PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

LLEC Energy Dashboard Suite: User Engagement for Energy-Efficient Behavior using Dashboards and Gamification

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Abstract:
With growing concerns about climate change and increasing energy costs, energy-efficient use of buildings offers an opportunity to decrease CO_2 emissions and costs. The behavior of building occupants plays a significant role in the process of improving this efficiency both for new and existing buildings. Therefore, we introduce a suite of web-based software applications that aim to encourage energy-efficient building occupant behavior in an office environment under the Living Lab Energy Campus (LLEC) initiative, using the campus of Forschungszentrum Jülich as a demonstration. The suite of applications, developed via a co-design process, provides means to view energy consumption data at various levels of aggregation, and to receive real-time recommendations and incentives for behavior change. Through the *Energy Dashboard*, users can monitor and analyze heating, cooling, and electrical energy consumption at building level. Leveraging IoT-enabled sensors and actuators, *JuControl* offers an interface to view room-specific indoor environmental, heating and ventilation data, and allows occupants to control the room heating by specifying a personal temperature setpoint range. Occupants also receive real-time feedback via recommendations for energy efficiency improvement, alongside periodic behavior evaluation in the form of ratings. The serious game *JuPower* gives users the opportunity to compete in teams to design a CO_2-minimal alternative virtual energy system for the campus, whilst the users' real-world energy-related behavior is translated into in-game effects, thereby providing incentives for energy-efficient behavior via game rewards and social interaction. The interrelations among the applications, deployment strategies, and first outcomes are discussed.

Keywords:
Occupant Behavior, Office Building, Energy Efficiency, Gamification, Serious Game, Energy System Visualization, User Engagement

1. Introduction

In the EU, the building sector contributes 40% of the energy consumption and over 30% of the CO_2 emissions [1], [2]. According to estimations, 75% of the buildings in the EU are energy-inefficient [3].

Within the building sector, occupant behavior has been identified as a key factor in the energy efficiency of buildings and is often implicated in the difference between modeled and actual (post-occupancy) energy consumption of buildings [4, 5, 6]. According to the PROBE studies (Post-occupancy Review of Buildings and their Engineering), this difference is usually a factor of two: the actual consumption is twice the modelled consumption [4, 7]. Similar results are also reported by other studies (e.g. as cited in [8]). Furthermore, in one simulation study of energy behaviors of office occupants with profiles classified as one of austerity, standard, or wasteful, it was estimated that the wasteful profile can use up to 90% more energy than the standard energy profile in a one-person office, while the austerity profile can use up to 50% less energy than the standard profile [9].

Clearly, there is potential for the improvement of energy efficiency in buildings through energy-efficient occupant behaviour. However, there are challenges in engaging occupants and triggering behavior change. First, building occupants in public buildings are usually indifferent to the energy efficiency of their behavior because they are not conscious of their impact on the energy consumption and are not responsible for the energy costs [10]. To solve the consciousness issue, energy consumption should be monitored through measurement data. But this leads to issues of privacy and data security, especially for a country like Germany where privacy is taken more seriously than in most other European countries, with supporting structures like the works council and Data Protection Officers serving to protect employees from privacy infringements [11, 12, 13, 14].

Furthermore, the issue of occupant apathy to energy consumption in public buildings is not easy to address in a top-down, management-initiated and sustained fashion in a European country like Germany. Only in the light of the energy crisis occasioned by the Russia-Ukraine conflict was there more assertive drive from government to save energy across the country. In spite of this, occupant behavior still requires more intrinsic motivation for its transformation.

In this work, the objective is to develop and test applications that are effective in influencing building occupants' behavior through intrinsic motivation. We focus on occupant interactions with the heating, cooling and air conditioning (HVAC) system in naturally ventilated office buildings under real-world conditions. This work is incorporated in the Living Lab Energy Campus (LLEC), in which a part of the infrastructure of Forschungszentrum Jülich GmbH (FZJ) is transformed to a test-bed for e.g. monitoring and control approaches for future building and district energy systems. Our case study consists of a subset of office buildings in FZJ with different years of construction (ranging from the 1970s up to recently completed buildings), which are representative of the office building stock. Figure 1 gives an overview of the chosen setup in the equipped buildings. All selected buildings, like all FZJ buildings, were already equipped with digital calibrated meters to measure electricity, heating and cooling demand, e.g. for billing purposes. For research purposes, an interface was set up between the facility management's proprietary system and the research ICT platform. In addition, all offices, meeting rooms and kitchenettes in the selected buildings were equipped with wireless indoor air quality sensors (to measure CO_2 concentration, temperature and relative humidity), window and door status sensors, and wireless thermostats. Due to the heterogeneity of the buildings and in order to limit the retrofitting effort in the existing buildings to a sensible level, the sensor network makes use of wireless (EnOcean) sensors. On top of this, a subset of the selected buildings was equipped with wired (KNX) actuators for shading, lighting and underfloor heating control and push buttons with integrated displays. To allow for transfer of the developed approaches to buildings in the outside world, all sensors and actuators used are commercially available. More details can be found in [15].

