, nothing, slightly colder, colder, much colder]
7. Would you like to change the temperature? [yes warmer, no, yes colder]
8. How do you experience air quality at the moment? [acceptable, neutral, not acceptable]
9. How do you currently rate the air quality? [very fresh, fresh, slightly fresh, ok, slightly stale, stale, very stale]
10. Are you within distance of a door or window that is regularly open? [yes, no]
11. How active is your day? [pretty active, hybrid, teams meeting]
12. What you are wearing today? [thick clothes, normal, thin clothes]
13. Do you have any feedback?

Figure 7: Snapshot of the questions in the questionnaire.

3.2 Results

As previously mentioned, workers' surveys regarding thermal comfort questions were collected during the experimental campaign, and the data was analyzed. In particular, two main responses of the workers are of interest: Thermal Acceptability and Thermal Comfort Sensation. Thermal Acceptability and Thermal Comfort Sensation ratings are obtained for each day through the analysis of the survey and are distinguished for every floor or location inside the buildings. The thermal comfort analysis is performed by comparing the Thermal Acceptability and Thermal Comfort Sensation of the experiment days and the reference days (the days with a conventional operational strategy), see Figure 8 for an example.

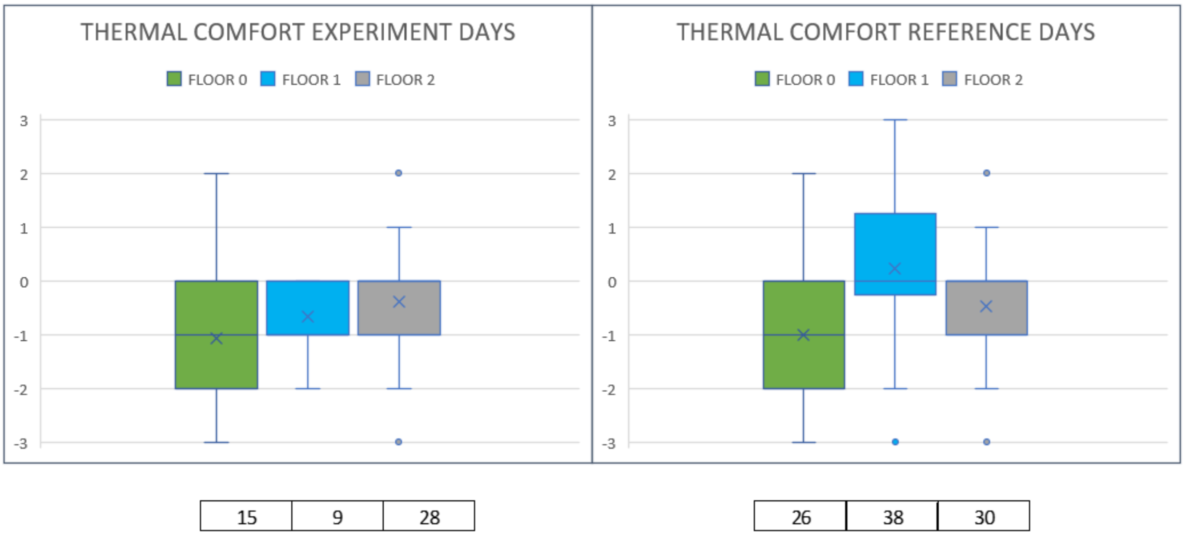

Figure 8: Example of reported thermal comfort sensation votes between an experiment day and a reference day in one of the BAM buildings (-3 = very cold; -2 = cold; -1 = slightly cold; 0 = neutral; 1 = slightly warm; 2 = hot; 3 = very hot). The votes are shown per floor; the number of votes are shown below the boxplots.

A statistical test is conducted to assess the statistical similarity between the experiment days and reference days. Due to the non-normal distribution of the data, the Kruskal-Wallis (KW) test is used to determine if there is a statistically significant difference between Experiment Days and Reference Days.

The KW test is a non-parametric method for testing whether samples originate from the same distribution. It is used for comparing two or more independent samples of equal or different sample sizes. If the p-value < 0.05, this casts doubt on the null hypothesis and suggests that at least one sample mean is significantly different than the other sample means. The p-values of Thermal Acceptability and Thermal Comfort Sensation between the Experiment Days and Reference Days are shown in Table 1.

Table 1: Results of the Kruskal-Wallis test.

Kruskal-Wallis test	p-value
Thermal Acceptability for Reference Days & Experiment Days	0.55
Thermal Comfort Sensation for Reference Days & Experiment Days	0.19

The results indicate that there is no significant statistical difference between Experiment Days and Reference Days. Therefore, it is possible to conclude that thermal comfort was not jeopardized during the experimental campaigns. These findings suggest that adaptive comfort strategies can be employed for energy flexibility purposes while ensuring the thermal comfort of office workers.

4 WP2: Develop a building virtual test environment with a model-based controller that predicts the available building energy flexibility

4.1 Overview of the model development

The objective of this work package was to develop a virtual test environment (i.e., a computational model) capable of representing the temperatures and energy flexibility measured in buildings during the experimental campaign. The model could be utilized to evaluate the existing flexibility potential and explore strategies for enhancing the energy flexibility of buildings. The following general steps were followed.

4.1.1 Defining building model complexity

Building F of the BAM campus was chosen as the case study building to initiate model development; this building served as Building 1 within the tool. To understand the required model complexity (spatial resolution and temporal resolution), four modeling complexity levels were defined. Then a simulation study was conducted to select the most appropriate model complexity for this project.

The first and simplest model consisted of a one-floor model with just one thermal zone (1F1T) with adiabatic ceilings and floors. The aim was to represent the middle floor of the 3-story Building 1. The advanced version of 1F1T was the model with one floor and three thermal zones (1F3T); here, the difference with more thermal zones was examined. Again, in this case, the ceilings and floors were adiabatic. The third model consisted of three floors with one thermal zone each (3F3T). The final model consisted of three floors with three thermal zones each, totaling nine thermal zones (3F9T).

4.1.2 Comparison of measurements with simulation results

With the selected model from the previous step, a response test was conducted. This test compared the model's performance with the measured performance of the building during flexible management. To do this, the adaptive comfort strategies were implemented in the model, and the comparison with meaured data was addressed. Specifically, the gas consumption and the air temperature profiles of the model were compared with the measured data. During the campaign, a few sensors were placed in the building, allowing for the comparison of temperature profiles (measured and simulated). For more details regarding the modeling, refer to EngD thesis.

4.1.3 Simulation framework development

When Building 1 of the tool was able to provide realistic performances, the next step involved the development of the simulation framework acting as controller and data post-processor for all the other buildings. The simulation framework was developed using Matlab 2022b as the controller and EnergyPlus 9.6.0 as a building performance simulation software. The purpose of the simulation framework is to provide a realistic prediction of the expected energy flexibility for a full year for a specific building. The NEN5060_18 weather scenarios are used as input for weather conditions. The simulation framework provides results for various cases per office building (see also Figure 9):

- The reference case: The gas boiler is replaced by a heat pump; two conventional control strategies are applied (1.1 and 1.2); an example of one of these strategies is included in Figure 2; fixed electricity prices are used for calculations;
- A comparison case with a PV system and a battery: The reference case is expanded with PV and an electric battery; calculations are done with fixed electricity prices (2.1 and 2.2) and dynamic electricity prices (2.3 and 2.4);
- An energy flexibility case with comfort strategies: The gas boiler is replaced by a heat pump; the optimization algorithm aims to reduce operational costs by searching for the best comfort strategies

per day and adjusts the building's electricity demand accordingly; calculations are done with fixed (3.1) and dynamic (3.2) electricity prices;

- A comparison case with a PV system and a battery + comfort strategies: the electricity demand as calculated for case 3 is now applied to a variant with a PV system and an electric battery; calculations are done with fixed (4.1) and dynamic electricity prices (4.2).

