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Data-driven method to visualise thermal comfort and impacts of behaviour, according to requirements of end-users developed with ML algorithms

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SUMMARY

This task contributes to Result 5 of the Brains4Building project: Methodology & data for user-centred approach in smart building control. The goal was to determine data-driven strategies to support flexible energy management by investigating strategies to provide feedback on the indoor environmental quality of a building to building occupants and facilities managers.

Smart buildings increasingly integrate automated systems to manage energy efficiency. However, reducing occupant control over environmental settings can negatively affect satisfaction and productivity. To address this, feedback mechanisms that enhance occupants' understanding of energy management decisions are being explored. We investigated a method to deliver information flows from occupants to facilities managers, and vice versa, to decrease the risks of occupants' discomfort and dissatisfaction and to provide more information and possibilities for the control and management of the buildings. Interpretable machine learning (ML) models were being developed to help users visualize how different factors influence thermal comfort based on the ML-based personalized thermal comfort model (developed in D3.05), which integrates user characteristics, occupants' behaviour, and environmental factors. This model supports energy flexibility by identifying acceptable deviations in temperature settings that maintain comfort while improving efficiency.

The project's findings contribute to the scientific and practitioner communities by providing actionable insights into energy flexibility. Future work will refine feedback strategies and integrate user-centric interfaces to balance energy efficiency with occupant comfort.

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1 INTRODUCTION

The goal of this task was to determine data-driven strategies to support flexible energy management, by investigating strategies to provide feedback on the indoor environmental quality of a building to end users (namely, building occupants and facilities managers). The outcomes will be made, by the end of the project, open and available to the scientific and practitioners communities.

The goal of the Brains4Buildings project is twofold. On the one hand, it looks into increasing the energy efficiency of buildings through fault detection and diagnosis and predictive maintenance. On the other hand, it aims at reducing costs and alleviating the stress on the grid by increasing the self-use of renewable energy, taking advantage of variable tariffs, and avoiding power peak demand through energy flexibility. F Fault detection and diagnosis focuses on identifying and preventing malfunctions and failures in buildings, while energy flexibility focuses on adjusting energy production and demand within the building, and/or district level. For both strategies, a high level of digitalisation and automated communication and control are needed. This implies that many (technical) challenges must be addressed. However, while the FDD strategy could benefit from the use of occupants-related data, occupants and their behaviour could pose a challenge to achieving energy flexibility strategies.

Therefore, in this task, we have focused on a method to provide information flows from occupants to facilities managers, and vice versa, to decrease the risks to occupants' comfort and satisfaction and to provide more information and possibilities for the control and management of the buildings.

2 STATE OF THE ART: CURRENTLY USED APPROACHES FOR ENERGY FLEXIBILITY MANAGEMENT

2.1 Introduction

With the help of partners from WP2, we have defined the common currently used approaches for peak shaving and load shifting, making an inventory of the strategies used for different types of buildings and control systems.

2.2 Results from Workshop with Consortium Partners

Three strategies have been identified within WP2 that are or can be used for energy flexibility management. These strategies focus on an economic benefit.

1. Under a certain amount of power - always because you can reduce contract, so peaks
2. Variable contract - prices change per hour. Focus on the forecast for actions the next day, use energy when prices are low, they want to focus here now. Prices the next day and per hour.
3. Not used much yet - congestion management - network balancing (already exists) - they get paid to use or not

Therefore, the main question from WP2 is within which range of indoor conditions can the building be kept without affecting too much the occupants.

During the B4B consortium meeting in March 2024, all consortium partners present at the meeting participated in a Mentimeter questionnaire in which their views regarding energy flexibility management were requested. The questionnaire was prepared by the leaders of WP2 and WP3. The results of the questionnaire are presented in this section. The following questions were asked:

1 - Which of these 3 strategies do you think will be the most commercially interesting for building managers?

- *Permanent peak-shaving and reduce the contracted power*
- *Use a variable tariff and adapt energy use to energy prices*
- *Become a Balance Service Provider or a Congestion Service Provider via an Aggregator*

Using a variable tariff and adapting energy use to energy prices seems to be the most preferred option by the participants, obtaining 23 votes as first choice, 16 as second and 10 as third. The second preferred option seems to be using permanent peak-shaving and reducing contracted power, which obtained 16, 21 and 12 votes respectively. Last, becoming a Balance Service Provider or a Congestion Service Provider via an Aggregator seems to be the least preferred option, obtaining 10, 12 and 27 votes respectively.

2 - What would be a better method/alternative method to define a comfort range?

METHOD	VOTES
ATG METHOD	11
PVE / ISO 7730	2
DIFFERENCIATING BETWEEN MEN/WOMEN	3
INDIVIDUAL MEASURED	3
OCCUPANTS' SURVEY	10
SPECIFIC TEMPERATURE RANGE	12
INFORMATION	2
OTHER	7

3 - What would be a better/alternative method of defining a period of time outside the comfort zone for a day?

