A Fog Architecture for Decentralized Decision Making in Smart Buildings

Andreas Seitz
Technische Universität München
Munich, Germany
seitz@in.tum.de

Jan Ole Johanssen
Technische Universität München
Munich, Germany
johansse@in.tum.de

Bernd Bruegge
Technische Universität München
Munich, Germany
bruegge@in.tum.de

Vivian Loftness
Carnegie Mellon University
Pittsburgh, PA, USA
loftness@cmu.edu

Volker Hartkopf
Carnegie Mellon University
Pittsburgh, PA, USA
hartkopf@cmu.edu

Monika Sturm
Siemens Corporate Technology
Vienna, Austria
monika.sturm@siemens.com

ABSTRACT

The integration of humans into smart buildings raises challenges between meeting individual preferences and the generic rules set to optimize energy effectiveness of interest to organizations. Merging the individual preferences of multiple occupants that share thermal zones compounds the challenge. To address related challenges, we have developed FRODO (Fog Architecture for Decision Support in Organizations), an architecture designed to establish a location-aware environment for conflict negotiation and decision support that is based on fog computing. This paper describes the model transformation from a centralized software architecture towards a decentralized Cyber-Physical System (CPS) which encompasses sensors, actuators, and the occupants of smart buildings. The transformation is implemented through MIBO, a framework that allows occupants to control their environment. MIBO has been extended to introduce a fog layer for improved negotiation and conflict resolution. This enables additional benefits to be optimized, such as increased quality of service, reduced latency, and improved security and resilience. The fog layer, introduced with FRODO, allows occupants and organizations to express and discuss conflicts in decision-making, at their point of origin.

CCS CONCEPTS

•Software and its engineering →Design patterns; •Computer systems organization →Embedded and cyber-physical systems; *Cloud computing;*

KEYWORDS

Cyber-Physical System, Human-in-the-Loop, Smart Building Fog Computing, Decision Support, Software Architecture, Model Transformation

ACM Reference format:
Andreas Seitz, Jan Ole Johanssen, Bernd Bruegge, Vivian Loftness, Volker Hartkopf, and Monika Sturm. 2017. A Fog Architecture for Decentralized Decision Making in Smart Buildings. In *Proceedings of The 2nd Workshop on Science of Smart City Operations and Platforms Engineering, Pittsburgh, PA USA, 21 April 2017 (SCOPE 2017),* 6 pages.
DOI: http://dx.doi.org/10.1145/3063386.3063768

1 INTRODUCTION

While smart cities and in particular smart buildings delight in sensor and actuator rich environments, occupant controls in commercial buildings are disappearing rather than increasing. Most commercial buildings are being designed to lock out the occupant. This implies serious consequences for both indoor environmental quality and energy conservation.

The future in low energy buildings with high environmental quality builds on a new paradigm: articulated buildings with dynamic facades as well as responsive mechanical and electrical systems that support environmental surfing—for nature's free daylight, solar heat, natural ventilation, and night cooling. In the office of the future, every light fixture, thermostat, and air diffuser will be a point of information and control for occupant comfort and energy efficiency. The challenge is to integrate the diverse data protocols of embedded digital addresses and develop the instructional, motivational, and supportive control interfaces. CPSs in combination with the human in the loop model will be transformative for environmental quality, human health, and organizational productivity as illustrated in the following scenarios.

Artificial lighting consumes 10% of all electric energy in the US. Properly integrated enclosures in facades can provide opportunities for daylighting while enhancing productivity and health. Yet daylight depends on the current season and time of day dynamic and is strongly affected by weather.

Heating and cooling are the fastest growing sectors of electric energy use in buildings, especially in the face of climate change. Natural ventilation is an invaluable resource for saving energy and enhancing productivity as well as health. Ventilation does not need to be provided when a building is not or only partially occupied. In comparison to heating or cooling, which might require to be adjusted several hours before occupancies, ventilation can immediately satisfy occupants. Furthermore, outdoor environmental air qualities—when unacceptable—require filtration equipment and air to air heat exchange components. As with the lighting scenario, airflow is yet dynamic and depends on various external factors such

---

SCOPE 2017, Pittsburgh, PA USA

as as building enclosures, orientations, locations, and urban heat island effects of building conditioning, as well as weather.