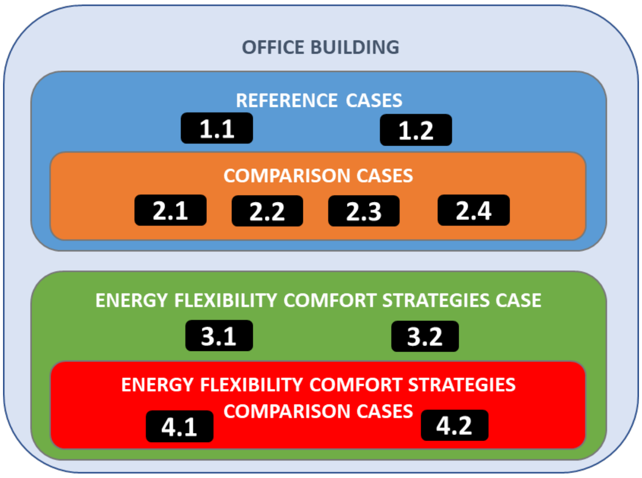

Figure 9: Overview of various cases.

4.1.4 Populating building flexibility database

The final step involves extending the functionality of the simulation framework applied to Building 1 to the NWO iCare office buildings database (Papachristou C., 2019)[8]. After filtering relevant office buildings from the database, the office database is integrated with the simulation framework. Due to the extensive size of the database and the associated high computational time, only a subset of buildings has been simulated. Using Latin Hypercube Sampling (LHS), a selection of buildings has been chosen for simulation. Finally the full database has been populated using a surrogate model, which has been trained and tested with the results of the simulations.

4.2 Results

4.2.1 Building model complexity

The four resolution models (described above) were simulated while investigating the sensitivity of the infiltration rate and ventilation schedule. To assess and select the best resolution model, the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) of the hourly heating demand and hourly air temperature were compared. According to the ASHRAE Handbook 2002, the calibration benchmark for CV(RMSE) on hourly data (for yearly simulations) is 30%. Models with lower values are considered sufficiently calibrated for that PI. Analyzing the CV(RMSE) of hourly air temperature for the different resolution models revealed that for every model the CV(RMSE) was below 8%. Therefore, for this PI, every model is accepted. Essentially, because of these low values, the choice of the best resolution model is determined by the CV(RMSE) of hourly heating demand. In Table 2, the CV(RMSE) in % for hourly heating demand of occupancy ventilation schedule (weekdays) and total heating (weekdays) demand are presented.

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[8] Papachristou, C. (2019). Designing a decision support tool for high performance office buildings focusing on energy flexibility: supporting decisions on thermal comfort control strategies and building design parameters. Technische Universiteit Eindhoven.

Table 2: CV(RMSE) in % for hourly heating demand of occupancy ventilation schedule and total heating demand (weekdays).

	OCCUPANCY SCHEDULE	YEARLY HEATING DEMAND [kWh]	CV(RMSE) HOURLY HEATING DEMAND
	REALITY	171928	-
INFILTRATION 0.25 ACH	1 FLOOR 1 THERMAL ZONE	143338	29.1
	1 FLOOR 3 THERMAL ZONES	140166	30.7
	3 FLOORS 3 THERMAL ZONES	112295	49.7
	3 FLOORS 9 THERMAL ZONES	108791	52.4
INFILTRATION 0.5 ACH	1 FLOOR 1 THERMAL ZONE	186744	25.5
	1 FLOOR 3 THERMAL ZONES	184293	24.3
	3 FLOORS 3 THERMAL ZONES	125046	40.3
	3 FLOORS 9 THERMAL ZONES	121894	42.6

In Table 3 the CV(RMSE) in % for hourly heating demand of heating/cooling ventilation schedule (weekdays) and total heating (weekdays) demand are presented.

Table 3:CV(RMSE) in % for hourly heating demand of heating/cooling ventilation schedule and total heating demand (weekdays).

	HEATING/COOLING SCHEDULE	YEARLY HEATING DEMAND [kWh]	CV(RMSE) HOURLY HEATING DEMAND
	REALITY	171928	-
INFILTRATION 0.25 ACH	1 FLOOR 1 THERMAL ZONE	177246	20.8
	1 FLOOR 3 THERMAL ZONES	173902	20.0
	3 FLOORS 3 THERMAL ZONES	143713	27.0
	3 FLOORS 9 THERMAL ZONES	140211	29.5
INFILTRATION 0.5 ACH	1 FLOOR 1 THERMAL ZONE	220837	45.5
	1 FLOOR 3 THERMAL ZONES	218397	43.7
	3 FLOORS 3 THERMAL ZONES	157853	20.1
	3 FLOORS 9 THERMAL ZONES	155180	21.6

Although the best model (in terms of CV(RMSE) value) is the 1F3T with an occupancy ventilation schedule and an infiltration rate of 0.25 ACH, the selected resolution model is the 3F3T with the heating/cooling ventilation schedule and an infiltration rate of 0.5 ACH. This model is chosen to represent Building 1 of the tool. The choice is based on the low CV(RMSE) (also considering the total heating demand) and the model's characteristic of having three floors, which is beneficial for performing further analysis on the air temperature profiles.

4.2.2 Comparison of measurements with simulation

The goal of the response test is to represent the thermal behavior in the Building 1 model as measured on the experiment day of the experimental campaign performed in building. The results of only Strategy 1 for the response test are described here (other strategies were studied, but the results led to the same conclusion). To better represent the thermal behavior of the building, the simulation started on January 1st, and the correct occupancy rate was considered for the experiment day, as well as the initial temperature at the beginning of the strategy for each floor. In Figure 12, the comparison between the model (orange) and the real building gas consumption data (blue) is shown.

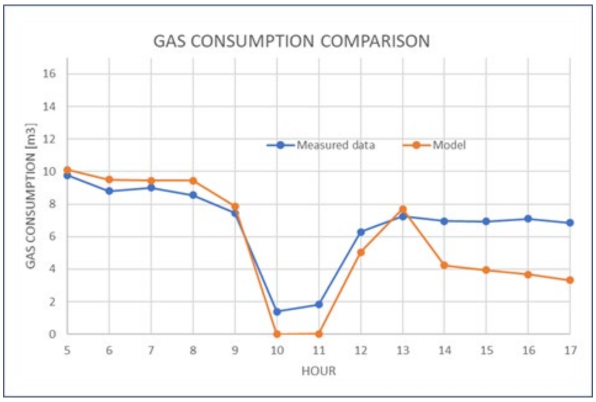


Figure 10: Comparison between the model (orange) and the real building gas consumption (blue) data.

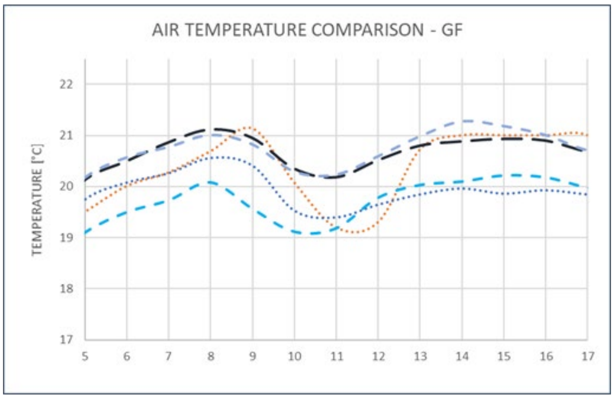


Figure 11: Comparison between the model (orange) and the real building air temperature (blue lines) for the ground floor, updated strategy.

