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Track and trace for optimal process control of energy flows within a building

Wim Zeiler[a]*, Timi Labeodan[a], Gert Boxem[a], Rik Maaijen[a], Joep van der Velden[b], Jan-Willem Dubbeldam[b]

[a]*TU Eindhoven, Vertigo 6.28, Eindhoven, 5600 MB, Netherlands*
[b]*Kropman Building Services, Laglandseweg 84, Nijmegen, 6545 CG, Netherlands*

Abstract

Building process control without including the occupant behaviour is a sub optimal solution. New developments are ongoing to develop energy efficient control strategies to include human behavior and especially occupancy in the process control of buildings. This paper presents a short overview of available technologies for integrating occupancy in building operations. Initial results from the implementation of one of these technologies in an office building are presented as well as the framework for the use of a more intelligent multi-agent based building energy and comfort management system to achieve worthwhile energy reduction.

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Keywords: Multi-agents; energy efficiency; occupancy detection.

1. Introduction.

Energy use during building operation currently represents about one-third of the total energy consumption in most developed countries[1,2]. Towards effort to improve the energy consumption in buildings, a number of strategies for improved building energy and comfort management (BECM) systems have been proposed and currently been

* Corresponding author. Tel.:+31402473714.
E-mail address: w.zeiler@tue.nl

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implemented in both new and existing buildings[3]. BECM systems are control systems for building services installations that use computers and distributed microprocessors for monitoring, data storage and communication [4,,5]. The general objective of a BECM system is to fulfil occupants' comfort requirement with efficient use of energy during building operation[5, 6].

Of recent, there has been growing emphasis on the need for a shift from the conventional notion of comfort in buildings based mainly on room temperatures and that perceives building occupants as passive building occupants, to that which recognises the role of inhabitants engagement in the comfort process[7, 8]. This paradigm change involves new responsibilities of communication and dialogue as dynamic and adaptive processes necessary to achieve optimal building performance. In addition, it requires control and management tasks to be performed in a dynamic, non-deterministic and hence complex environment, which the design paradigm of current BECM systems is unable to address adequately[6, 9, 10]. Energy management within buildings can be improved by applying the latest development in information and communication technology (ICT). The potential savings of energy due to better use of ICT is well documented[11], however, in most of these studies, user behavior is often ignored despite having a large impact on the energy consumption of buildings. As presented by the authors in[12], it is possible to identify a number of control strategies based on accurate building occupancy such as

- Lower temperature demands in unoccupied areas. It was shown by the authors in[13] that building energy reductions can be obtained when temperature was lower in winter period and higher in summer period;
- Maintaining lower ventilation rates in unoccupied areas; leading to less ventilation losses and building energy needed;
- Supplying airflow based on occupancy; two studies[14,15] looked at dynamic airflows based on the CO_2 concentrations. Applying these strategies, savings of between 15% to 56% were shown to be achievable from reduction in ventilation.
- Responding to dynamic heat loads on a timely manner; if a change of the occupancy is detected in real time HVAC systems could respond to these changes immediately, before the temperature varies to an extent that is detectable by thermostats;
- Operating HVAC systems based on occupant preferences; by knowing the identity of occupants, HVAC systems can adjust and maintain set points to ensure individual occupant comfort.
- Learning energy use patterns; if the systems are able to profile the pattern for both the occupant and workplace it can proactively operate for optimum individual comfort setting and energy use.

The occupant is important in relation to the energy consumption[16]. Occupant presence and user behavior have a large impact on space heating, cooling and ventilation demand, energy consumption of lighting and room appliances[17] and thus on the energy performance of a building[18]. Therefore it is important to include human occupancy to improve building process control performances. The concept of how this could be included within the building systems process control is presented in Figure 1. For the set control objective with the user central in the control of building systems it is most important to detect the individual user on a specific workplace within a time span of minutes because the inertia of the building systems is in this order of magnitude. Therefore an indoor occupancy detection and positioning system needs to be developed which can communicate with the Building Energy Comfort Management system. The indoor occupancy detection systems should be individualized, i.e., it should be able to detect , track and identify individuals in a spatial area.