Addressing these challenges, CPSs approaches must be effective for daylighting, natural ventilation and cooling include sunshine and daylight sensors, louvers and light shelves, external shades, internal blinds as well as operable windows with temperature, wind pressure and rain sensors, and room fans.

Innovative interfaces with the digital addresses of these technologies offer up to 80% energy savings for lighting, cooling, and ventilation, improve visual, thermal and air quality levels for the changing nature of work, adapt to seasonal changes in climate, introduce shade and overheating controls, deal with time of day variations in facade temperatures, as well as increase human health and organizational productivity.

Each of these outcome metrics is dependent on engaging occupants and multi professional decision makers doing design, engineering, construction and operations to create effective systems and most critically control systems. Yet in the US, light switches, operable windows, and blind controls are disappearing, and central controls are set to uniform levels with marginal time of day, season, or daylight response. Advanced sensors and actuators with individual control interfaces gain insight from and provide information for the effective design engineering, construction, and operations of building systems. Such advanced building mechanical, lighting, networking, power and security systems can successfully improve our energy and environmental management capabilities. These systems add humans into the control loop, save energy and meet electricity peek demands even including photovoltaics energy production.

Every operable window, mechanical diffuser, secure door, as well as the richness of sensors that inform their management will soon be addressable, creating CPSs for smart buildings. Hereby, the true power of CPSs can be found in the ability to customize our environment to individual preferences at the lowest energy demand, moving beyond central control systems. For instance, occupants who prefer lower lighting for computer work, smartphones will let them dim the artificial light with a gesture, using the smartphone's compass and gyroscope [14]. Occupants who prefer less air conditioning, smartphones let them lower the fan speed or partially close the air conditioning valve. Furthermore, dashboards for occupant control put humans in the loop to increase indoor comfort and environmental quality, as well as reduce annual and peak energy loads. This is central to the global climate agreement for net zero buildings and communities.

This paper is structured as follows. Section 2 gives an overview of related work. Section 3 describes the Intelligent Workplace as well as MIBO and addresses its limitations. Section 4 presents the transformation from MIBO towards FRODO, based on the idea of fog computing, presenting the newly proposed architecture. Section 5 provides an outlook on our plans for future work.

2 RELATED WORK

CPSs allow the change of control logic for hardware devices and software at runtime. Actuators can react to changes while taking sensor data into account. CPSs provide increased computational capabilities and enable the integration of the user and the environment within a system [9, 12, 15]. Furthermore, Peters' dissertation predicts that "Cyber-Physical Systems will have a significant impact on future buildings, as they will be embedded in all types of objects and structures" [12]. The term fog computing was initially introduced by the industry. In [1], Bonomi et al. of Cisco were the first proposing the architecture. In their work, they describe the value of extending cloud computing and thereby enabling new services within Internet of Things (IoT) and CPSs. Similar concepts are Mobile Edge Computing[1] and Cloudlets [16]. Both concepts bring services closer to the edge and thereby reduce latency, enable new services, and improve the quality of services.

Li et al. present EHOPES in [10], a data-centered fog platform for smart living. They focus on the flow of data between various sensors and actuators in order to make the appropriate decisions. In addition, they employ the fog computing paradigm in order to reduce both latency and the amount of transferred data.

Stojmenovic et al. describe in [17, 18] the need for fog computing as a use case for decentralized smart building controls. The authors propose a fog based architecture in which sensors are applied in smart buildings. Furthermore, they use distributed decision making and activation at fog devices to react to different data. Decisions are purely based on sensor data and do not involve the human in the resolution process. In addition, Stojmenovic and Wen list the IoT and CPSs as possible application scenarios for fog architectures: they outline the integration of "abstractions and precision of software and network with the dynamics, uncertainty and noise in the physical environment" [18]. In [6], Lopez et al. describe the need for edge-centric computing, stating that the movement of centralization and consolidation is outdated. The authors argue for a shift towards decentralization. Furthermore, humans should be "part of the computation and decision making loop, resulting in a human-centered system design" [6].