In Figure 11, the comparison between the model (orange) and the measured building air temperature (blue lines) for the ground floor is depicted. Each blue line represents data extracted from an installed sensor at a specific location on the ground floor. Differences of up to approximately 1°C can be observed between the various sensors; this variation is partly due to the accuracy of the sensors, but also because of their specific locations within the building (e.g., some sensors are closer to windows than others). The model calculates the air temperature at the center of the thermal zone while assuming fully mixed air, so it is expected that the model approximates the average of the measured temperatures. The figure shows that the simulated temperature follows the same pattern as the measured temperatures; the temperature decrease after changing the setpoint also follows the same rate.

4.2.3 Simulation framework development

The energy flexibility comfort strategies case (Case 3.1 and 3.2 from Figure 9) are the core of the simulation framework. In this case, 56 adaptive comfort strategies (28 for heating and 28 for cooling; see the EngD thesis) are tested each day of the year for the selected office building. The strategy that provides the best combination of operational costs and Predicted Discomfort Hours is identified, and implemented in the optimization for the following day, continuing throughout the year. The objective function for selecting the strategy is to minimize the combination of Predicted Discomfort Hours and operational costs for heating the building, ensuring a comfortable environment at minimum cost.

The EPEX spot prices for electricity are used as input to the model, which helps provide energy flexibility services to the grid by prioritizing energy usage when electricity costs are low. This approach supports grid balancing and promotes the penetration of renewable energy sources (RES) in the energy mix. The primary constraint when using the lowest energy price is maintaining the thermal comfort of the user. Due to the nature of the objective function, for every office, every day of the year, different adaptive comfort strategies are tested to ensure thermal comfort while reducing operational costs compared to the reference cases.

The thermal demand data extracted from the EnergyPlus 9.6.0 simulations is converted to electricity consumption based on the seasonal coefficient of performance (SCOP) of an air-to-water heat pump (HP). The total costs for electricity, CO_2 emissions for grid import, and Predicted Discomfort Hours are calculated.

EnergyPlus 9.6.0 always starts the simulation with the same initialization temperatures in the model, and it is not possible to set custom values. Due to these limitations, the following simulation process is needed, as illustrated in Figure 12. Within the time window (blue bar), the strategies are tested (orange) on the last day (D) of the simulation, and the best strategy is selected (orange becoming green). The time window then shifts by one day. The previously selected strategy is implemented on the day (D) before the last (D+1), and the strategies are tested again on D+1. This process continues for all the days of the year.

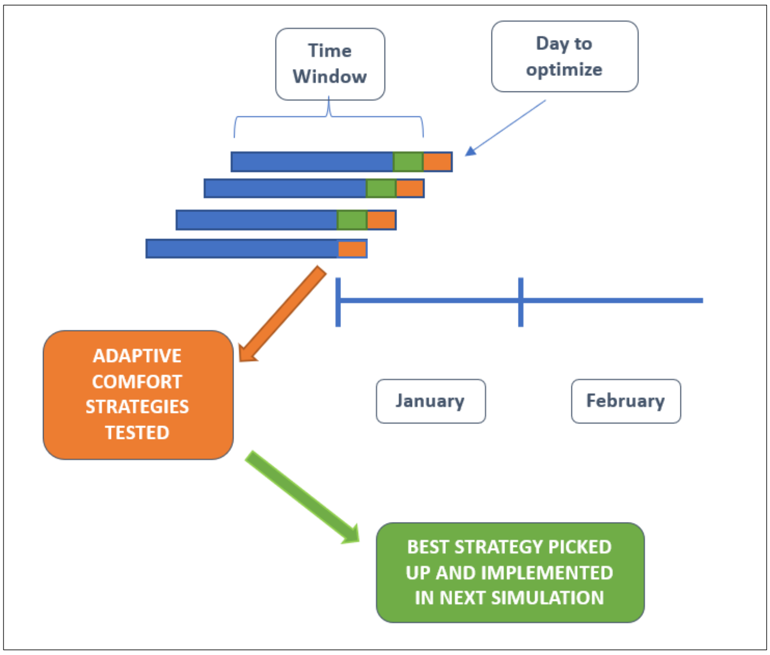


Figure 12: EF comf case simulation process.

Simulation results for Building 1

In this paragraph, the Building 1 model was used as the initial input for the simulation framework to assess energy flexibility over a full year. This first run of the simulation framework with a building model was also utilized to test and refine the workflow of the simulation framework. Below, a comprehensive performance analysis is provided for Building 1; the final database contains more concise results for each building.

The performance of Building 1 is analyzed for a set of cases (see Figure 9). The PIs can be sensitive to several assumptions in the model, particularly the IRR, which is influenced by assumptions concerning costs (such as maintenance, installation, etc.). Therefore, a sensitivity analysis was conducted. Four sets of parameter assumptions were ultimately investigated using available commercial information on BAM business cases. Table 4 shows these sets of assumptions.

Table 4: Sets of assumption parameters for sensitivity analysis of simulation framework for Building 1.

Assumption	**1**	**2**	**3**	**4**
SCOP	3	3	2.5	3
HP purchase	122k€	180k€	180k€	191k€
HP maintenance	2%	5%	5%	5%
Battery Capacity/Power	100kWh /50 kW	100kWh /90 kW	100kWh /90 kW	200kWh /180 kW
Battery purchase	100k€	81k€	81k€	205k€
RTE	80%	90%	90%	90%
PV kWp	40 kW	38 kW	38 kW	76 kW

In Figure 13, the sensitivity analysis results are depicted based on the four assumption sets for all cases. The sensitivity analysis is performed using two main PIs: PDH and IRR. It is important to highlight the behavior of the IRR:

- Positive IRR: The cash flow becomes positive after a few years into the lifespan.
- Negative IRR: The cash flow becomes positive only in the last years of the lifespan.
- NaN IRR: The cash flow never becomes positive during the lifespan.

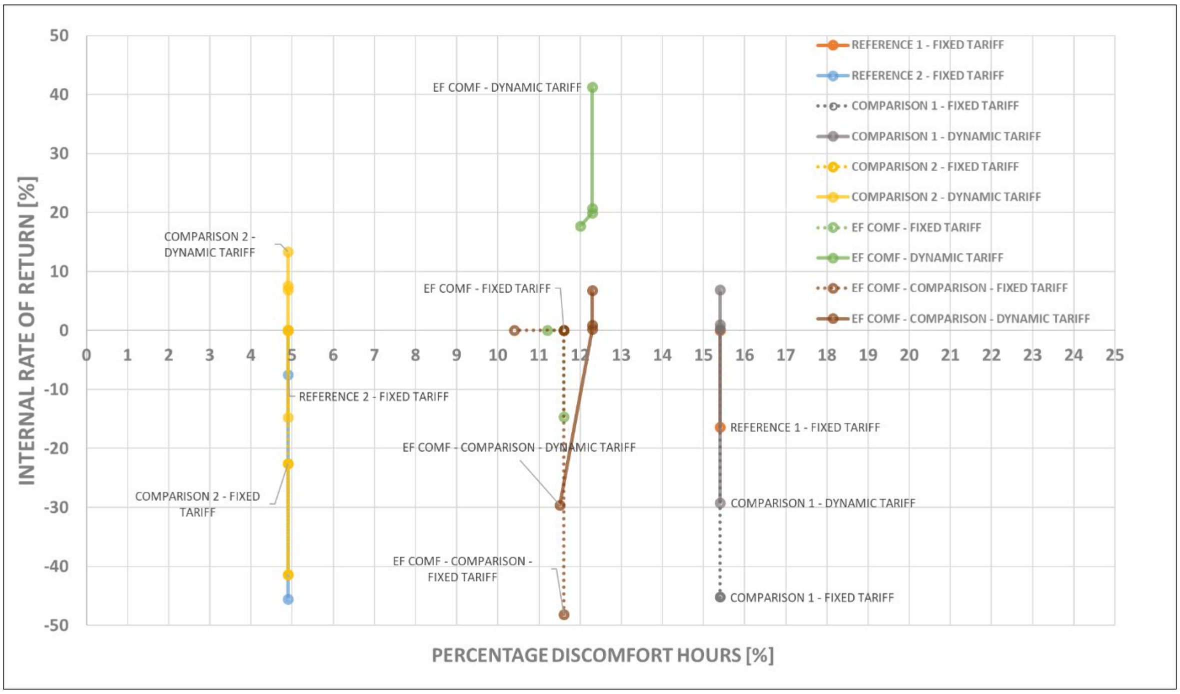


Figure 13: Results sensitivity analysis of simulation framework for Building 1.