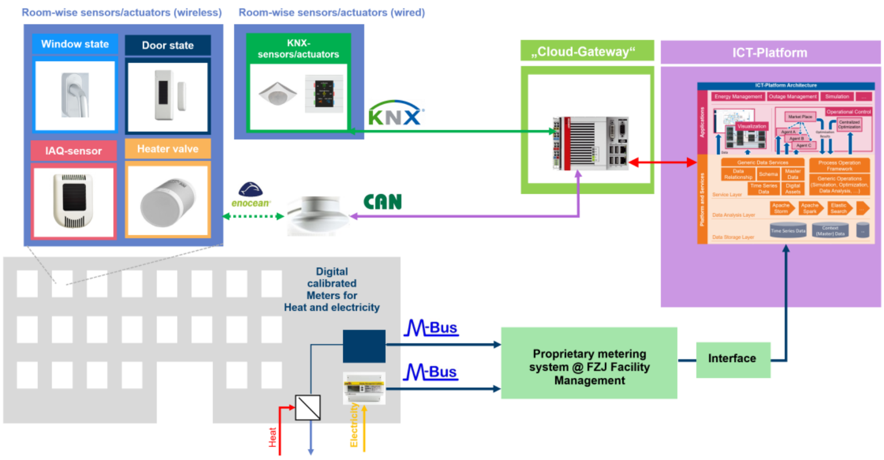

Figure 1: Setup of digital meters, sensors and actuators in buildings

To meet the challenges in bringing about behavior change, we develop applications for building occupants for visualization and control of the building energy system through a human-machine interface (HMI). Additionally, we introduce real-time behavior evaluation and recommendations for the occupants, supported by *gamification* and a serious game. We evaluate the effectiveness of various combinations of these behavior intervention measures. Only initial results from the individual parts of the system are available as at the time of this writing, the fully coupled system has only just been deployed.

1.1. Literature Review

The interaction of occupants with the building and its energy system is the focus of several large-scale studies. For example, the DataFEE project[1] focuses on the development of tools and methods for the analysis of the interaction of occupants with buildings. Likewise, the IEA EBC Annex 66 project [2] and the IEA EBC Annex 79 project [3] focused on modelling occupants and occupancy, as well as the integration of occupancy in building models. Related to these occupant-centric studies, various behavioral intervention projects have

[1] Available at https://www.ebc.eonerc.rwth-aachen.de/cms/E-ON-ERC-EBC/Forschung/Forschungsprojekte2/Projekte-Nutzerverhalten-und-Komfort/ cviyk/DataFEE/?lidx=1

[2] http://www.annex66.org/

[3] Available at https://annex79.iea-ebc.org/

been carried out to address energy efficiency of occupants in buildings. These interventions take one of several forms, including provision of information through visualization, active feedback through various means of communication, and numerous gamification and serious games. One main element for providing information and visual feedback in energy systems is the use of *energy dashboards* [16]. These dashboards provide a Graphical User Interface (GUI) for visualizations regarding energy-related data. Additionally, interactive dashboards provide good User Experience (UX) and encourage interactions with the information being presented. To make such GUIs effective, their design follows Human-machine interface design principles. Rogers, Sharp and Preece [17], who worked extensively on these design principles, highlight the principles of *visibility*, *feedback* and *constraints*. The principle of visibility refers to making actions and functionalities obvious to the user, while the principle of feedback prescribes that the interface should give users notifications when an action has to be performed or has been completed. The principle of constraints refers to limiting user actions in the interface if they are not valid. In the context of energy behavior interventions, these principles encourage the use of energy dashboards. Whilst some studies show that dashboards are beneficial, other studies indicate, however, that visualization alone does not lead to sustainable energy-saving behavior [18, 16]. Most studies related to occupant behavior interventions focus on gamification and serious games.

Gamification is defined as ”the use of game design elements in non-game contexts” [19]. A distinction exists between *serious games*, which is the development of full-fledged games for non-entertainment purposes, and gamification, which just involves the use of game elements or ”atoms” in an otherwise non-game context [19]. Such game elements include leaderboards, badges, and points. Gamification aims to achieve real-world behavior change by means of an engaging and fun experience.

Several studies have used different gamification concepts with the intention of motivating users to take action for enhanced energy efficiency. In the review by Johnson et al. [20] the authors investigated 25 gamified applications and serious games in the domestic energy consumption sector. The results of the behavioral interventions are classified into four categories: behavioral, cognitive, learning and knowledge acquisition, and user experience. Behavioral interventions refer to real-world and in-game actions and aspirations to save energy, while the cognitive aspect refers to affective and motivational elements, including energy-related opinions, self-awareness about energy saving and motivation to engage in energy-conserving measures. Learning and knowledge acquisition refers to learning effectiveness and knowledge accumulation, and finally user experience refers to the perspective of the user towards the game, including engagement, usability and satisfaction. The results of the majority of the studies (a total of 17 out of 25) fall into more than one result category. The user experience is the most frequent, followed by cognitive, real-world behavioral, knowledge, then in-game behavioral categories.

Across the studies, the results were not exclusively, but mostly, positive. About half of the reviewed interventions explored serious games and the other half explored gamified applications. Among the employed applications were seven mobile apps, nine browser apps and five computer games. While around half of the applications feature integrations with the real world, the others are completely digital without real-world integration.

AlSkaif et al. [21] introduces a conceptual framework based on gamification for residential building user engagement. They classify the framework requirements and link them to corresponding high-level gamification objectives. The five groups of game design aspects implemented are information provision (statistics, messages, tips), rewarding system (electricity bill discounts, virtual currency, prizes/offers/coupons), social connection (competition, collaboration, energy community), user interface (dashboards, leaderboard, progress bar, message box, notifications, degree of control), and performance status (points, badges, levels).

1.2. Research Contributions

The contributions of this paper are as follows. First, we report on various implementations of user behavior interventions with respect to energy efficiency, starting with visualization of energy systems at different levels of spatial granularity, through to provision of a Human-Computer Interface (HCI) for controlling the energy system. Furthermore, we discuss the application of gamification and user behavior evaluation, and the coupling of these to a serious game. When the experimental results are complete, we intend to extensively analyze and discuss the contributions of the various combinations of these interventions to occupant behavior improvement. In this paper, however, we only discuss initial results, since the full-fledged experiment has only been running for a very short time as at the time of writing.