Humans are important factors and have to be taken into account for novel, adaptive distributed systems. These considerations may lead to innovative human-centered applications. Furthermore, Lopez et al. elaborate on both the optimization of energy usage as well as the improvement of quality of life within the domain of smart cities [6]. Faruque and Vatanparvar present a case study in [4] to use fog computing as a platform for energy management. The paper focuses on the design, implementation, and distribution of home energy management (HEM) systems for reaching zero net energy and improving the efficiency of buildings. Thereby, reducing the overall energy consumption.

All references point out the need for a shift towards a decentralized architecture to satisfy different requirements of the systems.

3 EXISTING APPROACH

Building automation systems are used to automatically adapt and control smart buildings according to external factors. These systems follow a rule-based approach for controlling smart buildings performance. In contrast, event-based approaches—such as MIBO—let occupants individually control their environment [12]. In this section, we describe the Intelligent Workplace as well as MIBO and reveal limitations of the deployed architecture.

---

[1] http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing

3.1 The Intelligent Workplace

The Robert L. Preger Intelligent Workplace (IW) at Carnegie Mellon University in Pittsburgh is the first *living* (contentiously updated and improved), and *lived-in* (experienced by students, staff and faculty, measured, reported, and verified performance) laboratory of the building industry. It was realized with net zero waste in construction and the relocation of occupants while reaching interior system distributions reaching the highest indoor environment quality (IEQ) consuming 80% less non-renewable energy of US commercial buildings at the time of 1997 [8].

The Intelligent Workplace is the home of the Center for Building Performance and Diagnostics at CMU. It hosts controllable fixtures that can be accessed individually and offers a variety of building technologies, such as dynamic light-redirection louvers, multi-layered enclosures (external, facade integrated, and internal enclosures). The IW supports natural ventilation, passive and active heating and cooling, as well as daylighting glare control [11].

The goal of the IW is to reveal chances to save energy by specifically designed buildings, which not only results in cost efficiency due to optimized operation when comparing to conventional buildings, but also in a reduced ecological impact of the building [8].

3.2 Rule-Based vs. Event-Based Approach

Office buildings are equipped with building automation systems for managing large control zones. Technology for heating, ventilation, and air conditioning (HVAC) depends on contexts addressing light incidence, temperature, and predefined time intervals, resulting in a rule-based approach. Figure 1 outlines an example for a rule-based controlled smart building. As soon as a context change is detected, the building automation management system applies matching rules and issues commands to concrete instances of fixtures.

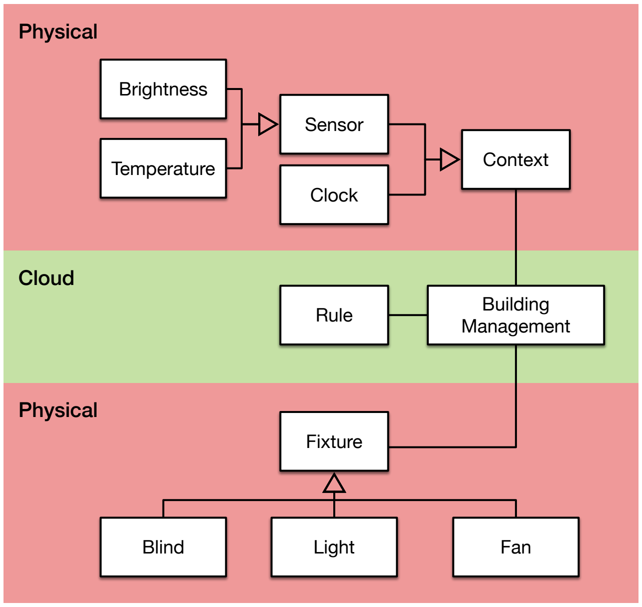

Figure 1: Ruled-Based Approach of Controlling Smart Buildings Using General Rules for Large Control Zones.

In the scenario of building automation systems, rules are applied on a large-scale for every office of the building. For instance, a temporal reduction of light incidence caused by a passing cloud might lead to shut down the blinds in all offices, without any occupant interaction and without having addressed their individual performance preferences and behaviors.

