# Knowledge-based building management combining human perception and building automation systems

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***Abstract*—User feedback offers high potential for improving comfort satisfaction and adapting processes in building operation and management. However, comfort in building zones is usually quantified using sensor devices of building automation systems while feedback of building users is only manually analyzed by facility managers. The goal of the recently started project 'HumBAS' is to combine subjective human perception and objective data originating from building automation systems to improve comfort for building users and infer recommendations for facility managers using knowledge engineering. An intuitive interface for the acquisition of human perception as well as a knowledge-based integration of objective and subjective comfort measurements are developed in order to describe an automatic process for direct consideration of user feedback and detection of problems in building management. The paper presents related work, gives an outlook on the overall project goals and addresses first results.**

## I. Introduction

A primary goal of building automation and building management is the efficient utilization of energy and resources in order to maximize comfort for building users [1]. Quantification of comfort is usually based on objective measurement and empirical models (e.g., ISO 7730). According to the current state of the art, various technical systems (installation, measurement, and automation engineering) are at hand that aim at providing high user satisfaction.

Problems arise as users and their continuous feedback are not directly involved in the overall process. Influences on their satisfaction are not or not adequately considered (e.g., activity, state of health, weather perception, or influences of other persons). While user feedback is an important source for energy-efficient and comfortable building operation as well as for the development of novel services for users based on their needs and actual problems, manual processing of user feedback is a high effort for building management and in particular technical facility management. In order to include user feedback in an appropriate way and bring it in line with sensor measurements, an automatic integration is necessary, first. For this purpose, the design of an intuitive interface for simple and fast collection of human perception regarding various comfort parameters is mandatory.

Furthermore, the integration of these feedback records into existing integration solutions of building automation systems is a central challenge that is subject to research. In this context, compliance with requirements regarding privacy of user data is essential. By the combination and semantic modeling of objective sensor measurements and subjective user feedback into a common knowledge base, results of a recently started project entitled 'Knowledge-based building management combining human perception and building automation systems' (HumBAS) will allow deriving statements on occurring problems in building management processes, such as significant deviations between measurements and user feedback. Expert knowledge and additional context information with respect to the building, the installed automation systems, the building operation strategies, and the subjectively perceived influences shall be integrated. Thus, a more revealing interpretation of common sensor measurements will be enabled. The used methodology is based on approved approaches of knowledge engineering (e.g., ontologies and reasoning).

As a first result, relevant related work on capturing user feedback and human perception in the context of comfort has been investigated and integration of heterogeneous building automation based on semantics-based modeling of building automation systems has been analyzed (Section II). Based on this analysis, open problems have been identified (Section III) that allow to narrow down goals and expected results of the HumBAS project (Section IV). The paper concludes with an overview on work-in-progress and further steps to be taken (Section V).

## II. Related Work

### A. Capturing user feedback and human perception

The research of human-computer interaction names the term 'user experience' as the quality of experience that a user perceives while interacting with a system which is crucial in the design of new technologies [2], [3]. ISO 9241-210 defines user experience as 'a person's perceptions and responses that result from the use or anticipated use of a product, system or service' [4]. User experience presents a continuous process related to, for example, learning experiences and self-explanatory interactions, social environments, privacy, diversity, feedback, aesthetics, use context, and especially interaction design and information design [5]–[10]. Aspects of user experience are tackled by existing approaches that deal with capturing user feedback and human perception. In this relationship, addressing of privacy issues is important due to the direct collection of user-related data. Depending on the application, users are willing to share assignable data and information. Nevertheless, appropriate design approaches are necessary that tackle the privacy aspects with care.

For capturing common user feedback in buildings, the Web application 'Yousense' (Figure 1) was presented in [11]. It enables users to share information about their current feeling and to provide additional contextual information, including time, location, and activity. The kind of feedback that can be captured is quite general (e.g., beautiful view, tasty coffee) and does not necessarily have relation to building automation-relevant comfort of users. Integration of data from building information models (BIM) as well as feeding back data into the building automation system is not considered.