2. Occupancy detection

Building occupancy information is a crucial factor that should be considered in the control strategy of building operations for improved energy efficiency and occupant comfort. Building systems generally operate according to fixed schedules and to assumed occupied and unoccupied periods of the day as in EN 15232 (e.g. 8 AM to 7 PM). They do not consider when buildings are partly occupied which could be of influence as occupancy in buildings varies from day to day and from time to time [20,21,22]. To get a better understanding of the occupancy, Mahdavi[22] extracted behavioural trends and patterns for groups of building occupants from long-term observational data from different buildings[23]. Figure 2 shows that there are considerable differences of the mean occupancy at workplace for the different building types. Looking closer at a profile obtained from observations in an insurance office depicted in figure 2c, standard deviation of up to 15% is visible.

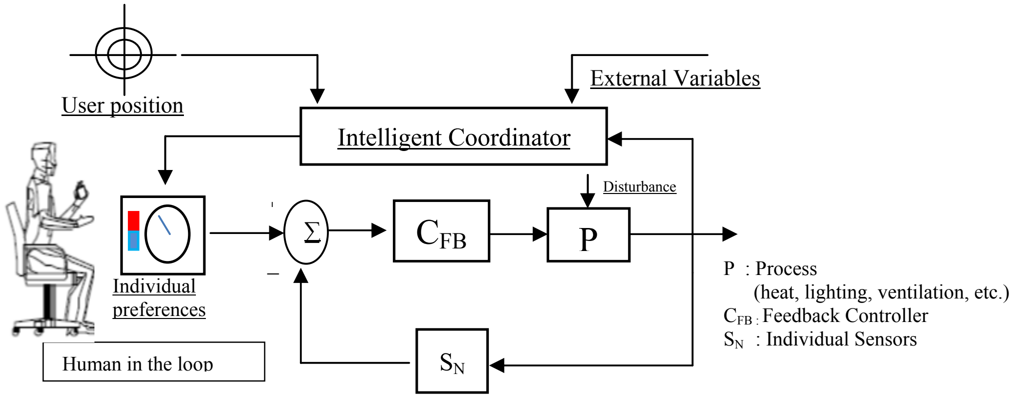


Fig. 1. Proposed block diagram of the controlled system and the intelligent coordinator for taking the human in the control loop of building systems.

Although these figures give a better representation of the building occupancy. However, still a lot of information is missing, e.g.: Variation of occupancy from time to time; location of the people within the building and which individual is at what position in the building.

Despite all effort, no current model is capable of describing the individual human position in buildings. This was also acknowledged by Mahdavi[23], who concluded that different researches tried to describe the human position and its actions by a model. From all the models he investigated it turned out that interactions with buildings' environmental systems are difficult or even impossible to predict at the level of an individual person.

User presence is a complete stochastic and random process, where even the next state of presence cannot be described by the previous. For optimal building operation real-time information about the building user is needed.

Dynamic control of building services systems in relation to actual building occupancy profile presents an opportunity for more efficient use of energy for improvement of occupants comfort. However, human occupancy information was not until recently considered in buildings energy performance analysis[24]. The use of real-time occupancy information has been shown by a number of studies[25,26,27,28,29,30] to have the potential to provide the worthwhile energy savings required to reduce the energy consumption of office buildings without compromising on occupant's thermal comfort needs. Spataru and Gauthier[30] tested the performance of various technologies for monitoring people within buildings to be able to assess potential energy reduction due to activity and occupancy. They found that each technology has intrinsic restrictions. Therefore it is necessary to discuss the different techniques.

2.1. Passive infrared systems

Occupant detection in current buildings is typically accomplished using passive infrared (PIR) and ultrasonic motion detectors[31]. There are some other drawbacks of this human detecting method: a).The sensor has binary output, b). It is not capable of detecting which individual is at what position and how they move, c). False off as stationary occupants at workplaces could be considered absent. To meet those drawbacks, Dong et al.[26] proposed a system that collected data through CO_2 detection, acoustic and PIR sensors. The average accuracy became 73% in counting occupants. The dependency on CO_2 is a major disturbance, where it takes time to build up the CO_2 level as a cumulative effect of various factors other than occupancy, such as outdoor air quality, ventilation rate, opened windows. In building energy management, PIR sensors are most often used in lighting systems and energy savings of between 10 to 45% have been shown to be obtainable from the use of PIR sensors in lighting systems control[27]. For actual demand driven control of HVAC systems in a large university building, Agarwal et al.[31, 32] utilized a combination of both PIR sensors and magnetic door sensors to determine real-time occupancy in rooms on a whole university floor. The output of the combined sensor was transmitted via the universities wireless network to a central server which communicated the status of the room to the building management system for demand driven HVAC control.