Every dot on the graph represents a specific case, with cases grouped by color and line type indicating the market tariff. Generally, dynamic tariffs appear more favorable across all cases, leading to higher IRR. When the IRR is positive, the investment in HP, battery, and PV proves beneficial. Few cases show positive values, with EF comf cases yielding the best outcomes in terms of IRR. However, the comparison 2 case with a dynamic tariff also shows favorable IRR, albeit with better PDH. Across the specific range of results between cases, only one case typically provides different outcomes, primarily in assumption set 1. Eventually, assumption set 4 is selected for further simulations due to its technological parameter similarity with real business cases. Refer to Figure 14 for a visualization of the results using assumption set 4 for Building 1.

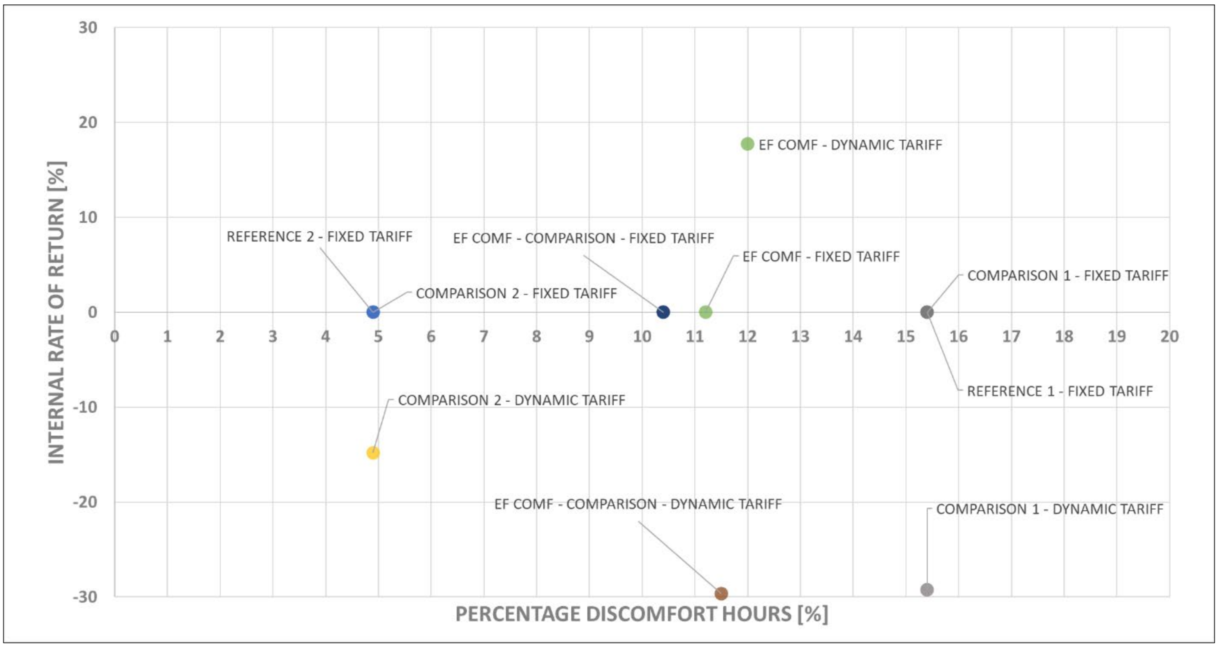


Figure 14: Results simulation framework for Building 1 with assumption set 4.

It's crucial to emphasize that the multi-criteria decision-making process allows each user to identify the best solution based on their specific needs. However, it's notable that in this particular case, achieving a positive IRR with an acceptable PDH is primarily ensured by the EF comf strategies case, as anticipated.

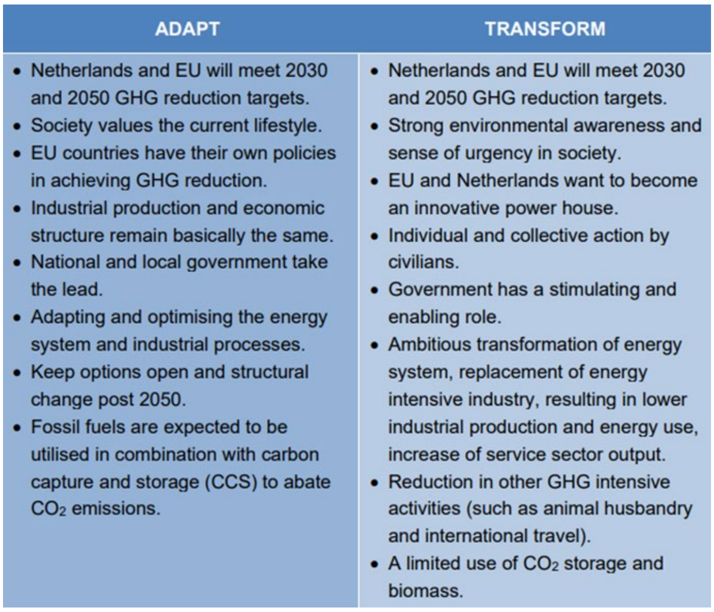
Uncertainty Analysis on EPEX Spot Prices

As observed, the only uncontrollable variable pertains to the EPEX spot prices. Predicting actual electricity prices for future years, and subsequently evaluating building performance under such conditions, is indeed challenging.

For Building 1, as well as for populating the database, the historical year chosen for optimization reference was 2019, deemed closest to "normal" behavior. It's worth noting that energy prices in 2020-2021 during the COVID-19 pandemic and in 2022 amid the Russia-Ukraine conflict differed significantly from typical patterns. However, to validate this choice, an uncertainty analysis was conducted for Building 1, utilizing historical data (EPEX spot prices from 2020, 2021, and 2022) and market scenarios from existing literature.

In collaboration with TROEF, TU/e Electrical Engineering department, and TNO, market scenarios for day-ahead electric energy prices were developed. Specifically, TNO's Adapt and Transform scenarios for 2030, 2040, and 2050 were utilized. These scenarios align with the Dutch Climate Act objectives, aiming for a 95% reduction in greenhouse gas emissions by 2050 compared to 1990 levels, and a 49% reduction by 2030 as outlined in the Dutch Climate Agreement.

The Adapt scenario builds upon existing infrastructure and lifestyle while significantly reducing CO2 emissions. In contrast, the Transform scenario envisages behavioral shifts in Dutch society toward a more sustainable economy, resulting in a less energy-intensive economy overall. Further details about the Adapt and Transform scenarios are depicted in Figure 15.