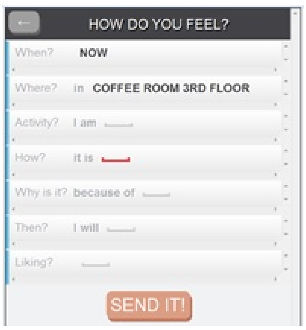


Fig. 1. YouSense App [11]

Another Web application called 'myBuildingMessage' was introduced by Huber et al. [12]. The application asks users about their satisfaction with respect to the building by using only one closed and one open question. Thus, users can give their general feedback on the building in natural language. The focus of the application is not limited to comfort. The evaluation is carried out automatically by means of text recognition software. User statements are visually prepared and evaluated, but there is no automatic response to user feedback using building automation. Contextual information from model-based building management is also not integrated.

The 'TherMOOstat' Web application (Figure 2) was developed to capture user feedback on thermal comfort [13]. Via a Web interface, users of the building can provide feedback on their thermal sensation. The application was tested in several stages in a real-world experiment, and it allows a retroactive effect on the technical equipment and the users via the building automation system. Although the application focuses on the observation of the thermal user comfort, other comfort dimensions that are in close interaction with the thermal sensation are not considered. Building data models are not used. However, an automated adaption of set points of technical equipment via the building automation system is studied.

'Comfy' is a commercial tool that allows occupants to interact with an air-based heating and cooling system via smartphone in order to increase or decrease the temperature in the room of the user [14]. The approach relies on the installation of a hardware interface which connects the local building automation to a cloud platform. The approach is limited to automation solutions using the BACnet protocol. The system, first, has to be configured manually. Information from the model-based building management is not included.

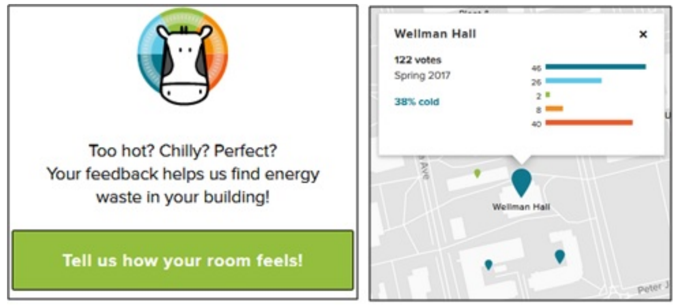


Fig. 2. Screenshots from the TherMOOstat Web application [13]

The Center of the Built Environment (CBE) at the University of California has been working on building user satisfaction for twenty years. Based on this work, the 'CBE occupant feedback toolkit' was developed which enables users in buildings to be surveyed in a detailed Web-based questionnaire [15]. The results of the survey are evaluated automatically. A large number of aspects of comfort is recorded and evaluated. The survey is usually conducted once over a certain period of time. There is no integration and retroactive effect on the users by means of building automation. Moreover, there is no consideration of model-based building management.

The 'OfficeVitae' system [16] records sensor readings and feedback regarding the comfort of users in offices. The results are evaluated automatically and visualized in floor plans of the offices. Measured values include carbon dioxide, temperature, humidity, volume, brightness, occupancy, and motion. The approach does neither pursue integration and retroactivity via building automation, nor does it integrate with model-based building management. However, both sensor readings and feedback are investigated.

So-called 'Smiley Boxes' are a common application for capturing user feedback on the cleanliness of restrooms in public buildings [17]. These allow the recording of user satisfaction in public spaces. The recorded feedback is used for the planning of cleaning team operations and as an alarm signal to detect heavily contaminated rooms immediately. The systems have already been in use for several years, for example, at airports. It is not known if there is a connection to model-based building management systems.

In the current state of the art, some drawbacks can be identified that limit their use in the proposed design of a more intelligent building management considering human perception and user feedback with direct integration of building automation systems in order to increase comfort satisfaction regarding different comfort aspects. As shown, there are already several approaches that are able to capture user feedback. However, none of the presented solutions meets the requirements for a system to fulfill the intelligent model-based building management through user feedback as specified in the project goals, like

- recording several aspects of comfort (e.g., thermal, audio, visual, air quality)
- automatic evaluation of user feedback based on qualitative and quantitative data
- closed loop between users and the building via building automation
- integration of model-based building management including BIM and CAFM

The fulfilment of these main requirements of the presented solutions is summarized in Table I. As illustrated, there is a need for an innovative design approach focusing on all four major requirements in order to enable automatic and seamless feedback integration.