ALTERNATIVE	VOTES
MORE INFORMATION ABOUT COMFORT	2
SURVEY	5
OCCUPANCY SENSORS	10
SCHEDULES	7
ALWAYS WITHIN COMFORT ZONE	4
DIFFERENTIATE PER TASKS	4
OTHERS	6
DON'T KNOW	1

4 - What other building parameters would you consider interesting to analyse in terms of their impact on increasing energy flexibility?

		VOTES
BUILDING RELATED	Building orientation	2
	Envelope characteristics	10
	Building use/type	6
	HVAC type	5
	Solar shading	4
	Sensors available	2
	Other building related	4
OCCUPANTS RELATED	Occupancy	8
	User type	2
	Thermal comfort requirements	1
INDOOR/OUTDOOR PARAMETERS	Outside temp	2
	RH	1
OTHER	EV infrastructure	3
	PV panel orientation	1
	Energy use	2
	Internal heat gains	1

5 - In what type of buildings would you consider applying flexibility?

TYPE OF BUILDINGS	VOTES
FULLY AUTOMATED BUILDINGS (CONTROL IS OUT OF THE HANDS OF THE OCCUPANTS).	3
HYBRID (SOME AUTOMATIZATION, SOME CONTROL BY THE OCCUPANTS).	9
ALL BUILDINGS.	23

6 - Do you expect negative consequences (e.g. complaints) from the occupants?

CHOICE	VOTES	%
YES	32	88,89
NO	4	11,11

7 - How would you inform the occupants about actions that might affect their comfort?

CHOICE	VOTES	%
WE WOULD NOT INFORM THEM AT ALL.	5	14,29
WE WOULD INFORM THEM VIA GENERAL EMAIL / INFORMATION LETTER.	5	14,29
WE WOULD INFORM THEM WHEN SOMETHING IS EXPECTED TO HAPPEN (I.E. ON A DAILY BASIS IF NECESSARY).	7	20
THEY CAN SEE THE INFORMATION THEMSELVES VIA APP/WEBPAGE/SCREEN/MONITOR ETC.	18	51,43

8 - Whom would you inform?

CHOICE	VOTES	%
WE WOULD INFORM THE GENERAL MANAGER / CLIENT / OWNER, BUT NOT INDIVIDUALS.	7	19,44
WE WOULD INFORM INDIVIDUALS.	29	80,56

The results show a tendency to be transparent towards the occupants of the building (questions 7 and 8), and a trust in the methods and technology to achieve flexible management without compromising comfort (questions 5 and 6). Furthermore, we can still see that, while the importance of building characteristics and services is well acknowledged (question 4), the role of users-related information is mostly still confined to occupancy (either through schedules or occupancy sensors), although some other aspects have been described, such as differences among users (based on physiology, type of work and preferences). It is important to notice, however, the fact that prescribed temperature ranges are mentioned to the same degree as known thermal comfort methods and surveys to occupants. Thus indicating the large diversity of views in the topic.

2.3 Influence of building and user characteristics on behaviour and indoor climate requirements

Previous research has already shown the impact of building characteristics on the energy performance and indoor quality of buildings. For example, the thermal mass of a building opens the possibility of storing energy as heat, and the presence of transparent/translucent elements in the building will influence the solar gains. Likewise, the influence of occupants' behaviour on energy performance has also been widely investigated. This is evidenced by the great amount of research carried out to determine occupancy patterns in office buildings. These patterns representing occupants' presence, and use of lighting, electronics, and HVAC systems have been used to model the occupants' behaviour in these buildings to make more accurate energy predictions or for building control. The deliverable 3.8 of this project deepens on these patterns.

To diminish the influence of occupants' behaviour in office buildings, and due to the increasing number of smart building services, we see a shift towards reducing the interactions between the occupants and the buildings through partially or fully automated systems (Loengbudnark et al., 2023; Hellwig et al. 2020). One of the main characteristics of smart buildings is the automation in the control of the building systems (see deliverable 4.4 on the Smart Readiness Indicator). Automated building control systems are expected to maintain good indoor environmental conditions to ensure occupants comfort (Boerstra et al 2015).

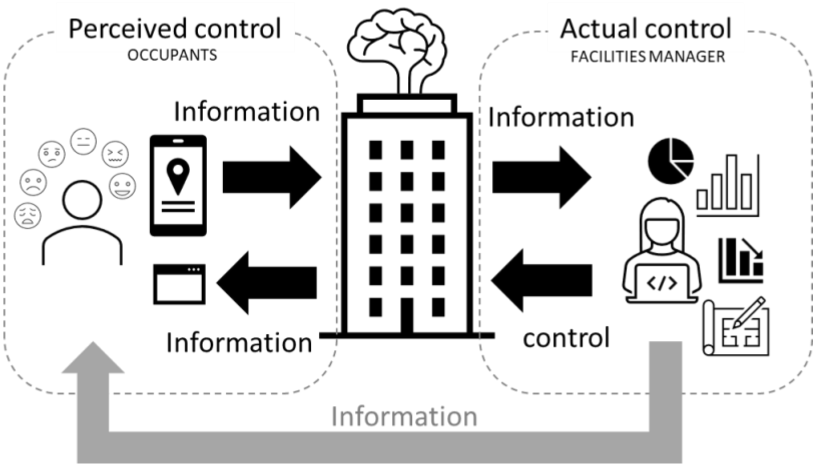
However, previous research has shown that reducing occupants' (perceived) control over their environment can inversely affect their satisfaction, as well as their productivity (Loengbudnark et al, 2023; Hellwig 2015). Boersta et al 2015, Göçer et al (2019) and McCunn et al (2018) have found a direct relationship between perceived control over people's own environment and satisfaction and/or productivity. In a study by Brager et al. 2004, automated building features were found to decrease occupant's tolerance to factors causing discomfort. Thus, in the field of energy-flexible smart buildings, (the lack of) occupants' (perceived) control over their environment might significantly affect their satisfaction and productivity.