ADAPT	TRANSFORM
• Netherlands and EU will meet 2030 and 2050 GHG reduction targets. • Society values the current lifestyle. • EU countries have their own policies in achieving GHG reduction. • Industrial production and economic structure remain basically the same. • National and local government take the lead. • Adapting and optimising the energy system and industrial processes. • Keep options open and structural change post 2050. • Fossil fuels are expected to be utilised in combination with carbon capture and storage (CCS) to abate CO_2 emissions.	• Netherlands and EU will meet 2030 and 2050 GHG reduction targets. • Strong environmental awareness and sense of urgency in society. • EU and Netherlands want to become an innovative power house. • Individual and collective action by civilians. • Government has a stimulating and enabling role. • Ambitious transformation of energy system, replacement of energy intensive industry, resulting in lower industrial production and energy use, increase of service sector output. • Reduction in other GHG intensive activities (such as animal husbandry and international travel). • A limited use of CO_2 storage and biomass.

Figure 15: Adapt & Transform scenarios by TNO 2022.

Appendix D of Peluso (2023) provides a comprehensive explanation of the methodology and specifics behind the development of market scenarios. For the Adapt and Transform scenarios, datasets for electricity prices are generated for the years 2030, 2040, and 2050. Each scenario distinguishes between fluctuating and smooth behaviors, representing volatile and less volatile energy markets, respectively.

Figure 16 illustrates the impact of these EPEX spot price scenarios on Building 1, particularly focusing on the EF comf case. Several observations can be made:

1. References 1 and 2 are included for comparison purposes, aiding in the assessment of the realism of the PDH range using scenarios and historical data.

2. Regarding the IRR, most scenarios and historical data from 2019, 2020, and 2021 fall within a similar range, validating the reliability of the 2019 data. Consequently, it is reasonable to utilize 2019 as the reference year for optimization.
3. However, the year 2022 stands out as a black swan, lying well outside the expected range, highlighting its unpredictability and unique circumstances.

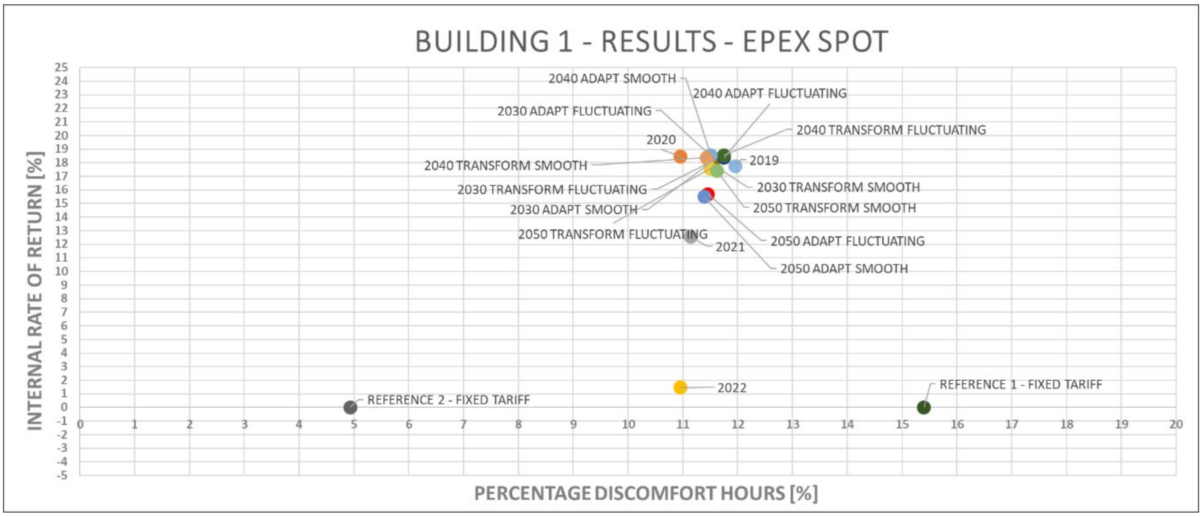
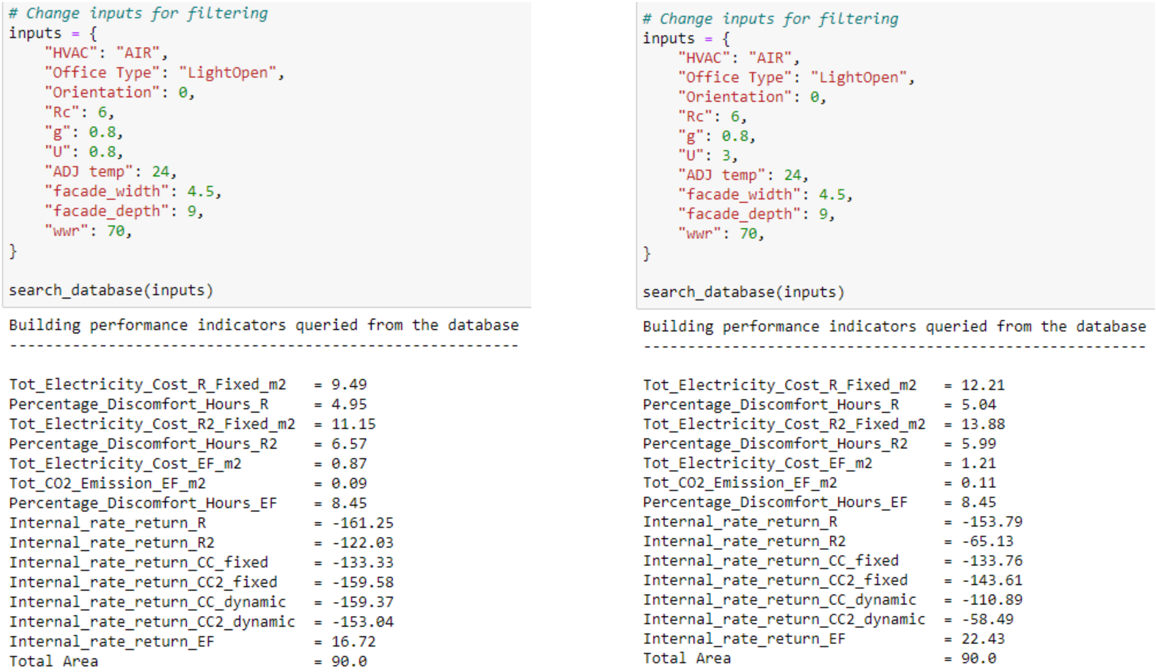


Figure 16: Uncertainty analysis on EPEX spot prices for simulation framework for Building 1.