In contrast to rules-based approaches, event-based approaches put the occupants in control of their surroundings as shown in Figure 2. Rather than relying on external factors, event-based approaches rely on interaction with the occupants of smart buildings.

Peters presents MIBO, a framework that combines natural and intuitive user interfaces by focusing on multimodal user interaction technology [12]. Enabled by a combination of multiple modalities such as gestures or speech, an integrated approach for controlling building fixtures can be established.

3.3 MIBO Architecture

As shown in Figure 2, Peters introduces the concept of a *Definition* in order to provide an interaction model for smart buildings which enables occupants to control their surroundings [12, 13].

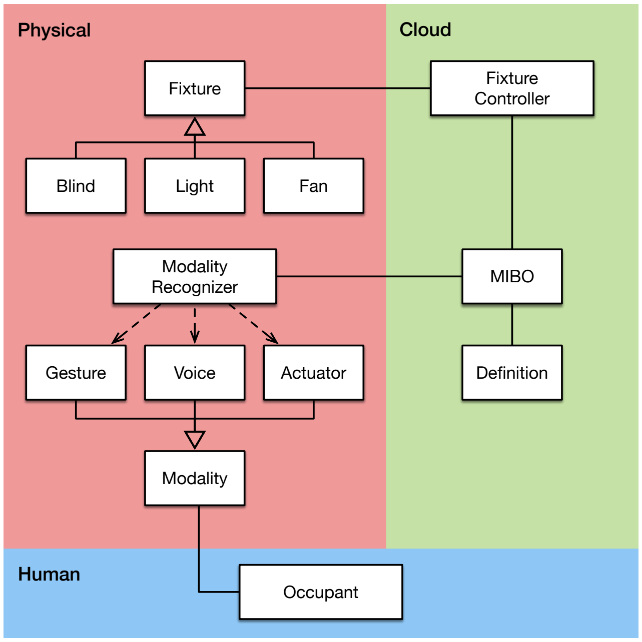

Figure 2: Event-Based Approach of Controlling Smart Buildings by Involving the Occupants.

The MIBO framework implements a fusion process to enable multimodal controls [12]: starting with information gathered from modality agents, extracting its concrete meaning, and finally executing actions in accordance to the defined interactions.

MIBO implements the blackboard pattern as core component for processing the provided modality information: knowledge sources for modalities are encapsulated as agents within the modalities component and are continuously posing hypothesis on the blackboard which serves as a repository [2].