Additionally, building automation might diminish occupants' awareness and sense of responsibility regarding energy consumption levels (Gunay & O'Brien, 2014). Implementing a feedback strategy for centralized control systems could enhance occupants' understanding of the system's control decisions, promote acceptance of the strategies used, and help them feel more satisfied with the temporary discomfort resulting from these adjustments.

Other aspects might affect both the possibilities for energy flexibility and the (perceived) control of occupants. First, the type of buildings' occupants will have an effect on the flexibility, since this will determine how much indoor conditions can deviate from the standards. Furthermore, the capacity of occupants to control their environment also depends on the building characteristics, such as building layout, type of HVAC systems, type of interfaces, and the organisational characteristics of the company/enterprise housed in the building, which might also affect building control, especially in open plan and shared spaces. These contextual variables will be important when determining the strategies to allow for more energy flexibility without compromising the occupants' well-being.

2.4 Impact of flexible management strategies for building users

Based on this preliminary analysis, we have determined the possible impacts of flexible management approaches (defined with consortium partners) to the users' activities and acceptability, focusing both on users' active participation in the control of the environment (opening windows, changing HVACs settings, controlling lighting and blinds), and on passive participation (providing input on their own comfort and satisfaction). Based on the systems and requirements of the project partners (WP2), we have determined the **information flows to increase users' understanding of building operations and the consequences of actions.**



Two main groups can be made in relation to types of building systems: those fully automated and those in which the user has some or full control. It most cases, buildings have some mix of automated and manual controls. At least, most buildings offer the users the possibility to open windows, although this is not the case in all buildings. Thus, the requirements for the data-driven methods can be categorized, per system, into active (control) strategies and passive (feedback) strategies.

Feedback strategies for active system control

Data-driven visualisation strategies can be developed for active system control (via the control panel or building elements) aiming to achieve more energy-efficient occupant behaviours and building operation. On the one hand, these could be directed to the occupants, for example, to close or open a window or operate manual solar shading devices. On the other hand, this type of feedback could be directed to the FM, informing about the current thermal comfort of occupants, and the factors influencing their comfort. In this case, the FM could take actions that can lead to an increase in energy efficiency without compromising occupants' comfort.

Feedback (passive) strategies for awareness and understanding

Feedback strategies can also be developed for buildings in which the user cannot modify the environmental conditions in the building, thus aiming to increase user awareness and understanding of the system's actions in relation to their comfort and energy efficiency, with the final objective of increasing user satisfaction and acceptability.

In either case, the first step is to develop a data-driven approach to gather and analyse and understand the thermal comfort of the building's occupants. The results from activity 3.2 are, therefore, the starting point for this feedback strategy.

The feedback strategies will be further explored in the last task of the project, in relation to the use-centric building interfaces.

3 INTERPRETABLE MACHINE LEARNING TO PROVIDE FEEDBACK TO SYSTEMS AND PEOPLE

Through interpretable Machine Learning, building users can understand and visualise how different building, user and context related variables affect comfort. In this task, we have developed a user-centric, data-driven method making use of ML algorithms to provide relevant and understandable feedback to end users (building occupants, facilities managers and building owners) that can lead to better decisions regarding indoor environmental comfort and energy efficiency when managing the building in a flexible way.

In the annexe to this deliverable, we present a methodology to use interpretable machine learning tools on an ML-based thermal comfort model to determine what adaptations, either on behaviour or control settings, can be changed to retain comfort while indoor parameters are modified to allow for energy flexibility.

The personalized thermal comfort model (developed in task 3.2) considers the occupants' characteristics, behaviours, and contextual characteristics that influence the occupants' thermal comfort. The thermal comfort model intends to increase the energy efficiency of the building by providing information about the occupants' thermal comfort to set a baseline performance against which users 'complaints' can be checked before being used in FDD systems, thus differentiating between likely equipment faults and individual preference anomalies.

In this task, we go further by using interpretable AI to look into the building, contextual and behavioural aspects that could be modified while keeping a good thermal comfort level for the occupants. In this way, temperature settings could deviate from what is considered as a comfortable range to achieve energy flexibility. This approach allows us to visualize how much the temperature ranges could be widened without compromising the occupants' comfort and well-being.

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ANNEX: METHODOLOGY TO USE INTERPRETABLE MACHINE LEARNING TOOLS ON AN ML-BASED THERMAL COMFORT

Paper under review:

Understanding thermal comfort using self-reporting and interpretable machine learning

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