This work is organized as follows: Section 2. describes the purpose and features of the applications developed, Section 3. presents results and discussion of the co-design process of the applications as well as the occupant behavior evaluation. Section4. summarizes and draws a conclusion.

2. Methodology

The LLEC Energy Dashboard suite includes multiple web applications that interact with each other to provide a wide range of functionalities.

2.1. The Energy Dashboard: Visualization of Energy Data

The Energy Dashboard provides an interface through which staff members and visitors can gain insight into the energy demand of the campus. Via the Dashboard, users can view both historical and real-time heating and electricity data at the campus level as well as for individual buildings, see Figure 2.

Additionally, the Dashboard shows operation data of so-called *energy demonstrators*, which are proof-of-concept energy systems for generation, conversion, and storage of renewable energy and waste heat. The goal of the Dashboard is to drive user awareness regarding energy systems in general, as well as to improve the public understanding of the represented systems.

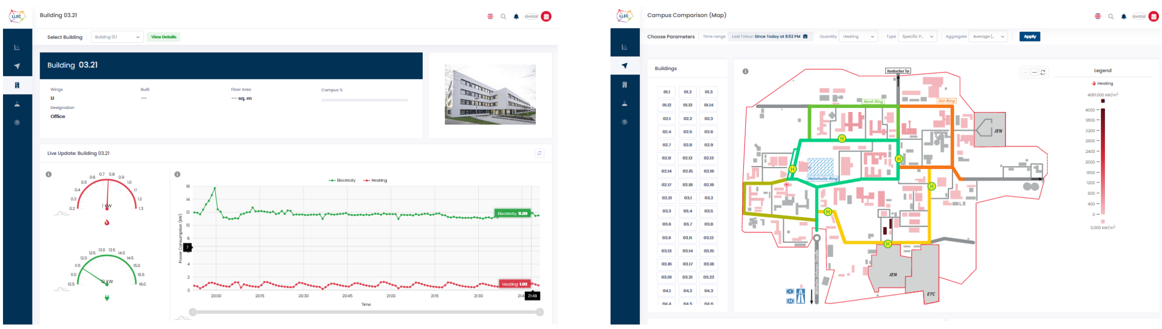

Figure 2: Screenshots of the Energy Dashboard. *Left*: Exemplary building page showing live electricity and thermal demands. *Right*: Comparison of buildings demands for thermal power.

2.1.1. Data

Currently, the two main data measures are electricity and heating demand. Timeseries data for those measurements is visualized on the dashboard at one-minute resolution. The main landing page of the energy dashboard shows the overall consumption of electricity and heating energy for the whole campus using a mix of chart types. This is the highest-level data that is visible on the dashboard. More details for the same consumption data for electricity and heating is also available on the building-level. Via an interactive campus map or a list of building IDs, a single building can be selected to view its data. This data is also available in the form of the same 2-hour-live-chart. Additionally there is a 48-hour historical data bar chart, in which the data is hourly aggregated.

2.1.2. Access rights

One important aspect of the whole framework is data security. There are different levels of access for the energy dashboard, as not all data is visible to every user. Authentication is via Shibboleth, and roles are assigned based on the authenticated user. The basic staff role can view data for the whole campus and single buildings, but buildings in restricted areas on the campus are not available. Admins can escalate their authentication level to view more data like number of sensors reporting for each data point, additional plots, and access to the restricted buildings. The guest role uses login credentials without Shibboleth authentication, and is only permitted to view the campus-level consumption and a special subset of buildings.

2.2. JuControl: Visualization, Control and Gamification

The effects of the behavior of a single office occupant in the context of a whole building are not necessarily directly visible. To account for that, selected buildings were equipped with additional sensors and actuators for data acquisition and control at room level. This allows the collection of more datasets like CO_2 concentration, humidity or window states. The measurement data on room level is visualized via the web-based application *JuControl* (see Figure 3), which is integrated into the Energy Dashboard.

Besides the more detailed visualization of data, *JuControl* also enables users to control actuators in their room via an online interface, in addition to the physical controls available at the actuators themselves.

2.2.1. Automatic heating control

Within LLEC, the equipped rooms form a test-bed for testing different innovative control approaches, e.g. model predictive control-based room controllers. In addition to the control options in the rooms, *JuControl* provides the central user interface for the comfort preferences of the room occupants that are taken into account by

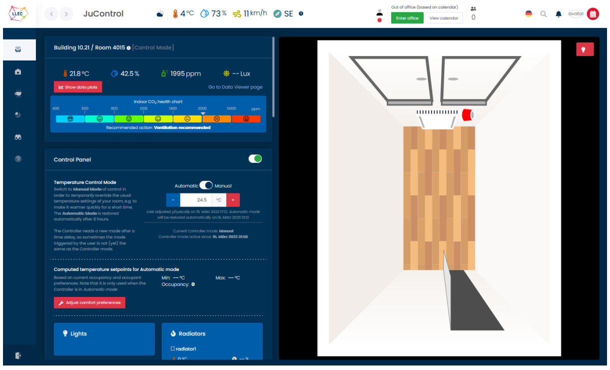

Figure 3: JuControl: Exemplary room view

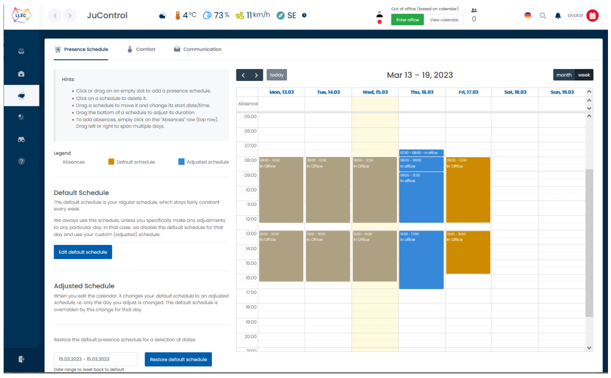

Figure 4: JuControl: User specific time schedule for the expected presence in the office