4.2.4 Building flexibility database

To populate the tool database, surrogate models were employed. These models underwent training and testing using simulation results obtained from a subset of buildings within the filtered office database. This paragraph In the step, the previous model is used to populate a database with the most common variations of office buildings (based on a database from the NWO iCare project). For each building variant (with variations in window size, Rc values, U values, facade area, floor area, etc.), different performance indicators are calculated. These performance indicators encompass aspects related to energy flexibility, finances, sustainability, and comfort, which are then stored in the database. Additionally, for each building variant, a reference calculation is performed (using the conventional control strategy) and a comparison with alternative solutions (such as electric batteries and PV panels) is conducted. Due to the large number of building variants (approximately 10,000) in the database, it is not efficient to use the detailed calculation model for each variant (among other reasons, due to the long calculation time; on a laptop with average speed, the calculation for one building variant takes about 1 hour). Therefore, it was decided to train a surrogate model based on a sample from the database. The building variants in this sample were calculated with the detailed model, after which the results were used to train the surrogate model. In the project, various types of surrogate model methods were tested, and 5-fold cross-validation was applied. The best performing methods were random forests and GBT; GBT was ultimately chosen because it was faster to calculate. The surrogate models show a minimum R^2 of 0.92. The surrogate model can then quickly calculate the entire database (in a few seconds). This database was then made searchable using simple Python scripts. Figure 17 shows an example of a query in the database.



```
# Change inputs for filtering
inputs = {
    "HVAC": "AIR",
    "Office Type": "LightOpen",
    "Orientation": 0,
    "Rc": 6,
    "g": 0.8,
    "U": 0.8,
    "ADJ temp": 24,
    "facade_width": 4.5,
    "facade_depth": 9,
    "wwr": 70,
}

search_database(inputs)
```

```
Building performance indicators queried from the database
----------------------------------------------------------

Tot_Electricity_Cost_R_Fixed_m2   = 9.49
Percentage_Discomfort_Hours_R     = 4.95
Tot_Electricity_Cost_R2_Fixed_m2  = 11.15
Percentage_Discomfort_Hours_R2    = 6.57
Tot_Electricity_Cost_EF_m2        = 0.87
Tot_CO2_Emission_EF_m2            = 0.09
Percentage_Discomfort_Hours_EF    = 8.45
Internal_rate_return_R            = -161.25
Internal_rate_return_R2           = -122.03
Internal_rate_return_CC_fixed     = -133.33
Internal_rate_return_CC2_fixed    = -159.58
Internal_rate_return_CC_dynamic   = -159.37
Internal_rate_return_CC2_dynamic  = -153.04
Internal_rate_return_EF           = 16.72
Total Area                        = 90.0
```

```
# Change inputs for filtering
inputs = {
    "HVAC": "AIR",
    "Office Type": "LightOpen",
    "Orientation": 0,
    "Rc": 6,
    "g": 0.8,
    "U": 3,
    "ADJ temp": 24,
    "facade_width": 4.5,
    "facade_depth": 9,
    "wwr": 70,
}

search_database(inputs)
```

```
Building performance indicators queried from the database
----------------------------------------------------------

Tot_Electricity_Cost_R_Fixed_m2   = 12.21
Percentage_Discomfort_Hours_R     = 5.04
Tot_Electricity_Cost_R2_Fixed_m2  = 13.88
Percentage_Discomfort_Hours_R2    = 5.99
Tot_Electricity_Cost_EF_m2        = 1.21
Tot_CO2_Emission_EF_m2            = 0.11
Percentage_Discomfort_Hours_EF    = 8.45
Internal_rate_return_R            = -153.79
Internal_rate_return_R2           = -65.13
Internal_rate_return_CC_fixed     = -133.76
Internal_rate_return_CC2_fixed    = -143.61
Internal_rate_return_CC_dynamic   = -110.89
Internal_rate_return_CC2_dynamic  = -58.49
Internal_rate_return_EF           = 22.43
Total Area                        = 90.0
```

Figure 17: Database query comparison. Same building, on the left low U-glazing value, and the right high U-glazing value.

5 WP3: Investigate business cases

5.1 Developing the BE-flex tool

In this work package, a tool has been developed to enable users to search the database created in WP2. The BE-flex tool predicts the available energy flexibility of specific office buildings while considering the comfort requirements of office workers and local weather conditions. It primarily focuses on leveraging energy flexibility through adaptive comfort strategies and the building's thermal mass.

The functionalities of the tool include:

- Comparing the predicted energy flexibility of a specific building to a predefined baseline usage and other available energy flexibility sources, such as electrical batteries.
- Identifying building design improvements that can enhance available energy flexibility.
- Explaining the business case associated with predicted building energy flexibility, indicating whether it is of interest to the energy market.
- Presenting building performance using various performance indicators (PIs) related to sustainability, financial aspects, and the thermal comfort of office workers.

The mockup of the interface is designed for two types of users: non-technically skilled end-users and technically skilled end-users such as engineers and designers.

The initial step involves understanding and envisioning the final tool for end-users. A digital user-friendly interface was deemed the most suitable solution for leveraging the database efficiently. Through the digital interface, users can easily navigate, edit, view, and comprehend data, gaining valuable insights into the energy flexibility of their assets. A mockup of this digital user-friendly interface has been designed accordingly.

5.2 Results

5.2.1 Tool Mockup Interface

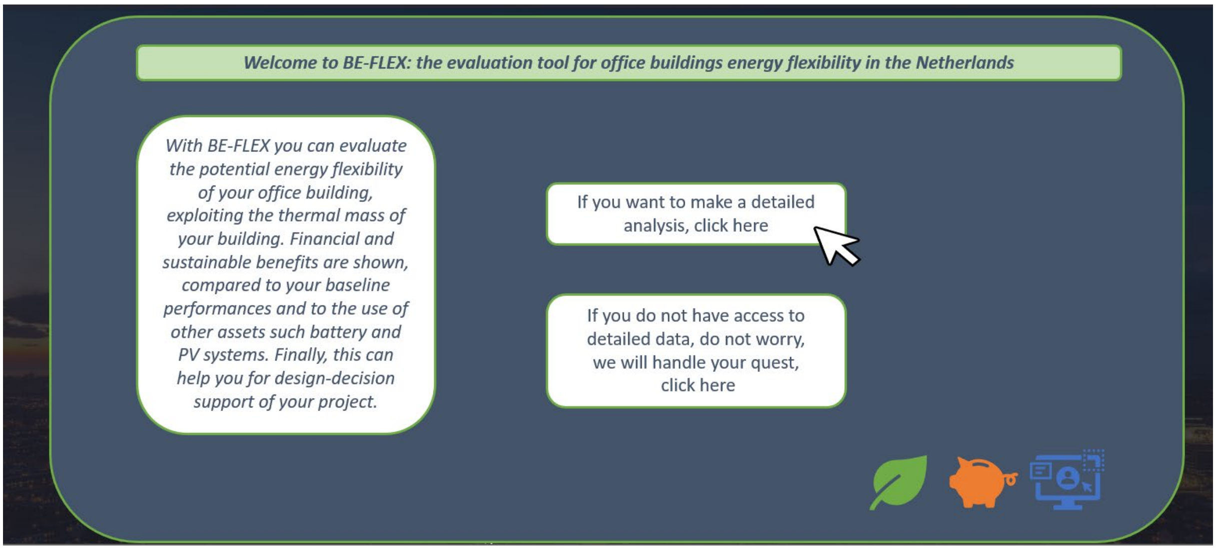
The following paragraph presents the mockup design of the BE-FLEX interface, which is crucial for making the database accessible and user-friendly to end-users. The interface allows users to navigate the database, explore its features, and retrieve information for their needs.

Drawing inspiration from a previous project that laid the foundation for the BE-FLEX project (Papachristou C., 2019), the design process for the tool's end-user interface also involved collaboration with the TROEF project (for more information on the TROEF project, please visit www.TROEF-energy.nl).

The BE-FLEX interface is conceived as a web page where users can easily navigate. It functions as a search engine for the developed database of Dutch office buildings.

BE-FLEX caters to two primary types of end-users: technically skilled users (such as engineers and building consultants) and non-technically skilled users (individuals with access to and understanding of building-related data but lacking professional expertise). Consequently, there are two main environments tailored to these user groups.

BE-FLEX page 1, depicted in Figure 16, offers a brief overview of the tool on the left side. On the right side, it presents two icons that allow users to access either detailed analysis (for technically skilled end-users) or general analysis (for non-technically skilled end-users).



Welcome to BE-FLEX: the evaluation tool for office buildings energy flexibility in the Netherlands

With BE-FLEX you can evaluate the potential energy flexibility of your office building, exploiting the thermal mass of your building. Financial and sustainable benefits are shown, compared to your baseline performances and to the use of other assets such battery and PV systems. Finally, this can help you for design-decision support of your project.

If you want to make a detailed analysis, click here

If you do not have access to detailed data, do not worry, we will handle your quest, click here

Figure 16: BE-FLEX page 1, welcome and choice of environment (detailed analysis).

As the initial step, the end-user can click on the "detailed analysis" button to navigate to the detailed analysis screen, illustrated in Figure 17. On page 2, the end-user can input information related to the office.