TABLE I
SUMMARY OF REQUIREMENTS FULFILMENT

| | Multiple aspects | Automatic analysis | Building automation | CAFM BIM |
|---|---|---|---|---|
| Yousense | + | - | - | - |
| TherMOOstat | - | + | + | - |
| myBuildingMessage | + | + | - | - |
| Comfy | - | + | + | - |
| CBE | + | + | - | - |
| OfficeVitae | + | + | - | - |
| Smiley Boxes | - | + | - | - |

### *B. Building automation system and technology integration*

Modern Building Automation Systems (BAS) are distributed systems where the control functionality is spread across a three level hierarchy [1] including field, automation and management level. Interoperability between heterogeneous technologies is addressed by integration solutions. The approaches are focused on the installed technical systems as well as their requirements and properties in order to ease maintenance and configuration done by facility managers or building operators. As integration solutions, information models together with Web Services based approaches are common [18]–[20]. Even ontologies are already used in several papers and scientific projects. For example, 'DogOnt' is an ontology that focuses on interoperation in home automation environments [21]. It contains classes and properties as well as restrictions to model building things, building environment, configuration states, functionality of controllable things, and home automation network components. The 'BOnSAI' smart ontology covers building functionality, hardware (e.g., devices), users (e.g., profiles), and context information (e.g., rooms) [22]. Other ontologies, like 'ThinkHome' [23], include additional concepts for energy-related information, external influences (e.g., weather), and user comfort. The 'smart control ontology' (Colibri) follows a service-centric approach for modeling data and functionality in building automation [24]. Data services, control services, and energy services are the basic modeling elements in this ontology. By enabling the modeling of context information including building structure, devices, and appliances as well as energy-related information and smart grid interaction, situations like the influence of actuating devices and their control services on certain building zones can be described. Another interesting ontology is 'Brick' which has a focus on the system-level view of the building infrastructure [25]. As an example for the use of ontologies in the field of user experience, the 'Human Comfort in Buildings' (HBC) ontology [26] formally specifies comfort-related experiences of occupants in buildings and provides links to building automation, spaces and technical equipment. Moreover, capturing human perception as introduced in [11] is supported by a semantics-based representation.

## III. PROBLEM AND RESEARCH NEED

Nowadays, integration of building automation systems into applications on the management (enterprise IT) level is a quite common task which is necessary in order to provide these applications with sensor data and offer the possibility to control devices remotely. On the contrary, the raw feedback of building users and inhabitants is not integrated in such management applications, yet. In fact, platforms or hotlines are provided for the building users in order to report problems regarding comfort or faulty equipment. As indicated by facility managers, there is often no automatic mapping of recorded feedback to a particular problem solution. Feedback in natural speech is manually assessed. The problem needs to be analyzed by the facility manager: Where did the problem happen? Which devices can correct the reported failure? Is some building automation equipment broken? Is the feedback justified or not?

Besides the manual interpretation of this feedback which is very labor-intensive, the process of giving feedback needs to be revised. Telephone hotlines or complex Web forms are not suitable for an automatic integration and processing. Moreover, the time required for giving feedback is ordinary too long which limits the feedback to highly important problems. Although a lot of research is done in the field of user experience and human machine interfaces, approaches, products, and solutions usually focus on single domains or simple parameters. As building comfort depends on several aspects, such as thermal, visual or acoustic comfort with all their subcategories (e.g., temperature, brightness, air quality, air draft), a more complex interface in the form of a user feedback tool is required in order to realize the proposed approach. Explicit research questions are formulated at the end of this section. In general, there is a need for a simple but powerful feedback tool that is accepted and can be easily utilized by users independent of their age or constitution.

The transfer of the gathered information that is captured by this feedback tool towards a subsequent processing unit should be based on standardized integration solutions. This will ensure reusability of the approach and enables interoperability with other technologies. For the application area of building management, existing approaches seem to provide a suitable basis as they are already used for various domains. However, there is a research need to decide if the offered meta-models are domain-independent and generic enough in order to represent the multidimensional feedback of users besides data of mere technical systems.