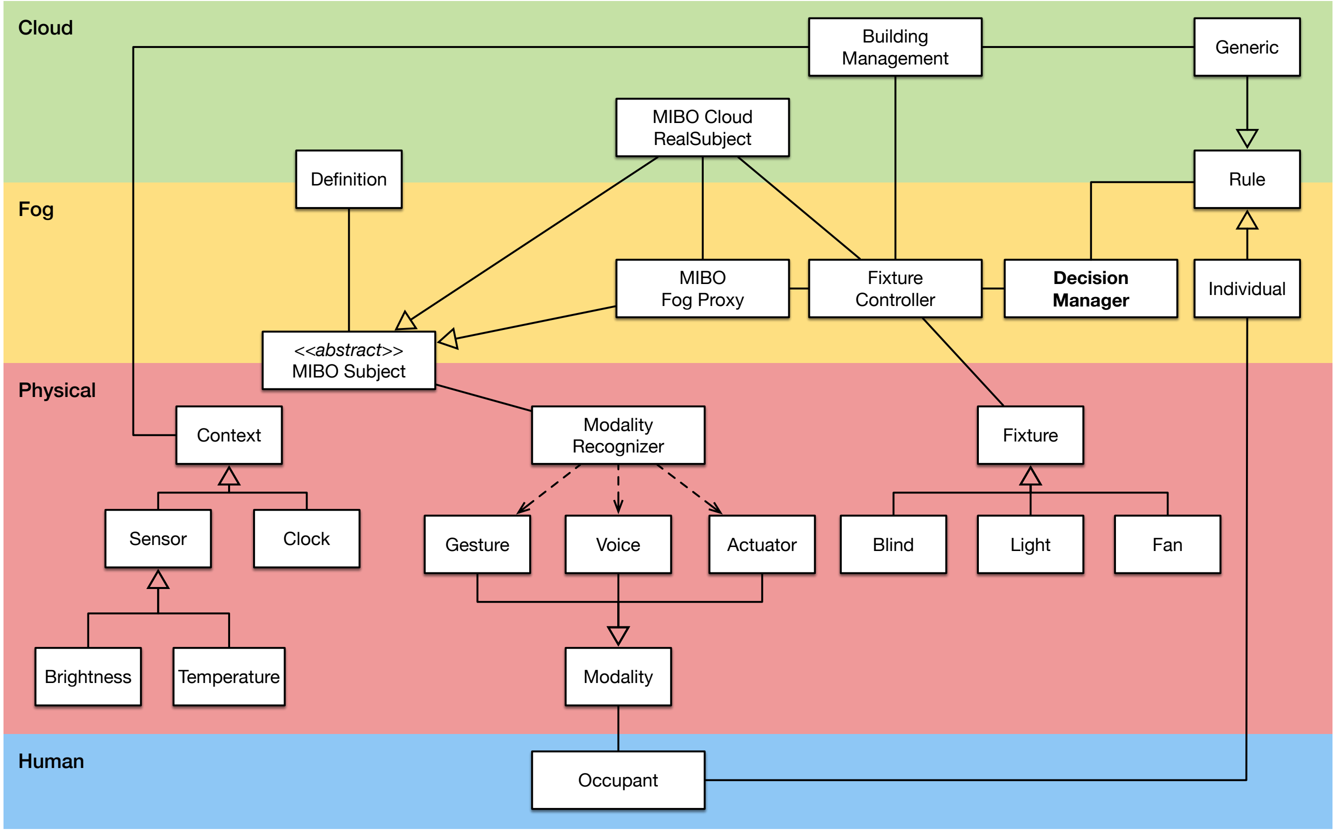

Figure 3: FRODO – Combining MIBO, Fog Computing, and the Proxy Pattern.

3.4 Limitations

MIBO focuses on the fusion of multimodal controls in smart buildings. It enables an intuitive and natural way of interacting with the surrounding. However, there are limitations posed by MIBO's architecture. When comparing Figure 1 and Figure 2, we notice, that MIBO is involving the human (blue area) but misses the physical context on which the rules of the building management are based. MIBO enables occupants to express their individual preferences towards their personal comfort, but does not deal well with contradictions that arise due to conflicting definitions and rules.

Furthermore, the framework relies on a cloud-based architecture. Incidents, such as network outage, would render the system unusable—a major disadvantage considering that controlling a smart building can be crucial in situations involving power outage or fire. Besides a single point of failure, having a central controlling component also implies a single point for attacks.

The fact that MIBO does not deal well with contradicting interests of occupants, an organization and the general goal of energy saving, as well as the limitations imposed by the cloud-based deployment leads to a shift towards fog computing. The transformation from a cloud-based deployment towards a fog-based solution is addressed in the next section in order to overcome these limitations.

4 NEW ARCHITECTURE

The limitations of MIBO, as well as the requirements imposed for individual human comfort and the goal of increasing global energy savings require the introduction of a new architecture. According to Hammer and Champy [7], we apply the concepts of fog computing as a disruptive technology, which leads to the transformation from a cloud-based deployment towards a fog-based deployment.

Based on the already existing cloud-based MIBO architecture, model refactoring as a reengineering technique is applied. We design FRODO, which stands for **F**og A**R**chitecture f**O**r **D**ecision Support in **O**rganizations. FRODO is based on the characteristics emphasized by fog computing, in particular availability, resilience, security, increased quality of service, and geographical distribution. The rationale of the architecture is based on the fact that the IoT has a significant impact on the economy [3].

4.1 Design

Figure 3 introduces the *Fog* environment (yellow) in addition to the existing *Physical* (red), *Cloud* (green), and *Human* (blue) environments. In line with the concepts of fog computing, existing components are not replaced, but rather extend given functionalities and enrich the capabilities. The proxy pattern, introduced by the Gang of Four in [5], is applied. The *MIBO* class of Figure 2 is split up into the *MIBO Cloud RealSubject* and *MIBO Fog Proxy*.