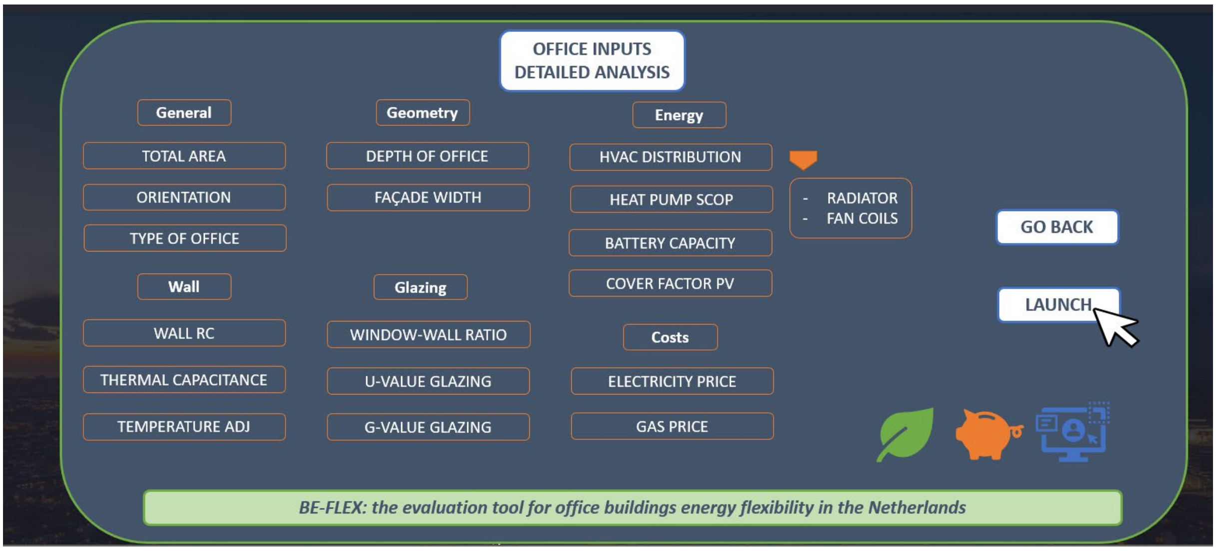


Figure 17: BE-FLEX page 2, detailed analysis.

The inputs are categorized into General, Wall, Geometry, Glazing, Energy, and Costs. Within each category, the end-user can input parameter values (such as total area in m2) and/or select predefined values (e.g., 40%, 70%, and 100% for WWR). For example, in Figure 17, the selection of the Heat Ventilation and Air Conditioning (HVAC) distribution system, either radiators or fan coils, is depicted. After entering each parameter, the end-user can select the "GO BACK" button to return to page 1 or click "LAUNCH" to query the database for the selected building. In the latter case, the search engine will provide the closest solution in the database based on the input data and extract the output. Providing all exact inputs is not mandatory; the tool will output the closest solution based on the inputs.

Clicking the "LAUNCH" button grants access to results on page 3, as depicted in Figure 17.

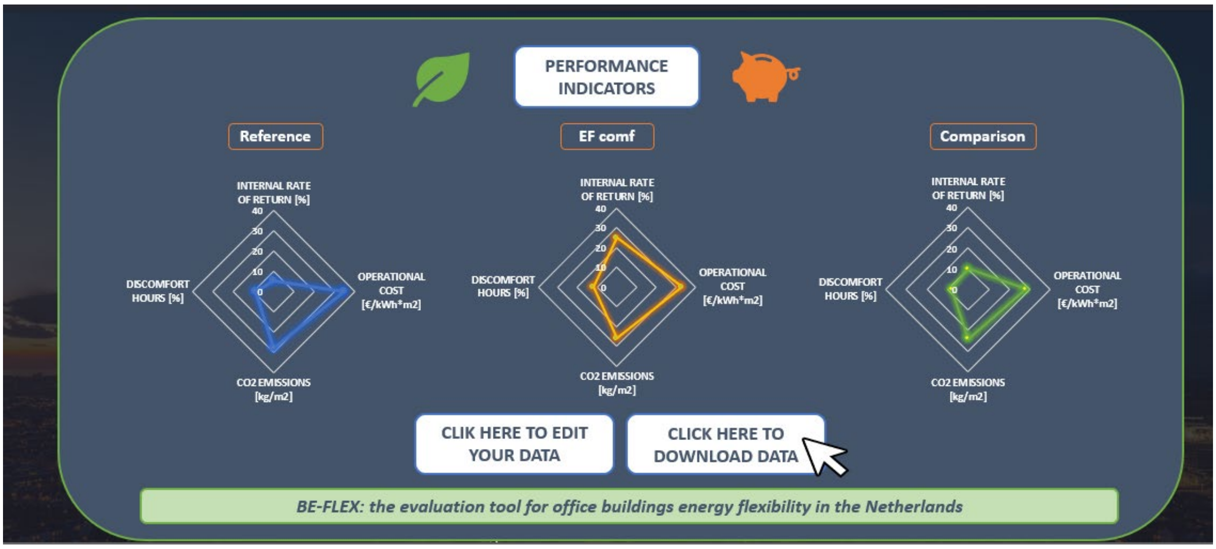


Figure 17: BE-FLEX page 3, examples of results in spider graphs.

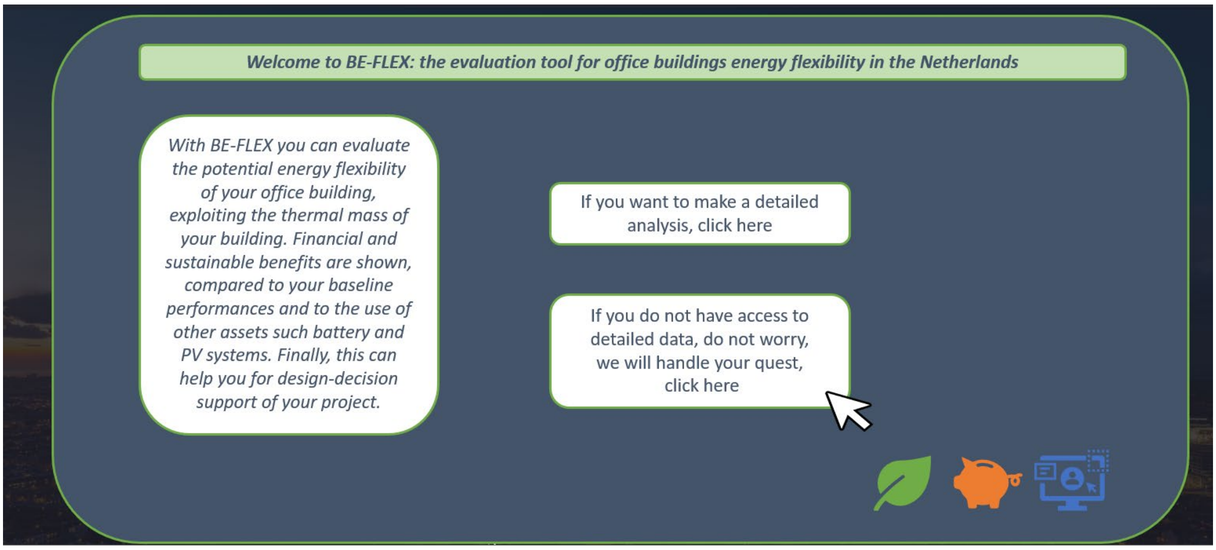
This page illustrates the performance of the specified building under various scenarios:

- Reference case: Demonstrates the building's behavior with conventional operational control strategies, utilizing either a gas boiler or HP.
- Energy Flexibility adaptive comfort strategies (EF comf) case: Illustrates the building's behavior with the implementation of adaptive comfort strategies optimized for dynamic electricity prices and user thermal comfort, utilizing an HP as a thermal source.
- Comparison case: Displays the building's behavior with HP, battery, and PV systems operated using conventional control strategies.