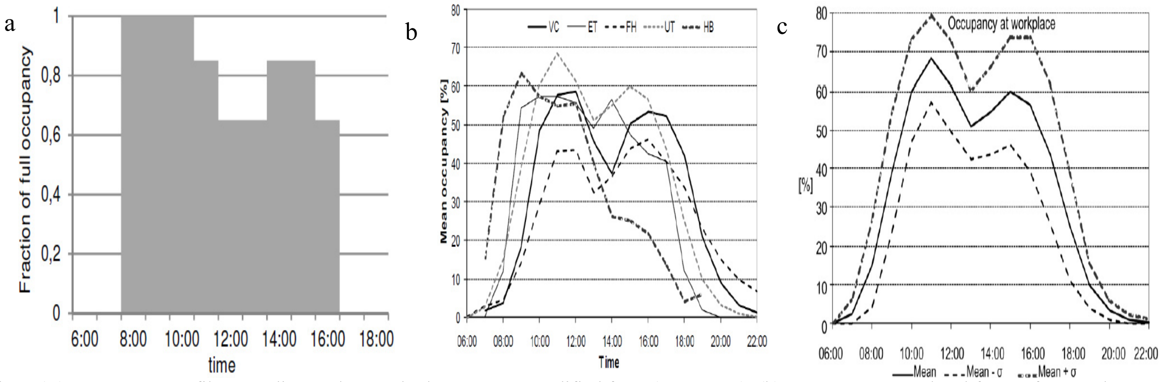


Fig. 2.(a) Occupancy profile according to the standard EN 15232, modified from (EN 15232), (b) Mean occupancy level for a reference day. VC: International organization (Vienna); FH: University (Vienna); ET: Telecom. services (Eisenstadt); UT: Insurance (Vienna); HB: State government (Hartberg) (c) Mean occupancy level at workplace and standard deviation for an insurance office Vienna, for 14 months, 89 workplaces, modified from Mahdavi [22].

Using low-cost devices and the existing infrastructure, energy savings of up to 16 % and 13 % for HVAC electricity and thermal energy use respectively were recorded. Unlike the active badge system which could be used for individualized functions, the system could detect occupancy, but could neither count nor identify occupants.

2.2. IT infrastructures

Melfi et al.[27] made use of the existing IT infrastructures to supplement traditional dedicated sensors to determine building occupancy. The applied sensing method is largely based on monitoring the MAC and IP addresses in routers and wireless access points, and then correlating these addresses to the occupancy of a building, zone, and/or room. The occupancy was based on the Wi-Fi signal from mobile phones, worn by the occupants. Another indication of occupancy is the use of the computer. In the study, the authors compared the accuracy of PIR, Wi-Fi connection and the PC activity. It was shown by the authors that the overall accuracy of PC activity is accurate to obtain the occupancy. PC activity could therefore give a good estimation whether someone is at his workplace or not, but the main disadvantage is that still the position in the building is not known, even when the occupant is behind his desk. The overall accuracy of the Wi-Fi connection is less high, though it shows some potential. Beneficial compared to the PC activity is that the position of the occupant is known at the level of several rooms. Though, there are two main issues which affect the accuracy as an implicit measure in the count and localization: a) overlap of access point coverage, and b) inconsistent Wi-Fi connectivity of mobile phones.

2.3. Vision based systems

As cameras are also a common feature in large commercial establishment for security purposes, researchers have explored its use also in occupant localization within building thermal zones. Erickson et al.[29] proposed and developed a system based on wireless network of cameras called OPTNet, 22 wireless camera nodes with on board image processing algorithm capable of compressing the captured data for efficient transmission to the processing server were installed along hallways in an office building. The developed system was able to detect transition with an accuracy of up to 94%. In order to limit errors due to false measurement, the system was combined with a wireless network comprising PIR sensors similar to the system developed by Agarwal et al.[32]By dynamically controlling the buildings HVAC system using the real-time occupancy data, it was shown that energy savings of 26% was possible while maintaining comfort Some other vision based systems have also been proposed[33,34] for identification of individual occupants within a space; however, these systems require significant processing power to stream real-time images wirelessly for real-time HVAC control. For most vision based systems, the major drawbacks are still privacy, cost and maintenance. Also line of sight obstructions significantly affect the accuracy of these systems.

