Towards Resolving Thermal Comfort Conflicts in Shared Spaces

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ABSTRACT

Thermal comfort is an important factor in building control, affecting occupant health, satisfaction, and productivity. Building management systems in commercial spaces commonly operate on predefined temperature setpoints and control strategies. Many systems target aggregated cohort comfort and neglect to consider the individual occupant's thermal preferences, leading to high dissatisfaction rates. While recent studies focus on personalized comfort models, such systems mainly operate on occupant preference prediction and do not investigate the reasons for discomfort.

This paper presents TREATI's human-in-the-loop decision-making process. TREATI is a framework that targets thermal comfort conflict resolution in shared spaces using rationale management techniques while considering both individual and cohort comfort. TREATI uses several levels of abstraction separating device management, event processing, context, and rationale management. This separation allows users to adapt the framework to existing building management systems to provide fair decision-making.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Ubiquitous and mobile computing**.

KEYWORDS

IEQ, rationale management, building control, human-in-the-loop

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1 INTRODUCTION

Indoor Environmental Quality (IEQ) is a crucial aspect for occupant health, productivity, and overall satisfaction, especially in commercial buildings [2, 4]. The four most common IEQ indicators are thermal comfort, air quality, visual quality, and acoustic quality, often with regard to energy efficiency. In particular thermal comfort – an occupant's satisfaction with the thermal environment – is a widely researched indicator, mostly due to its high subjectivity and impact on energy consumption in buildings [3]. Building management systems often follow pre-defined strategies or temperature setpoints, without considering each occupants' thermal preferences. This often leads to high levels of thermal discomfort among occupants [6].

Existing systems employ comfort voting systems where occupants can vote for their thermal preferences. Such systems often average across all occupants' thermal preferences to control a space's air temperature [12, 21]. However, instead of leading to a consensus in occupant preferences, this tends to cause general dissatisfaction. Other systems utilize non-transparent decision-making processes that hide temperature change decisions from occupants. Consequently, occupants are frustrated and dissatisfied [6]. Especially in spaces shared by multiple occupants, these systems cannot address the thermal comfort conflicts that occur on a daily basis.

Recent studies target personalized human-in-the-loop control systems [7, 14]. These systems employ personalized comfort models that are based on occupant input to control task actuators, with the goal of maximizing each occupant's thermal satisfaction. However, these models often disregard energy efficiency and fail to consider the implications for cohort comfort, such as to determine whether a change in the ambient air temperature would be more beneficial and energy efficient than utilizing task actuators.

TREATI, a framework based on an open IoT architecture, aims at optimizing thermal comfort in shared spaces in commercial buildings. It uses a multi-abstraction process that focuses on rationale management efforts to resolve thermal comfort conflicts. TREATI addresses cohort comfort, but also considers the individual's preferences in its decision-making process. Based on conflict's context, it evaluates applicable solution strategies and proposes a decision to thermal comfort conflicts. This paper discusses TREATI's decision-making process, guided by the following research questions:

RQ1 How can rationale management techniques solve thermal comfort conflicts regarding cohort comfort while also considering the individual?

RQ2 Which abstractions are necessary to identify and resolve thermal comfort conflicts while considering individual occupants' preferences?

2 VISIONARY SCENARIO

The following scenario is based on anecdotal evidence and a survey that was conducted within this research project, see Section 4.2. It describes the application domain and proposed solution:

> Imagine you are in an open-plan office with 10 other occupants. One of them is your dogmatic boss, Mr. X, who only wears suits to the office. As it is a warm summer's day with an outdoor air temperature of $31°C$ | $88°F$, you are wearing light clothing (0.7 *clo*).

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9.00 am - Everyone arrives at the office. The indoor air temperature is *21°C | 70°F*.
9.23 am - You start to feel a bit cool and request an increase in the air temperature using the building's thermal comfort voting application.
9.38 am - Six of your colleagues also vote for a warmer air temperature, while your colleagues Sami and Mr. X - who complains about it loudly - vote for a cooler temperature. Amanda does not vote as she is currently feeling comfortable, Charlie votes for the temperature to stay as it is.