the tested automated controls. Regardless of the control algorithms tested, the user interface itself already offers a great deal of savings potential through options that go far beyond the previous manual adjustment of thermostats. Office spaces are usually only used in a clearly limited time frame. Therefore, they offer a good opportunity to save heating energy by lowering the room temperature to an appropriate level while the office is not occupied, for example after working hours and over the weekend. However, for the comfort of employees, it is important to restore the correct temperature within the rooms in time. For this, *JuControl* offers users the ability to create an individual time schedule in which they enter their expected presence; see Figure 4.

In order to accommodate different needs, every user can also define their own comfort temperature range. Based on the schedules of all occupants of an office, *JuControl* then calculates a heating plan for the room. A controller script can query this heating plan via *JuControl*'s API and perform optimal heating control based on the desired temperature setpoints.

2.2.2. Manual control mode

Naturally, an occupant's schedule may not always match the actual presence in the office, for example when the schedule changes temporarily on short notice. For scenarios such as these, the occupant always has the option to switch to "manual control", in which the schedule and the associated desired temperature setpoints are overridden by the manual setting. Manual control can be triggered via the *JuControl* web interface or by physically operating the thermostats. In both cases, the new user-specified setpoint temperature is then targeted by the heating control. After a maximum of 8 hours, the control automatically returns to automatic mode, in which the presence schedule is used once again.

2.2.3. User Consent

Compared to the general building consumption, the parameters measured here are very sensitive data, as they allow drawing direct conclusions about individual persons or small groups of persons. For example, the CO_2 concentration in an office can be used to determine how many people were present in the office at a specific time. The data is only visible to an occupant if all the other occupants of an office agree to the usage of this tool. This poses an additional challenge when users change offices. Basically the following rules are applied: a user only has access to the data of the office they are officially assigned to, and only if all other occupants of this room have given their consent. If someone leaves an office, the person also no longer has access to newly generated data of this office. (However, they can view historical data.) If a new employee joins an office, everyone automatically loses their access rights until this new employee has also agreed to the data processing.

2.2.4. Gamification

JuControl features a gamification section, in which the energy efficiency of occupants' offices is evaluated based on predefined behavioral patterns related to ventilation habits and indoor temperature setpoints. The evaluations, which are currently limited to heating demand, are carried out by *Juracle*, an evaluation engine discussed in Section 2.4.. Corresponding penalties are awarded in the form of "wasted thermal energy" scaled to the size of the FZJ campus. Groups of office rooms compete in teams against groups from the same or other buildings. A leaderboard shows the ranking of teams based on performance and places each room's performance in the context of the team's and global performance. Additionally, a three-color traffic-light feedback system is used to convert the raw energy penalty values to normative feedback that allows occupants to determine if their performance is relatively good or bad.

Social interactions (competitions, teams) have been shown to be key elements of effective gamification [22, 23, 20]. To this end, gamification in *JuControl* is designed around teams and competition. Additionally, the performance of teams is coupled to a serious game *JuPower*, discussed more in Section 2.3. below. The *JuControl* gamification interface is shown in Figure 5 below.

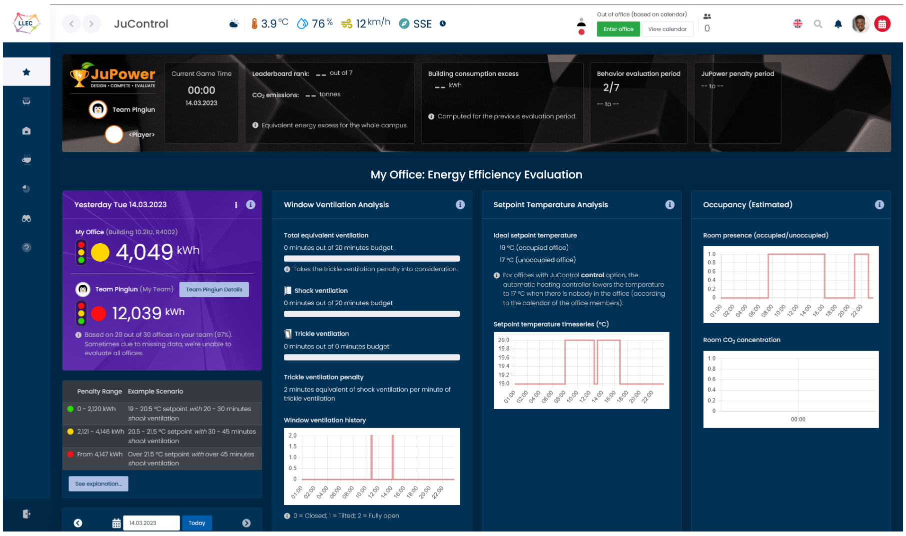

Figure 5: *JuControl* gamification interface showing integration with a serious game, *JuPower* (top dark bar), and evaluations obtained from *Juracle*. The charts show the timeseries for the input quantities for behavior evaluation – window state, setpoint temperature, and presence profile.