2.4. Wireless fidelity (WIFI) enabled devices

WIFI enabled devices such as personal computers, mobile phones and personal digital assistants (PDA) are very common devices available in commercial office buildings and have as well been explored for both individualized and non-individualized functions. Martani et al.[28] explored the use of WIFI enabled devices in two university buildings to survey human occupancy at different levels of granularity for non-individualized functions. The number of WIFI devices actively connected to the Wireless local area network (WLAN) were used as an estimate of occupancy in rooms. However since WIFI signals are able to penetrate walls error due to overlapping connections and inconsistent connectivity seriously affected its performance. Melfi et al.[27] also explored the use of WIFI enabled systems within a building for both individualized and non-individualized functions but encountered the same challenge; overlapping connections and inconsistent connectivity of WIFI enabled devices. In both cases, it was shown that an estimate of occupants' position and count in a room was possible using WIFI enabled devices within a building network but no actual connection was made with the building HVAC system for demand driven control. For individualized functions, Khoury and Kamat[25] explored the use of a commercially available dedicated WIFI-based positioning system which uses dedicated clients, the system however relies heavily upon many components using separate infrastructure.

2.5. Indoor global positioning systems (GPS)

As in satellite based GPS, transmitters send a one-way signal to the receiver allowing an unlimited number of receivers to independently calculate positions. For the calculation triangulation is used, where the angles are measures to known locations. With two known locations of transmitters, the absolute position can be determined. Results of an experiment conducted by Khoury and Kamat[25] indicated that the Indoor GPS tracking system consistently achieved a positioning uncertainty that fluctuated between 1 and 2 cm. Though, this system has one major disadvantage, where the indoor GPS needs a line of sight for positions tracking. The receiver needs to have a direct link to two of the receivers.

Table 1. Evaluation of different occupancy detection systems

			PIR		IT infra		Vision-based		WLAN		Indoor GPS		RFID	
	Factor	Max	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Functioning			(max 3)											
Spatial resolution														
Floor	1	3	2	2	1	1	2	2	1	1	1	1	2	2
Room	2	6	2	4	1	2	3	6	2	4	2	4	3	6
Workplace	3	9	0	0	2	6	1	3	1	3	3	9	2	6
Temporal resolution														
Minutes	1	3	2	2	1	1	3	3	3	3	3	3	3	3
Seconds	3	9	0	0	0	0	2	6	2	6	2	6	2	6
Occupant resolution														
Occupancy	1	3	2	2	2	2	3	3	3	3	1	1	3	3
Count	2	6	0	0	1	2	1	2	3	6	1	2	3	6
Identify	3	9	0	0	1	3	0	0	3	9	2	6	3	9
Activity	1	3	0	0	2	2	1	1	0	0	0	0	1	1
Total points		51		10		19		26		35		32		42
Percentage		**100**		**20**		**37**		**51**		**69**		**63**		**82**
Realization			(max 3)											
Flexibility	2	6	1	2	2	4	1	2	1	2	1	2	2	4
Reliability	3	9	0	0	1	3	2	6	2	6	2	6	3	9
Costs	1	3	3	3	3	3	2	2	1	1	0	0	2	2
Line of sight	2	6	1	2	3	6	0	0	3	6	0	0	3	6
Implementation	2	6	3	6	1	2	1	2	1	2	1	2	2	4
Adaptability	2	6	2	4	1	2	2	4	1	2	1	2	3	6
Total points		36		17		20		16		19		12		31
Percentage		**100**		**47**		**56**		**44**		**53**		**33**		**86**