In addition, the gathered information needs to be subsequently interpreted. A prerequisite for this is the consideration of relevant context information. Besides the feedback-intrinsic information, information of the building context, the outdoor conditions, the users activity, the current occupancy, or the installed building automation system with its controllers, sensors, and actuators has to be examined. Both modeling and linking these differing domains is a challenging task requiring intensive research work. Knowledge bases and ontologies for the combination of buildings with their building automation systems and external conditions are subject to previous and current research projects (see Section II-B). Although there is some work in the field of embedding human-expressed feelings regarding comfort perception, additional research needs to be done in order to generalize existing approaches.

Current building management is mostly operated on the basis of objective measurements coming from sensors of the building automation system. User feedback is, as stated above, only considered for major problems due to the high effort of giving feedback and manually analyzing this feedback. Once the feedback is automatically integrated in a knowledge base and linked with other monitoring data and context information, knowledge engineering methods can be used to evaluate the data sets and identify problems and potential solutions. For this purpose, expert knowledge from facility managers and building operators has to be formalized in order to derive reusable and generic rules. However, this should be done very carefully in order to derive correct conclusions and explanations. Misleading correlations have to be detected as far as possible. State of the art in building management does not deal with direct user feedback but tries to find problems in the automation system configuration based on sensed monitoring data. Thus, research using knowledge engineering is necessary to close this gap and provide a suitable set of rules and procedures to enable automatic processing and comparison of subjective user feedback and objective monitoring data.

In summary, need for research in several domains is identified in order to establish a user-centric, more intelligent building management. Some research questions addressed in the project HumBAS are listed in the following:

- Is there a homogeneous and simple way to integrate user feedback automatically?
- Which information needs to be captured in the feedback process?
- What are the requirements for a hardware or software-based user feedback tool that is able to gather multi-dimensional feedback?
- How can the subjective feedback and the objective measurements be combined?
- Which information can be deduced based on a comparison of both measurement paradigms?
- Which rules for facility managers and building users can be derived in order to give recommendations to reconfigure the automation systems and increase comfort?
- How much user feedback is required in order to get a critical mass for significant conclusions?
- Which incentive schemes are suitable to stimulate the users giving also positive and not only negative feedback?
- How can the privacy of the information and data provided by the users be protected?
- In which situations is user feedback able to replace common sensors?
- Are there strategies for comprehensive exploitation of the proposed approach?

## IV. Goals and Expected Results

In general, HumBAS is directed to investigate an automatic integration of building user feedback and to analyze this feedback paired with conventional building monitoring data in order to improve comfort of users and inhabitants as well as provide facility managers with information about potential reconfigurations and permanent problems in the building. The approach aims at establishing a building operation and building management that is fully capable of considering direct input from people in a building. This will enhance individual and collective comfort leading to higher user satisfaction. All in all, a user-compatible building management is researched. This can lead to a cost reduction by cutting down existing sensor devices if user feedback can replace some measurements. Also additional insights on room level can be gained in systems where no sensors have been installed before. Moreover, the personnel costs and time for building management can be lowered as user feedback is automatically processed. Lessons learned from feedback can also be used to assess building automation system installations and architectural measures for construction and refurbishment of new and existing buildings, respectively. A by-product might be an improved energy-efficiency, but this goal depends on the suggestions made by the knowledge-based analysis which cannot be estimated right now. The following list describes the expected results of the HumBAS project:

- **Information requirements:** A catalogue is specified including all necessary requirements on the relevant information that will be integrated into the knowledge base for further processing. Especially, the information gathered in the feedback is specified. This is based on an analysis of current feedback mechanisms of recording and processing. Different scenarios of giving feedback should be possible leading to mandatory and optional feedback information sets.
- **User feedback tool:** A feedback tool is designed able to capture user feedback in a simple and intuitive way. Field studies and interviews are carried out with prototypes and mock-up implementations in order to analyze suitable interface designs which can be based on hardware and software. The design process addresses the fact that the tool needs to be able to cover multiple comfort

parameters. The result is a set of designs meeting the requirements including acceptance by users, covering multi-parameter comfort, and simple handling.