1. As the votes come in, TREATI ***categorizes*** *each of the eight temperature votes as events that have to be resolved: 6x warmer, 2x cooler.*

2. TREATI then ***assesses*** *the events and* ***identifies potential sources for discomfort****: Two occupants sit beside an open door, leading to a draft in the room; Mr. X's desk is next to the room's south facade and the sun is shining into the room, warming his back.*

3. Based on this knowledge, TREATI ***evaluates several possible solutions*** *and reviews each* ***occupant's profile*** *in terms of expected thermal comfort after each change: Amanda's main motive is to save energy wherever she can, and an increase in air temperature by 2°C | 3.6°F would lead to a ~ 4% increase in energy efficiency, Charlie's expected thermal comfort would stay the same. Thus, TREATI proposes a* ***decision****: 'Increase air temperature to 23°C | 73°F, close shades next to Mr. X, turn on Sami's task fan, close door'.*

9.42 am - The facility manager reviews the proposed decision and applies the changes. Sami turns on their task fan and Mr. X closes his shades.
10.02 am - As the air temperature slowly increases, you start to feel more comfortable, Mr. X has stopped complaining that it is too hot, Sami feels less warm, and the others also appreciate the change in temperature.

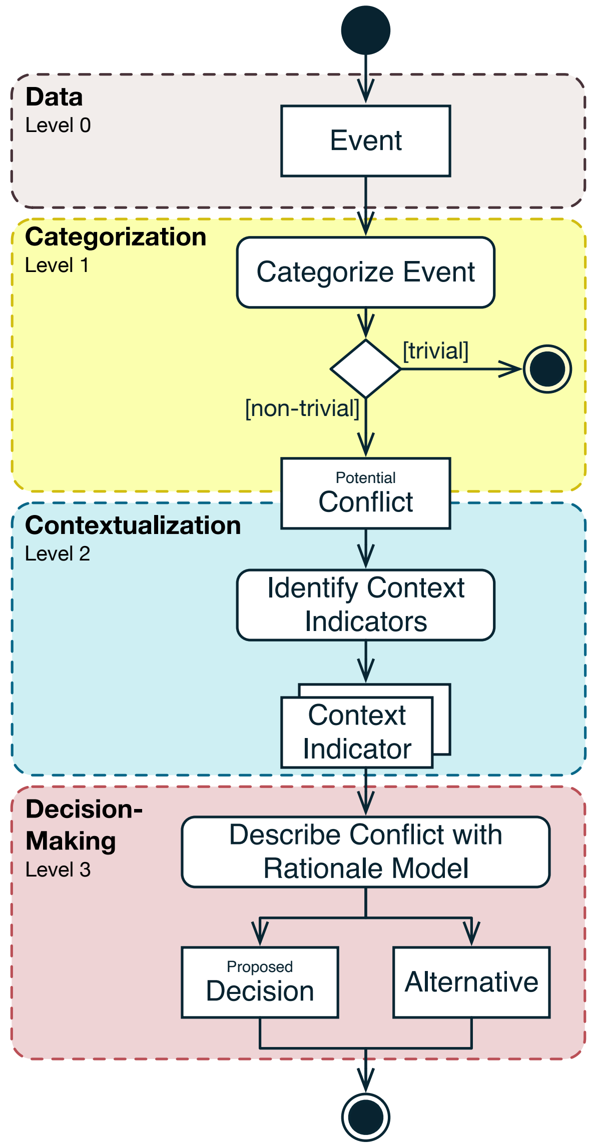

Figure 1: Decision-Making Process: TREATI uses four levels of abstraction to reach a decision to resolve a thermal comfort conflict. In Level 3, the Issue and Argument objects are excluded for simplicity. (UML Activity Diagram)

3 HUMAN-IN-THE-LOOP THERMAL COMFORT CONFLICT RESOLUTION

There is a need to involve each occupant in a fair thermal decision-making process in shared spaces due to many reasons. Most importantly: Anecdotal evidence suggests that decision-makers, higher-ranked, or senior office members often exploit their status to impose their own thermal preferences onto their colleagues; that ought to be prohibited. Since humans spend most of their time indoors, the indoor climate has a big impact on physical and mental health and productivity [2]. Employers desire productive employees and therefore must set a goal of creating a comfortable indoor environment.