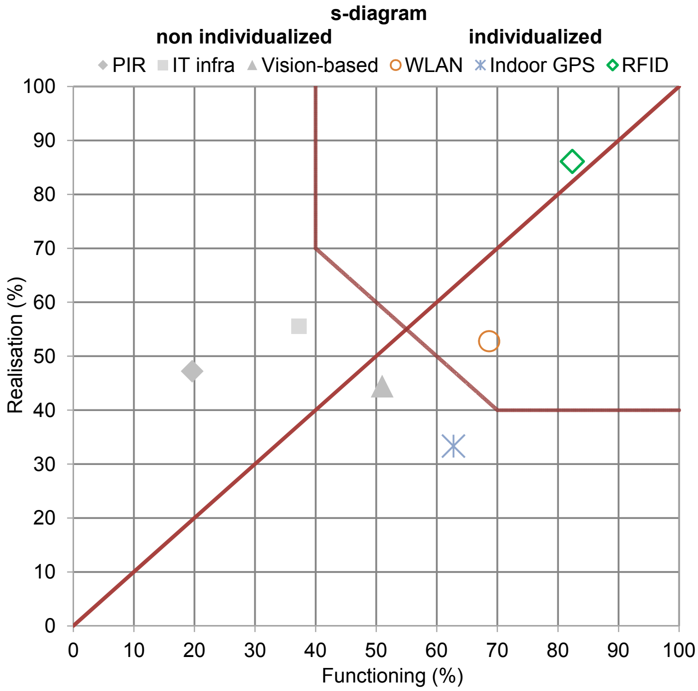


Fig. 3. S-diagram of Kesselring showing the evaluated functional and realization aspect for the different individualized techniques for detection of the user indoor position.

2.6. Radio frequency identification (RFID)

Radio frequency identification (RFID) is an effective technology for indoor localizations[12]. A RFID based occupancy detection system consists of readers, antennae, tracking and reference tags at a frequency of 915 MHz, and a server. The tracking tags are worn by the occupants to denote occupants' locations, and reference tags are deployed in the environment to provide references for location estimation with their own known locations. The readers in the room receive data of both the tracking and reference tags. After that the server retrieves data from the readers, and performs location calculations based on the signal strength. Tests with a dynamic environment a zone level detection rate was found of 76%. This percentage was probably lowered because of the small zones (3x3m).

3. Comparison of indoor localization techniques

The different techniques for detection of the human position are valued on how it functions and can be realized as projected by the Kesselring method. By applying this method singularities are made visible, whereas that in the normal choice tables a bar diagrams only could be retrieved with much effort[36]. The functioning criteria are based on the occupancy resolution divided into occupant, temporal and spatial resolution, as stated by Melfi et al.[27]. These criteria are important to meet the control objective of demand-driven building systems. The realization criteria are: flexibility, reliability, costs, line of sight, implementation, and adaptability. For both the functioning and realization, a weigh factor is added to the score.

Decision support methods are intended to help designers in making decisions. As people are limited in their capacity to process information, evaluation should be conducted in terms of each criterion separately. Subsequently, the values determined have to be aggregated into a score for the 'overall' value of each alternative. Kesselring developed a visualization technique, with which different variants can be compared with each other.

Within the Kesselring method, the criteria for the requirements are separated into a category for realization and a category for functionality. By doing this the strong point can be seen in the so called S-(Stärke) diagram. To visualize the scores the criteria of the program of requirements are separated in groups with relating requirements.

The first group of criteria has to do with the functionality of the design and the other group of criteria with the realization, see table 1.

The realization criteria are: costs, implementation, and adaptability. For both the functioning and realization, a weighting factor is added to the score. Regarding the different techniques, the following can be concluded:

- Non-individualized occupancy detection systems are more often easy to deploy and scalable. However, they score on average less high than the individualized occupancy detection systems. Additionally, these systems can hardly adapt to situations where the monitored zones are virtually partitioned.
- The score in realization of vision-based positioning systems is negatively affected by line of sight obstructions or light conditions (fluorescent lighting or direct sunlight). The problem with the line of sight is even more for the indoor GPS;
- It is shown that RFID techniques has the highest scores for both the functioning and realization criteria, hence is best applicable for sensing the building occupant for HVAC purposes. It is not known if RFID is able to detect the position on the workplace level.