2.3. JuPower: A Serious Game

JuPower is a *serious game* developed to enable players appreciate the trade-offs involved in energy system design. A *serious game* is a game developed for non-entertainment purposes, whilst ideally retaining the fun and engaging nature of entertainment games. The purpose of the gamification approach is to engage users and draw attention to the way their behavior affects their energy consumption.

2.3.1. Game design

In the game, the mission for players is to design a more climate-friendly energy supply system for a virtual version of the Forschungszentrum Jülich campus having heating and electricity demand. The electrical demand data is derived from actual historical data for the campus, while the thermal demand data is derived from a mix of Modelica [24] models of the actual buildings developed using the TEASER [25] tool, and historical data. The building models allow players to apply realistic retrofits at a cost in the game.

By design, the default energy source for heating in the virtual campus is an oil boiler, with electrical power being drawn from the virtual electricity grid. This assumption is different in many respects from the actual energy sources in the real campus.

To reduce the CO_2 emissions arising for the supply of energy to the buildings, new installations can be made in the game. Players have a fixed budget with which they can purchase new energy systems and components to replace the default energy system. The resulting energy system for the virtual campus is simulated afterwards for each team, and the teams are ranked continuously based on the total operational CO_2 emissions generated over the simulation period.

2.3.2. Game modes

JuPower admits three different modes of play that can coexist independently. These are:

- Sandbox mode, in which players try out features and learn the system without teams, competitions, or external time pressure. Essentially, the players' game actions and its effects are visible to the player alone.
- Standard game mode, in which players participate in teams in a predefined gameplay instance that is governed by a time schedule. In this mode, outcomes of the real-world behavior evaluation are fed into the game.
- Real-time mode, which is intended for more experienced energy system designers. Here, the game clock is synchronized to the real clock, and boundary condition inputs into the game, like weather and demand data, are derived in real-time from real-world data.

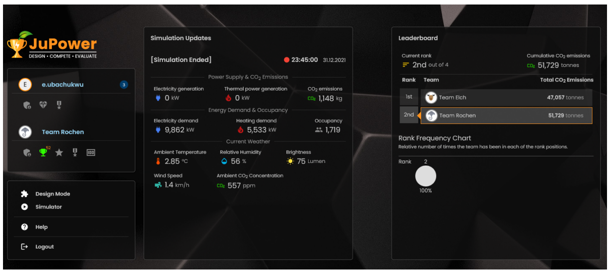

Figure 6: JuPower home page during simulation showing the energy widget (center) and the leaderboard (right).

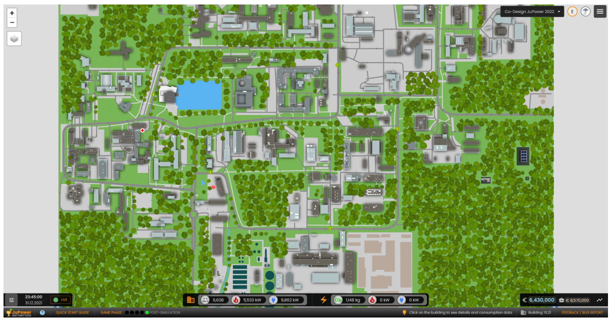

Figure 7: JuPower simulation page

2.3.3. Gameplay

A game run consists of *game phases*, each of which provides a defined set of interaction opportunities for the players. In the *design phase*, players design an energy system by installing energy system components on a stylized aerial view of the campus via drag-and-drop. The aerial map view faithfully mimics the main features of the landscape of the real campus. Each installation of a component requires cash and real-estate, and is subject to the availability of these resources. Players propose their designs to their teams and cast votes to determine which proposed design is adopted for the team. To enhance coordination and communication amongst players within a team, a rich-text chat functionality with mentions is available in the Proposals page. Furthermore, players tag and optionally describe their designs prior to proposing them.

The *pre-simulation phase* follows the design phase. In this phase, the most-upvoted design is automatically adopted for each team. Based on this design, the operation of the energy system over a certain period is projected by computing the dispatch of the components. The dispatch is the result of a Mixed-Integer Linear Program (MILP) optimization problem, solved using the Gurobi^{TM} [26] solver. Afterwards, the *simulation phase* starts, during which various system data and performance indices are shown in "real game-time" as the simulation progresses. The Key Performance Index (KPI) is the accumulated operational CO_2 emissions, and teams are ranked on a leaderboard based on this KPI. Figure 6 and Figure 7 below show the home page and simulation page, respectively, during simulation. The *post-simulation phase* allows players to take stock and reflect on their design choices.

2.3.4. Coupling with Real-world Behavior Evaluation

The real-world behavior penalties computed as part of the JuControl gamification described above, are transferred to JuPower as additional building demands. Specifically, for each team, the average weekly performance penalty is added to the thermal demand of the buildings in JuPower for that team. This has the effect of a proportional increase in CO_2 emissions in the game, and by extension a worsening of the performance of the energy system in the game.

2.4. Juracle: Occupant Behavior Evaluation Engine

Juracle is an engine that evaluates the thermal energy-related aspects of occupant behavior based on two criteria: window interaction (ventilation) and room heating (temperature setpoint). First, it defines the notion of an ideal occupant, and then computes the deviation of a given instance of occupant behavior from this ideal. Finally, it expresses this deviation in energy terms (kWh) as wasted energy. Two different but related focuses of such a behavior evaluation tool can be identified: behavior modification to conform with some predefined norm, or energy wastage estimation. These two goals are not necessary congruent, since aiming for one could imply violating the other. For example, previous research has shown that *trickle ventilation* during the heating season (i.e. with windows opened only a small angle while hinged on the bottom side) leads to severe energy losses, compared to the so-called *shock ventilation* (with windows fully opened while hinged on the side) [27]. (These multi-modal windows are commonplace in Germany.) However, trickle ventilation leads to more energy wastage only because occupants tend to leave windows in that state for long periods due to its poor efficiency in refreshing the room air, leading to the cooling down of the walls. Evaluation with focus on behavior modification discourages *patterns of behavior* like trickle ventilation, while focus on energy evaluation judges the energy impact of particular instances of behavior that lead to energy wastage.