Both classes are children of the abstract class *MIBO Subject*. The MIBO cloud real subject represents the real subject, whereas the MIBO fog proxy represents the proxy. Using the proxy pattern, we can operate independent of the availability of MIBO Cloud (remote proxy). We reduce the communication efforts with the real subject. Furthermore, we can perform the actions where they are triggered without the requirement to connect to the cloud at any time (virtual proxy). In addition, the proxy pattern allows to facilitate access restrictions towards the cloud component and therefore improves security aspects of the system (protection proxy).

According to the fog computing terminology, we refer to the fog proxy as fog nodes and introduce the MIBO cloud as a fog server [10]. Based on the separation of concerns, we can relocate components in different environments and geographically distribute nodes, running the fog proxy in an environment close-by the interaction with the occupant, whereas the MIBO cloud component remains in the cloud. The fog proxy represents a tailored clone of MIBO cloud with restricted knowledge regarding *Rule*s and *Definitions*. It stores definitions and rules which are required for the specific location it is deployed in, such as a specific room or office space within a smart building. Rules and definitions are placed on the edge between the cloud and the fog environment. Thus, the fog node and server are aware and capable of using both. Due to decentralization of the nodes, there is no need that both the fog node and server know about all existing definitions and rules, but rather are able to access the ones relevant for them.

Compared to Figure 2, we moved the *Fixture Controller* from the cloud to the fog environment. Fixtures are directly connected to the individual fog nodes next to them. In a scenario in which an occupant performs a set of modalities which are part of a definition stored at a fog proxy, the translation of these modalities to concrete actions is performed in the node. There is no need to forward the interaction to the cloud. This leads to a reduction in latency time between the performed modalities of an occupant, such as combined voice and gesture command, and the outcome, such as turning on a light.

The communication style between the *Modality Recognizer* and the MIBO framework is independent of the used *MIBO Subject* implementation. The abstract MIBO subject is providing the same interface as MIBO in Figure 2. Consequently, the modality recognizer is not aware if it either connected to a fog or cloud component.

Compared to Figure 1, we insert a taxonomy for rules in FRODO. We introduce *Individual* and *Generic* rules. Individual rules represent preferences of occupants that are performed depending on a specific *Context*. For example, occupants can define a rule that daylight is more important for them than the optimal illumination of their working place, which results in using less artificial light. This is considered an individual rule. *Generic* rules are based on a larger scale and are generally valid for every room in a building. They are defined by a facility manager and also depend on the context.

Generic and individual rules might be contradicting. For example, a generic rule could define to shut down blinds at a specific time of the day, whereas and individual occupant prefers to work with daylight throughout the day. The discrepancy between conflicting rules poses the need for a dedicated process to negotiate between them. The proposed architecture enables negotiation and decentralized decision making as described as follows.

4.2 Decentralized Decision Making

The distribution of fog nodes leads to decentralized decision making. The process of negotiation and decision making moves to the location where conflicts need to be resolved. Figure 4 shows the distribution of *Fog Nodes* in multiple rooms of a building. Each fog node needs to be aware of occupants' present within the room, their individual preferences, and every controllable fixture such as blinds, lights, or fans which can be reached using the fixture controller.