- **Privacy aspects:** Within the feedback process, potentially sensitive data are collected by the feedback tool. Suitable measures are identified in order to guarantee data privacy without losing interpretability and imposing restrictions on the processing capability.
- **Incentive scheme:** In parallel to the investigation of suitable user feedback tools, interviews are used to find out which incentive-based strategies can be used in order to promote the attendance of users to give feedback. The focus is on giving positive feedback as users usually tend to give negative feedback in case of failures or problems. The result is an ordered list of suggestions that can be applied by building owners and operators.
- **Ontology modeling:** Methods in the domain of knowledge engineering are utilized to combine all relevant domains into an ontology. Most important are the concepts and properties to link subjective comfort perception in the form of user feedback and objective comfort measurements by sensors. An ontology is developed that covers the needs stated in the information requirements catalogue.
- **Rule-based assessment:** By means of knowledge engineering methodology such as reasoning mechanisms, real-world data or test data are used to derive new knowledge from the combination of monitoring and feedback data. For this purpose, a knowledge base building on the developed ontology is filled with the available data and context information. Expert knowledge of facility managers is formalized to a set of rules that support building operators and enable comfort improvement for building users. The focus is on problems in the configuration of building automation systems and operation strategies, like a temperature deviation between objective measurement and subjective perception.
- **Feedback response loop:** As part of full and transparent user integration into the building management, a direct response loop back to the user is essential. Otherwise, the user is not aware of the actions taken according to the given feedback. At least, the submission of a feedback is confirmed. Moreover, optional details regarding the changes and suggestions made in knowledge processing are reported to the users.

In summary, Figure 3 sketches the main parts of the discussed goals for user feedback consideration in an overall building management concept. Feedback of users is collected in parallel to measurement data using an intuitive feedback tool design. In integration, objective and subjective data are combined and based on an abstract model, knowledge engineering methods are used to process the available information. Results and outputs of this rule-based processing help both facility managers and building users.

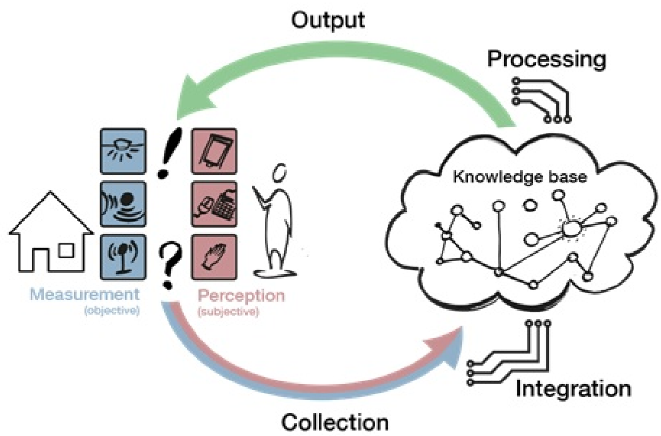


Fig. 3. HumBAS – Human perception and building automation systems

## V. Conclusion and Outlook

Based on stakeholder needs as well as on literature research of related work, use cases for the integration of user feedback into building operation strategies have been identified. Currently, work in progress concerns the development of a technical specification of the user feedback tool. Special focus will be given to usability, incentives for stimulation of user feedback, interaction mechanisms, and communication channels that will be provided for user feedback. A semantic information model that covers building information, building automation systems, measurement data, and user comfort requirements is designed as OWL ontology. In order to exchange data with the sensors and actuators of the building automation system, the necessary interfaces have to be provided. Similarly, the user feedback tool has to be enriched with appropriate interfaces integrated into the software prototype. Next, a simple description language is specified in order to enable the formulation of expert rules in a standardized common form. Similar to functional block descriptions, this language should be able to specify a set of inputs, the processing of these inputs, and the type of rule output. The result is a machine-readable set of facility management rules that can be executed by a suitable runtime engine. The final prototype will be tested in a field study. Using interviews with users or building operators, the acceptance of HumBAS will be analyzed.


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