Detailed indicators related to finance, comfort, energy, and emissions are depicted using spider graphs.

Users can modify the data by clicking the “CLICK HERE TO EDIT YOUR DATA” button or download data in CSV format using the “CLICK HERE TO DOWNLOAD DATA” button.

For non-technically skilled users, a general analysis can be explored by clicking on the bottom right button on page 1, as indicated by the cursor in Figure 18.


Welcome to BE-FLEX: the evaluation tool for office buildings energy flexibility in the Netherlands

With BE-FLEX you can evaluate the potential energy flexibility of your office building, exploiting the thermal mass of your building. Financial and sustainable benefits are shown, compared to your baseline performances and to the use of other assets such battery and PV systems. Finally, this can help you for design-decision support of your project.

If you want to make a detailed analysis, click here

If you do not have access to detailed data, do not worry, we will handle your quest, click here

Figure 18: BE-FLEX page 1, welcome and choice of environment (general analysis).

Page 4, as depicted in Figure 19, presents a simplified overview of the building's performance, focusing on key indicators such as energy consumption, cost savings, and thermal comfort. This interface is designed for non-technically skilled users, providing accessible insights without overwhelming technical details.

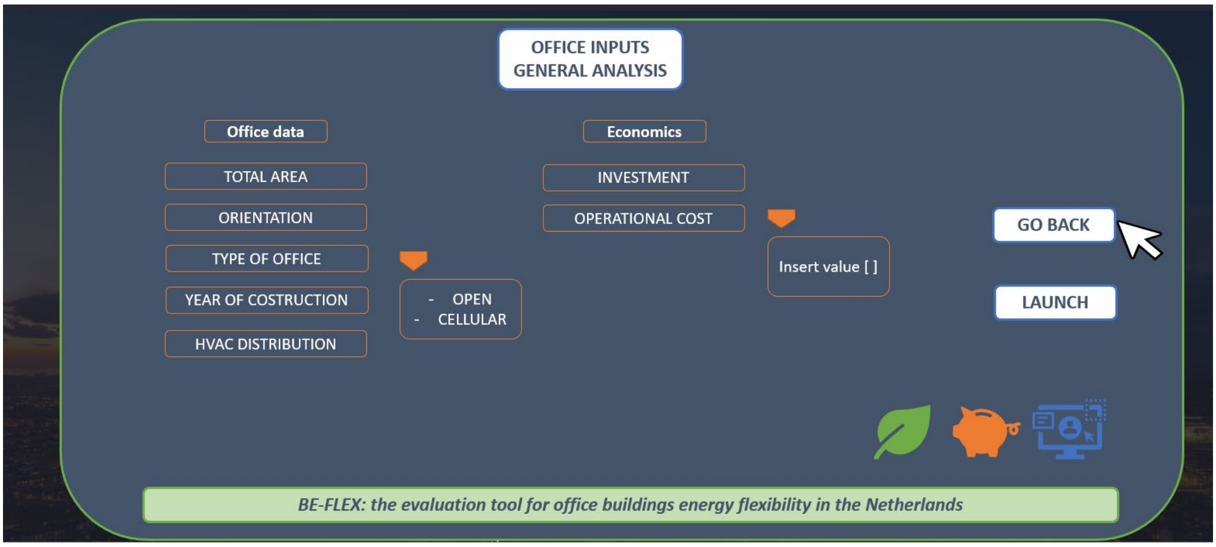


Figure 19: BE-FLEX page 4, general analysis.

Page 4 allows the end-user to input data similar to the detailed analysis, focusing on key parameters of the building such as total area, orientation, office type, year of construction, and HVAC system. By clicking the "LAUNCH" button, BE-FLEX's search engine will generate solutions based on the provided inputs. It's important to note that not all inputs will be used to query the database, resulting in a range of outputs. Clicking "GO BACK" will return the user to page 1.

Please note that the mockup interface does not represent the final user interface, as GUI engineering, brand integration, real-time back-end edits, and post-implementation steps are still required. Product deployment is not part of the current project, but initial collaboration with a third-party has commenced.

6 Conclusions and next steps

The final deliverable of this project is the BE-FLEX tool, designed to assess the energy flexibility achievable in office buildings through adaptive comfort strategies. At its core lies a precalculated database containing the energy flexibility potential of various office building configurations. While currently accessible via a simple Python script, a mockup interface has been developed as a starting point for potential product development (which is outside of the scope of this project).

The following points were key in the development of the database and prove its validity:

- Measurement campaigns conducted in four office buildings demonstrate the feasibility of employing adaptive comfort strategies in real-world scenarios to enhance energy flexibility without compromising thermal comfort.
- A computational building energy model has been created and validated using data from one of the office buildings.
- A simulation framework has been established, enabling yearly simulations of the building energy model while optimizing daily operational strategies. This framework facilitates the selection of optimal adaptive comfort strategies for each day and allows for performance comparison with other flexibility sources within the building.
- Surrogate models have been developed which can speed up the creation of the database.

Note that no intellectual property (IP) was developed during the course of this project. Our focus has been on research, experimentation, and knowledge dissemination.

6.1 Next steps

The current tool focuses on analyzing the energy flexibility benefits of individual buildings. However, as a next step, it could be expanded to investigate how a single building influences the performance of a cluster of buildings, such as in a local energy community. In such settings, additional mechanisms of energy flexibility, like energy trading, may come into play, as demonstrated in projects like TROEF.

Further developments could involve implementing edits in the back-end, including more building types (e.g., residential), energy systems, and additional scenarios. This could entail retraining and expanding the database to encompass a broader range of variables. Additionally, the engine could be deployed with client-specific front-ends to tailor the tool to specific user needs.

A future step might involve the actual control of the buildings. This could lead to cost savings of 10-20%, benefiting either the end-user or the energy service provider, depending on the distribution of responsibilities. In this scenario, it would be valuable to explore whether the simulation framework could be adapted to serve as an operational controller, enabling real-time optimization of energy use based on dynamic conditions.

7 Knowledge dissemination

As agreed with TKI Urban Energy (as a ‘condition of approval’ for this project), the work has been disseminated in various ways. Specifically, we have utilized publications and presentations to engage stakeholders.

Publications

The results of the project have been published in an EngD thesis and an article in the Dutch TVVL Magazine:

- Peluso, U. (2023). BE-FLEX: a tool to evaluate energy flexibility in office buildings through adaptive comfort strategies. EngD thesis, Eindhoven University of Technology.
- Peluso, U., Hoes, P. J., & van Goch, T. A. J. (2024). Tool voor de kwantificering van energieflexibiliteit uit thermische massa van gebouwen. *TVVL Magazine*, *2024*(2), 16-21.

We are currently working on an article for the international REHVA magazine. Additionally, part of this work will be published in a joint journal article, collaborating with an ongoing PhD research project related to the TROEF project.

Presentations

Throughout the project, the work has been presented multiple times to the members of the TROEF consortium (www.troef-energy.nl), which consists of various stakeholders, including building operators, building engineers, and DSOs. Additionally, the project has been showcased at a TKI Urban Energy webinar and multiple EngD events, including the EngD annual symposium.

8 Execution of project

The project commenced later than initially anticipated due to challenges in recruiting a suitable EngD trainee. This delay led to a shift in the project's start time. However, this had no impact on the project's content or objectives.

The project has been executed according to the original project plan. No significant changes have been made to the project's scope or activities. Additionally, there have been no deviations from the project's financial plan, ensuring that the budget has been adhered to as expected.