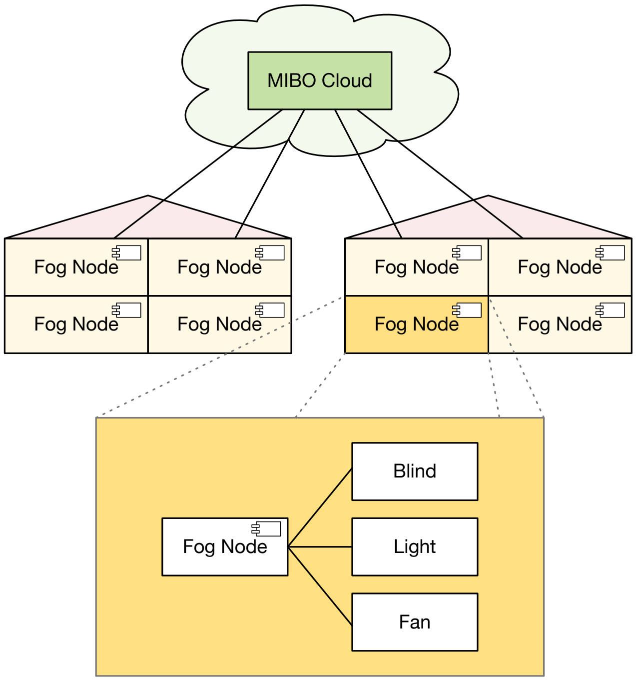

Figure 4: FRODO Component Diagram with Distributed Fog Nodes and Fixtures.

A *Decision Manager* as introduced in Figure 3 is part of each fog node and enables the negation between conflicting rules. In particular, it is the battleground for contradicting rules. The negotiation of finding the optimal decision with respect to needs and preferences of human occupants and the global goal of energy saving is addressed by the decision manager of FRODO.

Rules are not the only source for raising conflicts which need to be solved. Definitions which are triggered by events might interfere with defined rules. For example, an occupant might want to open the blinds in their office using a gesture. However, if a generic rule regulates that all the blinds should remain closed at this point in time, a conflict situation arises.

Therefore, the decision manger needs to provide conflict resolution strategies to resolve these issues. In [12], Sebastian Peters embraces ”strategies for the prioritization of users and consensus-based approaches with averages or medians being negotiated by the system to maximize the occupants' satisfaction” [12].

4.3 Discussion

We are able to improve an existing system by connecting the paradigms of fog computing with established software engineering knowledge such as design patterns.

Fog computing allows the decentralized and intelligent processing of data to interact with connected devices. Furthermore, it enables a smooth integration of cyber and physical components. Due to the geographical distribution of the fog nodes to specific locations, such as office spaces, we enhance the quality of services with devices in close proximity for occupants. The extension of the cloud-based approach enables us to fulfill the requirements stated in section Section 1 and overcome the limitations of Section 3.

Regarding privacy and security aspects, the proposed architecture provides the possibility for occupants to identify where their individual preferences are specified—on a remote repository or within their nearby fog component.

The fog computing concept encourages the seamless integration of heterogeneous smart objects and edge devices, such as sensors and actuators. Processing, storing, and communicating concepts are realigned with their cloud components. This raises challenges regarding the construction and maintenance of the underlying infrastructure.

Notably, introducing a decision manager does not solve the problem of securing the requirement of not dissatisfying of any objective in general. Instead, it sets the battleground for decision making processes and requires the specification of solution strategies.

5 CONCLUSION

We describe the need of putting humans in the loop within systems for smart buildings in order to reach advanced indoor and environmental qualities. We discuss MIBO, a framework that empowers occupants to control their surrounding environment and therefore enables them to satisfy their individual preferences with regards to health, productivity, and comfort.

With FRODO, we present an architecture to deal with interest conflicts and to support decision making processes. FRODO does not solve the conflicts itself, but rather establishes multiple decentralized points of interaction to negotiate, discuss, and decide on actions that should be performed in order to satisfy the individual preferences. Due to the fact that FRODO is based on the fog computing paradigm, conflicts can be resolved at the place of their origin. Further research is required to make successful decisions that satisfy all of the involved parties. Long-term efforts must address the related global climate agreement which requires completely sustainable building practices.

As part of our future work, MIBO and its cloud-based approach will not be replaced. Instead, we extend this work by distributing MIBO instances on fog nodes, leading to an improved quality of service for occupants, which is enabled by both the extensibility and flexibility of MIBO. In particular, we utilize the benefits of applying fog computing concepts, such as low-latency, security, resilience, and availability.

Therefore, first steps towards the combination of CPSs and fog computing are identified, while at the same time considering both the humans as individual occupants and addressing the global climate challenges. Currently, we are working on the implementation of FRODO. Thereby, we want to enable the evaluation of the proposed architecture.

REFERENCES

[1] Flavio Bonomi, Rodolfo Milito, Jiang Zhu, and Sateesh Addepalli. 2012. Fog Computing and Its Role in the Internet of Things. In *Proceedings of the First Edition of the MCC Workshop on Mobile Cloud Computing*. ACM, New York, NY, USA, 13–16.