Effectively, the behavior modification-focused method of intervention tends towards a rule-based system, in which a consistent set of relatively simple rules are defined by which user behavior is judged. These rules do not have to be accurate in the physics sense in its assumptions, but only need to be *self-consistent*, that is – roughly speaking – given similar inputs, they produce similar outputs. On the other hand, model-based systems are more appropriate when the focus is estimating energy wastage. Here, the physical processes involved and their relationships are represented using laws of physics.

2.4.1. Hybrid Evaluation Model

Juracle uses a hybrid approach: it focuses on the behavior modification goal, and derives a set of physics-informed rules with the following attendant characteristics. First, the ideal occupant is defined in terms of duration of window opening, and the chosen setpoint temperature. A quota is assigned for the ideal occupant and deviations are computed from this quota for real occupants. Secondly, trickle ventilation as a pattern of behavior is discouraged. Therefore a penalty factor scales the trickle ventilation duration to deplete the quota more quickly. Thirdly, the computed deviations based on the measured criteria are applied to a reference model to derive an estimate of the energy ”cost” of the deviations (in kWh). Finally, since the rule-based system has fewer parameters than a model-based system, it tends to be more easily scalable than a purely model-based system which has to take into account the variations of the physical properties of the different buildings and interactions.

The penalty derived from *Juracle* is applied to *JuPower* game as a demand increase for which CO_2 emissions must be minimized in the game.

2.5. Experiment Design

In order to evaluate the effectiveness of the suite of applications in concert, an experiment design has been conceived and the experiments are currently ongoing. Some of the questions that the experiment design aims to answer are:

- What are the effects of the behavior evaluation strategy on behavior, both in terms of user actions as compared to the ideal scenario, and in terms of actual energy savings?
- What additional effect does the JuPower serious game have when coupled with behavior evaluation, and what is its stand-alone effect?
- What are the effects of visualization and control, without evaluation?

To this end, the experiment design strategy involves grouping nearly 500 offices across more than ten buildings into teams with various combinations of features enabled for each team. Depending on the set of enabled features, these teams are grouped into independent experiment sets on the basis of feature compatibility. The design of each of these experiment sets provides the potential to answer specific research questions, such as those outlined above.

3. Results and Discussion

The *Energy Dashboard* has been used by more than 1,300 staff members since its release in mid-2020, or about one-fifth of the population of the campus. *JuControl* has been available in one building for well over a year, and has formed a core part of the heating regulation of the rooms in the building. However, as mentioned earlier, the main experimental run and evaluation of the suite of applications only just began, and only limited initial data on user evaluation is available. The *JuPower* game has only been played in test phases, and the development of *Juracle* was only recently concluded. Nevertheless, the results of the evaluations of the apps as stand-alone units are presented in the following sub-sections, covering mainly the user interaction and user experience evaluation and feedback obtained through co-design workshops.

3.1. Co-Design Process

The energy dashboard suite was developed using a co-design process. In this way, future users of the dashboard were actively involved in the development cycle and feedback and results were collected at several points in the process. A total of four co-design workshops targeting different aspects and developmental stages of the Energy Dashboard suite have been carried out, apart from various additional less-structured usability tests. During the co-design workshops, volunteers were granted alpha- and beta-stage access to test the dashboard components and provide feedback on existing features. Furthermore, during the co-design workshop events, potential features and further development concepts were discussed in detail. The results of these four workshops are summarised in the following paragraphs.

3.1.1. Co-Design Results: Energy Dashboard and JuControl

Beyond the standard requirements for user friendliness, the barrier to on-boarding for the applications should be as low as possible. By following a web-based approach, the applications do not require a separate installation step. Additionally, the responsive design that caters to different device sizes and orientations for the Energy Dashboard and *JuControl* made it possible to view these apps on mobile devices and tablets. Furthermore, to ease the burden of password management and mitigate potential security issues related to credentials, we integrated authentication via the institution-wide Shibboleth authentication. Thus, the authentication process was the same for the users as for most other services they access in their regular work.

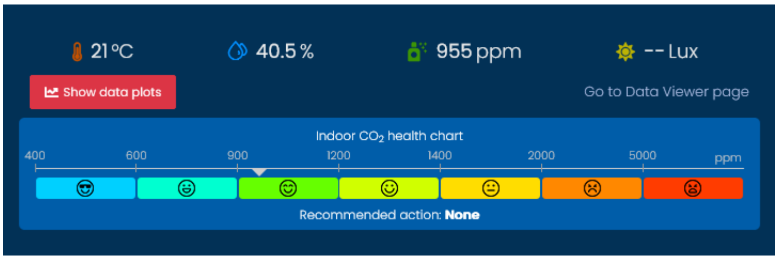

Figure 8: $C0_2$ health chart developed as a result of feedback from users, in order to understand the values shown.

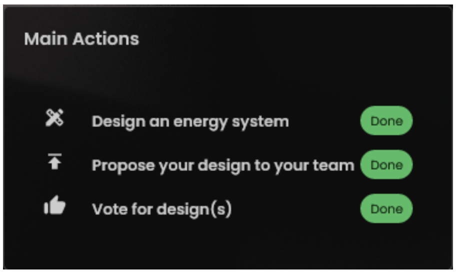

Figure 9: JuPower screenshot showing main actions and their completion status.