Thermal comfort literature either uses consensus models, with the minority group having disadvantages, or personal comfort models, which often disregard whether there may be a better solution regarding the cohort. In addition, conflicts are often either ignored or the minority group faces discomfort. Previous efforts that aim at resolving Internet-of-Things conflicts have resulted in one-sided solutions which only focus on the regarded factors' priorities and do not include the conflict's context or compare alternative solutions.

TREATI compares solution strategies in order to decide on the most acceptable resolution. It considers both cohort and individual comfort, with regard to the space's energy use. TREATI uses four levels of abstraction in order to identify and resolve thermal comfort conflicts. Each level includes occupant input, whether it is a vote, behavior model, or input. Figure 1 presents the dynamic behavior of this process. The respective parts in the visionary scenario are highlighted using the same background colors.

Level 0 - ***Data:*** Events occur [*grey*]
Level 1 - ***Categorization:*** Events are categorized into trivial and non-trivial events [*yellow*]
Level 2 - ***Contextualization:*** Relevant context indicators are identified [*blue*]
Level 3 - ***Decision-Making:*** The conflict is described using the Rationale Model and a Decision is reached [*red*]

An event is an occurrence of either a message, such as a sensor measurement, state change, for example when an actuator is switched on, or timed happening, e.g., many BMS are scheduled to shut down during nighttime and weekends.

Level 0 registers events, in particular environmental and biosignal sensor measurements, actuator state changes, and occupant votes. Environmental sensors include, for instance, outdoor air temperature, indoor air temperature, humidity, air flow, or wind speed sensors. Biosignal sensors can include skin temperature, skin moisture, or heart rate.

3.1 Level 1 - Categorization

Incoming events are processed, categorized, and filtered into trivial and non-trivial events as they occur. Non-trivial events are events that potentially lead to a thermal comfort conflict. Such events are, for instance, occupant votes requesting a cooler or warmer air temperature, or indoor air temperature sensor measurements that are below or above a predefined range. Occupant votes that indicate satisfaction with the environment are initially treated as trivial events, as they do not need to be resolved regarding the prevailing circumstances. Trivial events can be reviewed after a conflict has been detected in Level 2 and 3.

3.2 Level 2 - Contextualization

Existing systems already consider environmental and human factors in temperature control decision-making processes [3, 5, 10]. Human factors include metabolic rate, the occupant's preference in the form of a vote, activity level, or daily schedule [3]. Most environmental factors that are considered are indoor and outdoor air temperature, air velocity, and In this paper, context is defined as the circumstances a thermal comfort conflict occurs in that are important for its resolution. For example, an occupant may feel warm due to solar gain through the window, another may feel cold due to an open window and incoming draft. This Context Model describes all relevant factors regarding the conflict's circumstances. It considers all occupants' votes, the vote history, and other human factors, such as calendar schedule or clothing. These factors are further grouped into models, such as the Persona Model and the Space Model, to allow the assignment of different priorities in level 3. For instance, the Persona Model categorizes occupants regarding their thermal preferences and behavior in thermal conflicts while the Space Model includes the available and relevant devices and their relation to the respective space, e.g., the room layout. The Context Processor determines dissatisfaction causes using the Context Model. For instance, an occupant at a south-facing window may feel warm due to high solar gain, indicated through the location of the occupant in the space, solar radiance sensor, and the nearest shade's state.

3.3 Level 3 - Decision-Making

TREATI's rationale model is based on Kunz and Rittel [9]. Each conflict is described by:

- Issue
- (Proposed) Decision
- Alternative Decisions
- Arguments: Motives (Goals), Shortcomings

Based on a policy, the rationale management system evaluates solution strategies and forms a decision model. In each step, the policy considers the context (Level 2) and a persona model to select appropriate solution strategies for the given issue. The persona model assigns a persona to each occupant, describing their thermal preferences and behavior regarding conflicts. Solution strategies include approaches such as interactive occupant negotiation, democratic voting, or a round-robin vote prioritization.

The decision model then evaluates the solution strategies based on the expected the decision acceptability in terms of occupant satisfaction, energy efficiency, or situational applicability constraints. This model first aims at optimizing cohort comfort. Potential remaining conflicts are evaluated on an individual level, for instance by deploying personal comfort models [7, 23]. The decision model proposes a solution which can then either be applied or reviewed and accepted, either automatically, by the occupants, or by a dedicated space administrator.