[2] Frank Buschmann, Regine Meunier, Hans Rohnert, Peter Sommerlad, and Michael Stal. 1996. *Pattern-Oriented Software Architecture - Volume 1: A System of Patterns*. Wiley Publishing.

[3] A. V. Dastjerdi and R. Buyya. 2016. Fog Computing: Helping the Internet of Things Realize Its Potential. *Computer* 49, 8 (Aug 2016), 112–116.

[4] M. A. Al Faruque and K. Vatanparvar. 2016. Energy Management-as-a-Service Over Fog Computing Platform. *IEEE Internet of Things Journal* 3, 2 (April 2016), 161–169.

[5] Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides. 1995. *Design Patterns: Elements of Reusable Object-oriented Software*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA.

[6] Pedro Garcia Lopez, Alberto Montresor, Dick Epema, Anwitaman Datta, Teruo Higashino, Adriana Iamnitchi, Marinho Barcellos, Pascal Felber, and Etienne Riviere. 2015. Edge-centric Computing: Vision and Challenges. *SIGCOMM Comput. Commun. Rev.* 45, 5 (Sept. 2015), 37–42.

[7] M. Hammer and J. Champy. 1999. *Reengineering the Corporation*. HarperCollins.

[8] Volker Hartkopf, Vivian Loftness, Ardeshir Mahdavi, Stephen Lee, and Jayakrishna Shankavaram. 1997. An integrated approach to design and engineering of intelligent buildings—The Intelligent Workplace at Carnegie Mellon University. In *Automation in Construction*. Vol. 6. Elsevier B.V., 401–415.

[9] E. A. Lee. 2008. Cyber Physical Systems: Design Challenges. In *11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC)*. 363–369.

[10] J. Li, J. Jin, D. Yuan, M. Palaniswami, and K. Moessner. 2015. EHOPES: Data-centered Fog platform for smart living. In *Telecommunication Networks and Applications Conference (ITNAC)*. 308–313.

[11] Vivian Loftness, Volker Hartkopf, Stephen Lee, Jayakrishna Shankavaram, and Azizan Aziz. 2001. SMART BUILDINGS, INTELLIGENT BUILDINGS. In *Facility Design and Management Handbook*, Eric Teicholz (Ed.). McGraw Hill Professional, Access Engineering, 12.1–12.41.

[12] Sebastian Peters. 2016. MIBO – A Framework for the Integration of Multimodal Intuitive Controls in Smart Buildings. Ph.D. Dissertation, Technische Universität München. (2016). *https://mediatum.ub.tum.de/node?id=1304127*.

[13] Sebastian Peters, Jan Ole Johanssen, and Bernd Bruegge. 2016. An IDE for Multimodal Controls in Smart Buildings. In *Proceedings of the 18th ACM International Conference on Multimodal Interaction (ICMI 2016)*. ACM, New York, NY, USA, 61–65.

[14] Sebastian Peters, Vivian Loftness, and Volker Hartkopf. 2011. The Intuitive Control of Smart Home and Office Environments. In *Proceedings of the 10th SIGPLAN Symposium on New Ideas, New Paradigms, and Reflections on Programming and Software*. ACM, 113–114.

[15] R. Rajkumar, I. Lee, L. Sha, and J. Stankovic. 2010. Cyber-physical systems: The next computing revolution. In *47th ACM/IEEE Design Automation Conference (DAC)*. 731–736.

[16] Mahadev Satyanarayanan, Paramvir Bahl, Ramón Caceres, and Nigel Davies. 2009. The Case for VM-Based Cloudlets in Mobile Computing. *IEEE Pervasive Computing* 8, 4 (Oct. 2009), 14–23.

[17] I. Stojmenovic. 2014. Fog computing: A cloud to the ground support for smart things and machine-to-machine networks. In *Telecommunication Networks and Applications Conference (ATNAC)*. 117–122.

[18] I. Stojmenovic and S. Wen. 2014. The Fog computing paradigm: Scenarios and security issues. In *Computer Science and Information Systems (FedCSIS), 2014 Federated Conference on*. 1–8.