Again, users expressed the wish to have data shown on a spatial granularity level below the campus or building level, i.e. the floor or room level, so that they can reconcile the data to their own contributions. The implementation of this wish was the development of *JuControl*.

Furthermore, given the diverse range of specializations in the campus, it was necessary to not assume a knowledge of energy systems on the part of the users. This meant that all necessary information needed to understand the visualizations were made available in the application. For example, in *JuControl* a health chart is shown alongside the CO_2 concentration for the room, as shown in Figure 8. This was the result of feedback.

Yet again, whilst the applications are designed to maximize user interaction, users expressed fears about the apps being a distraction from work by requiring too much attention. To this end, a notifications management system was developed that allows users to be notified by email about certain events (e.g. when CO_2 concentration is above their defined threshold), or even turn off notifications completely. When the notifications are on, their frequency is throttled.

3.1.2. Co-Design Process for JuPower

For the JuPower game, for which two co-design workshops were conducted, the feedback were received and implemented. In general, the game was well received. Some key aspects are outlined as follows.

First, the game application included a manual that explained the objectives and functionalities in the game. However, multiple test users reported that they found this manual too long and not easily readable, and preferred scan-only help information with relevant information highlighted. In response, we introduced the Quick Start section with selected bolded text that summarized the most important points, alongside visual aids like images and illustrations. In the same vein, to reduce the risk of information overload, an *Actions* widget was introduced, which showed the three main steps involved in the gameplay and their completion status (see Figure 9). Additionally, a short tutorial video of about 15 minutes was made to introduce the main features of the game, which several participants found helpful.

Secondly, since the game usually runs over several weeks, and each stage of user interaction can be spread of several days, it was helpful to notify users of the game phase transitions and impending deadlines by email. The emails contained the relevant description for the phase, and any actions that were necessary were included as clickable links in the email.

Finally, to reduce the cognitive load required to play the game, we reduced the range of component options available to the player in the design of an energy system, based on feedback. Furthermore, the number of exposed parameters for each component was reduced to the bare essentials, in order to make decision making easier for the players.

3.2. Occupant Behavior Evaluation

The main experiment phase of the project for evaluating the energy efficiency of occupant behaviour ran from 13.03.2023 to 28.04.2023 (inclusive). Figure 10 shows the number of offices activated in *JuControl* by occupants (after all occupants in each office digitally granted consent for data visualization), broken down into pre-experiment and experiment periods. In about half of the teams, an activation level of at least 50% was achieved in the end, and more than 70% activation in a quarter of the teams.

Figure 11 below shows the evaluation results for one working week for an office, as well as the team average and the global average of all teams in the experimental group, while Fig 12 compares the average penalties for all teams in the given experimental group for a given working week. The colored regions correspond to a three-color traffic-light rating scheme, in which the energy penalties are assigned to traffic-light colors based on a predefined scheme. The color boundaries are: Green: up to 2,120 kWh; Amber: 2,121 kWh to 4,146 kWh; Red: over 4,146 kWh. The energy penalty value represents the amount of energy *lost* in a day in the campus, if *all offices in FZJ* would have a similar occupant behavior profile as the evaluated office or team.

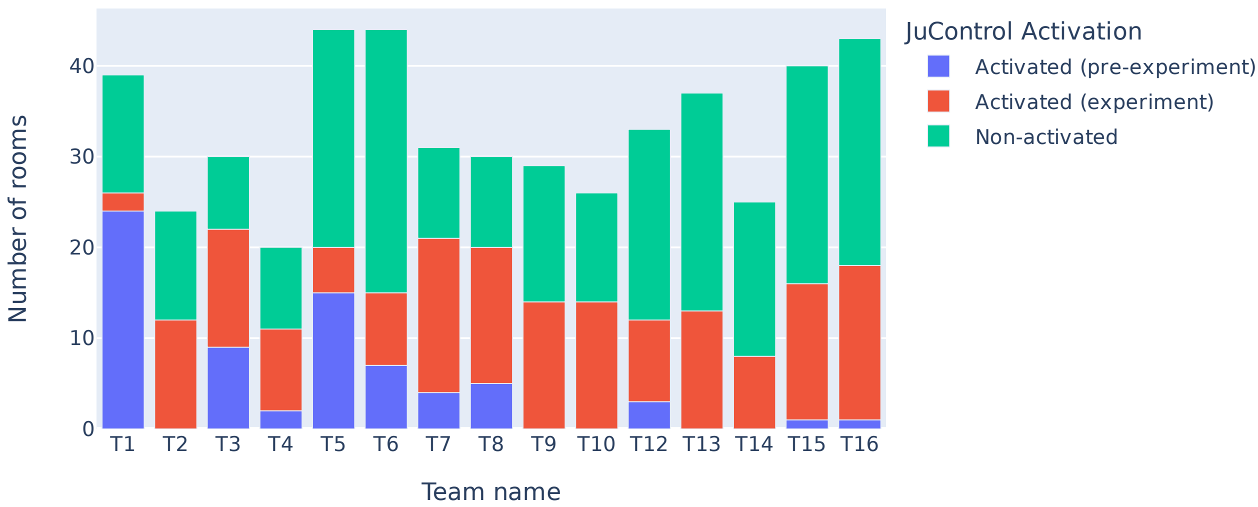

Figure 10: Activation of JuControl in offices by occupants, according to team. The pre-experiment status is shown (blue), along with the additional activation due to the experiment run (red), and non-activated offices (green). Teams T1 and T5 are located in pilot buildings, in which the initial test installations were carried out prior to subsequent extension to other buildings.