4 RESEARCH APPROACH & RESULTS

To validate TREATI's decision-making process, this project follows a formative mixed-methods research process which includes surveys and a simulation, based on scenario-based design [1]. Surveys serve the purpose of determining user experiences and validating concepts regarding conflict resolution techniques. A simulation validates TREATI's decision-making process, see Section 3, with environmental settings, functionality and dynamic behavior derived from scenarios, models, and real-world data. TREATI is synchronized with its simulation model to verify its functional, dynamic, and structural models. The simulation model uses data from the environment to identify issues and mismatches between TREATI and the simulation model. Mismatches are then rectified in an incremental and iterative process to update TREATI. The goal is to keep TREATI and the simulation model in sync. Further, prototypical implementations and human subject experiments address TREATI's usability and applicability.

Scenario-based design aids in describing the tacit knowledge that is necessary to define TREATI's underlying models. Visionary and simulation scenarios are derived from surveys, anecdotal evidence, and prior field work and are validated by domain experts. The scenarios have a particular focus on non-trivial conflicts, such as high temperature differences and a wide-spread distribution of occupant votes. For instance, a conflict with equal thermal preferences is resolvable by changing the air temperature while a conflict with evenly distributed votes for a warmer and cooler air temperature requires knowledge about the context. This permits testing the process' boundaries and identify potential loop holes during the simulation study.

4.1 Validation

The goal of the validation is to validate the TREATI framework against the environment and to verify TREATI against its simulation model, see Figure 2.

Based on an analysis of the real-world environment – including occupant behavior, domain experts, and sensor data – TREATI is defined in terms of its functionality, dynamic behavior, and architecture. The functional model consists of the use cases derived from the scenarios. The dynamic model describes the decision-making process. TREATI's framework and architecture are described in the structural model. The simulation model has already been validated against environmental data and lead to several changes in the simulation model, in particular solar gain data and an improved room model were added incrementally to the simulation model. Based on these changes, the TREATI framework was updated accordingly. TREATI has not yet been validated against the environment. This is work in progress and a user study is planned to complete the validation.

4.2 Survey

A survey with 100 valid responses conducted in July 2020 assessed the self-perceived thermal comfort conflict handling of occupants in shared spaces. Results include anecdotal evidence relevant for the decision-making process and provide the basis for the aforementioned Persona Model.

46% of survey's participants reported to be involved in at least one thermal disagreement per month. One participant mentioned that they feel uncomfortable voicing their discomfort due to their low position in their company's hierarchy. Four participants mentioned that they consider others' preferences when deciding on temperature-related actions. They also stated that they do not communicate their discomfort whenever they assume that their request would lead to others being dissatisfied. This indicates that inter-human relationships and personality play an essential role in thermal control, particularly in more equal-seeming conditions than solely in situations with dictatorial power over thermostats – as frequently suggested in the literature.

To address these issues, TREATI's decision-making process must include psychological human factors, in particular tacit knowledge [19, 20], as context indicators in the contextualization level and in the decision-making level, as part of the argumentation in the rationale model.

4.3 Simulation

TREATI's decision-making process is conceptually validated through a scenario-based simulation. The main objective is to validate the correctness and applicability of the proposed process, as compared to traditional and vote-based temperature control processes. Further, the applicability of the decision's proposed environmental tasks, e.g., raising the temperature, and task actions, such as asking occupants to remove layers of clothing or closing window shades, is evaluated. Using a simulation of the environment rather than real-world human subject experiments allows researchers, developers, and facility managers to determine and change variables without interfering in actual schedules or putting human satisfaction and health – due to the constant changing of the indoor air temperature and other factors – at risk. Events and environmental variables, e.g., an occupant's skin temperature or indoor air temperature, can be changed to identify shortcomings of the decision model, for instance decisions that involve contradicting tasks. Additionally, different context indicators can be added and removed to analyze their effect on a decision. Performing such experiments in a real-world setting would be time-consuming and costly. Next steps include an in-depth analysis of the required context indicators necessary to solve all pre-defined non-trivial conflicts, as indicated by early results of a prototypical simulation.