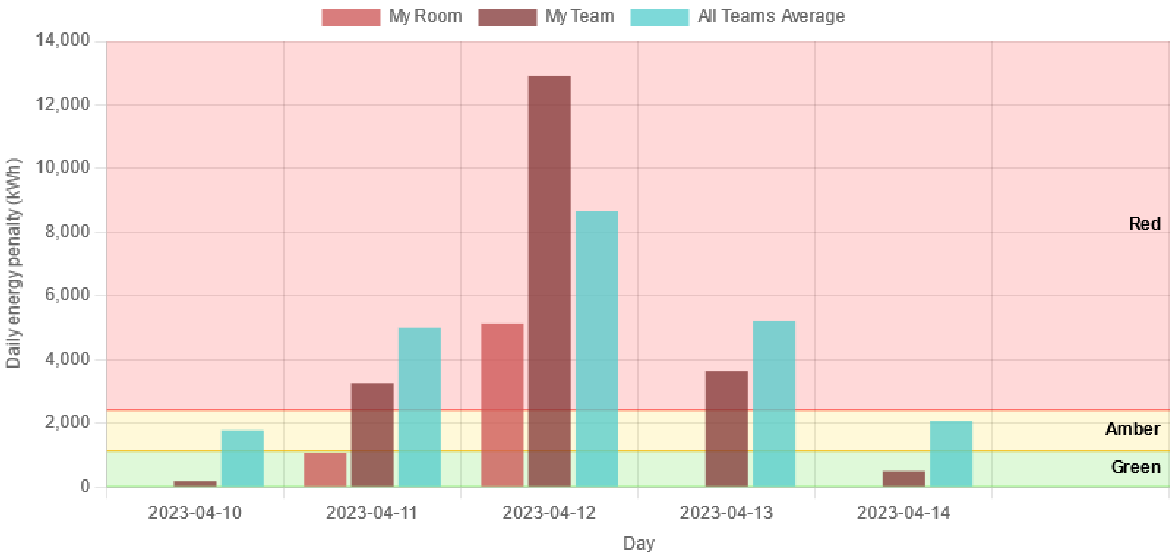

Figure 11: Evaluation penalties for the FZJ campus based on the occupant behaviour for an office ("My Room"), within a team ("My Team"), and for all teams in an experiment group ("All Teams Average") for one evaluation week (week days).

4. Conclusion

In this paper, a suite of user-facing applications that were developed at Forschungszentrum Jülich to drive user engagement with the overall goal of improving occupant energy behavior was described. With the *Energy Dashboard*, the user has access to building and campus level energy-related data, including consumption data for heating and electricity. Furthermore, comparisons can be made across buildings based on the data. *JuControl* increases the spatial granularity to the room level, and introduces data about other measures like indoor air quality. Furthermore, it enables the control of the occupant's heating energy system. These applications have successfully been used in the field for several months (extending up to 4 years in some cases). The *JuPower* game has been successfully tested and applied in the experiment phase, as well as *Juracle*'s behavior evaluation. In conclusion, the suite of software applications and the strategy of combining and deploying them hold great potential for influencing user behavior towards increased energy efficiency.

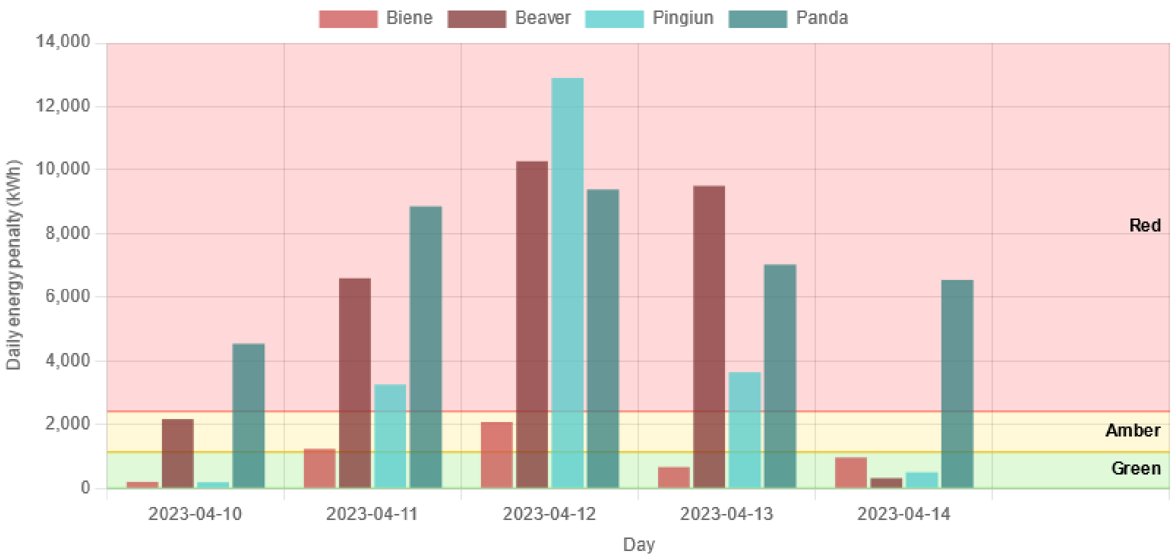

Figure 12: Evaluation penalties for the FZJ campus based on the average occupant behaviour within each team in an experiment group for one evaluation week (week days).

Declaration of Competing Interest

We have no conflict of interest.

Acknowledgements

The authors gratefully acknowledge the financial support by BMWK (German Federal Ministry of Economic Affairs and Climate Action), grant number 03ET1551A and 03EGB0010A.

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