5 RELATED WORK

The research presented in this paper draws conclusions from ubiquitous computing, building regulations, rationale management techniques, and negotiation theory.

Conflict identification and resolution methodologies have received particular attention in the last decade. Research in the areas of smart home [11, 13, 18] and smart cities [8, 16] have addressed the resolution of Internet-of-Things conflicts regarding contradicting services. Liu et al. deploy an event service to identify conflicts in their framework RemedIoT [13]. RemedIoT uses remedial action to address and resolve conflicts. Their conflict detection relies on pre-defined policies which define device state restrictions against other devices.

Analogue to previous efforts in thermal control, most smart home and smart city approaches have attempted service conflict resolution by proposing solutions based on priority, often resulting in partisan decisions. This ignores the conflict's context, adaptive policies, or alternative or composite solutions. Recent works have laid the basis for conflict resolution processes to address this.

The DepSys system resolves conflicts in the smart home among multiple systems and their inter-dependencies, while considering the impact on the environment [18]. Ma et al. have explored several conflict detection [16, 17] and resolution ideas [15] regarding services in smart cities based on Integer-Linear-Programming methods. CityResolver system tries to resolve conflicts in a multi-step approach that first generates a set of potential resolution options, then evaluates it regarding possible effects on the involved requirements and visualize the resolution options' trade-offs [17].

Seitz et al. have proposed to apply decision-making and negotiation techniques in the fog architecture FRODO [22]. FRODO targets occupant-controlled spaces, rather than automated commercial buildings, and solves conflicts between rules and events, based on pre-defined strategies.

6 CONCLUSION

The main contribution of this paper is a human-in-the-loop decision-making process with a focus on rationale management efforts to resolve thermal comfort conflicts. The process involves occupant input throughout its four levels of abstraction. These include event management (data level) and filtering of events (categorization

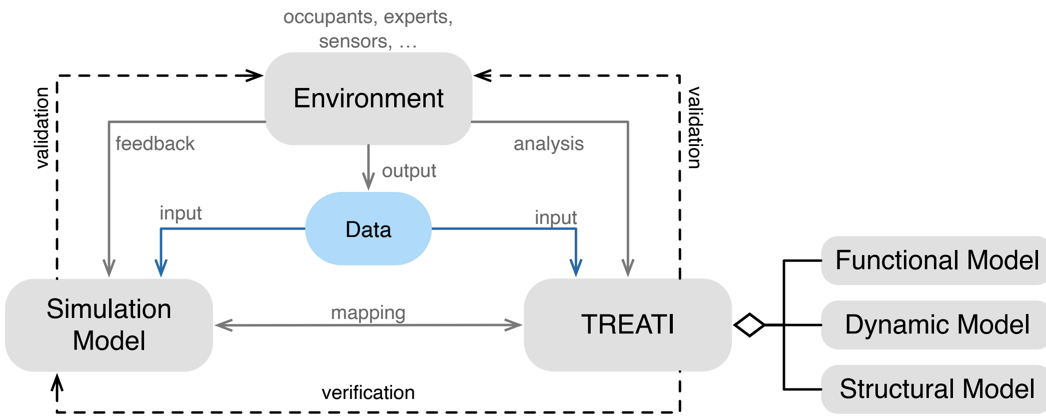

Figure 2: Validation Model: TREATI's simulation model uses the real-world environmental data to test scenarios and identify errors. These are then rectified in TREATI and are reconciled with the simulation model. This validation model is based on the work of [19].

level). The goal is to identify relevant context indicators, such as the environmental conditions and human factors, in the contextualization level and resolve conflicts with the rationale model in the decision-making level.

Future work includes an in-depth analysis of the presented process using a simulation to validate the process and test non-trivial conflicts, followed by a human subject experiment. Another goal of this research is to explore tacit knowledge and exploit it for TREATI's decision-making process. The validation of TREATI against real environment data is planned as a post-COVID-19 activity, with emphasis on whether TREATI allows for an overall higher thermal satisfaction among occupants over time. Open questions remaining are the extent to which occupants need to accept decisions and whether there is a correlation between occupant composition in a shared space and the outcome of conflicts.

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