4. Experiment

A wireless sensor network (WSN) based on RFID technique was installed on the case study office floor. Utilizing a low-cost, low power WSN system based on the MyriaModem and MyriaNed[36]. For communication between nodes, the network does not utilize any particular topology but utilizes a gossip mechanism. To accomplish synchronization between wireless nodes without the risk of a separate network evolving, a join mechanism is embedded in the nodes. Through this mechanism all nodes are synchronized. Using the complete third floor of an office building with surface area of approximately 475 m^2, comprising two large open-plan office spaces and 6 cell offices, the possibility to incorporate RFID tags into the operation of the building were studied. The applied system RFID localization system has the following characteristics features:

- The static and mobile nodes are physically the same as depicted in figure 7. The static nodes are programmed with a known location, and mounted on known spots of interest e.g. between the workplaces, nearby the printer, coffee machine and toilet;
- Mobile nodes are attached to occupants to denote occupants' locations, meanwhile the static nodes are deployed in the environment to provide references for location estimation with their own known locations;
- Based on signal strength from the surrounding static nodes, the mobile node takes over the location of the closest static node. The location is sent to the receiver which uploads the ID, time and location to the online cloud;
- This sensor network is a completely self-organizing WSN, meaning nodes need no configuration to form a network where nodes can freely enter and leave existing networks. Thereby the operation of the network never depends on particular topologies or on single nodes. The platform of the WSN is modular designed, meaning all other kind of different sensors and communication modules can be connected to the network.

The wireless static nodes as depicted in Figure 4 for position tracking of the occupants were placed at locations on the floor with high occupant flow and use pattern, such as workspaces, printers and coffee machine location. In total eighteen employees wore a mobile node the six weeks duration of the experiment. Since the interest is on the user, a closer look is made at the workplace level. Figure 5 shows the occupancy rate for four CAD workplaces in zone 22. Figure 6 shows the occupancy rate for four office workplaces in zone 20. A time step of 5 minutes is used.

5. Discussion

The measurements on the case study floor only took place for a period of six weeks in winter period. Firstly this means that the obtained results may only be accounted to this measurement period and secondly they are only valid for this case study floor. Mahdavi[23] already described that results from one building cannot be transposed without extensive calibration measures, considering differences in buildings use. A number of implementation challenges were experienced during the study, besides the issue of privacy of the occupants, the most important being occupants adaption to the use of RFID technology. Occupants at some points forgot to make use of the tags, which equivocally affected the results obtained. The average weighted accuracy of the measurements was 85% over the period of 6 weeks.

Fig. 4. Floor plan with the measured grid in the case study office (orange), formed by 30 static nodes, Floor occupancy hotspots as factor of the most occupied spot during the measured period.

However, further experiments with the use of mobile phones and user identification cards equipped with localization capabilities are been planned for use in further studies. Real-time measurement of actual building occupancy was shown through this experiment to represent a fraction of the standard occupancy profile. Despite the sparse and partial floor occupancy, the installed HVAC system remained operational at full capacity resulting in inefficient use of energy, so there is a potential for energy demand reduction.

5.1. The need for an intelligent, autonomous process control

The need for a more intelligent, autonomous and adaptable system for process control of building operations has lead researchers to explore the use of multi-agent systems in building operations. The concept of intelligent agent technology and designs based on the multi-agent (MAS) paradigm has in the last two decades been the focus of a number of researches and is at an intriguing stage in its development[37]. Very recently, commercial strength agent applications are increasingly being deployed in domains as diverse as manufacturing[38], the electrical power grid[39], transportation[40] as well as for energy and comfort management in the buildings[10]. A MAS system can in general be described using four of its main features - cooperation, autonomy, learning, and decentralized[41]. And in all these domains, these features of MAS have been leveraged upon to optimize various processes.

Building occupancy is generally perceived as a stochastic process, which is difficult to predict[17]. Using a multi-agent based coordination system and a network of wireless sensors, the authors in[6, 10] developed a system that was able to fine-tune the operation of lighting, HVAC and building appliances with actual building occupancy information and user preferences. In another similar study, using building occupancy information and preferences the authors in[4, 42] designed and deployed a multi-agent based system for transactive control of building systems in order to facilitate interactions with smart-grid for demand response programs. These studies also focus on individually aspects of building operations, i.e., energy conservation with very little consideration for occupants comfort. The design of an all-encompassing BECM system should however put into perspective all this various aspects, comfort and energy conservation in relation to all devices and systems composed in the buildings operation.

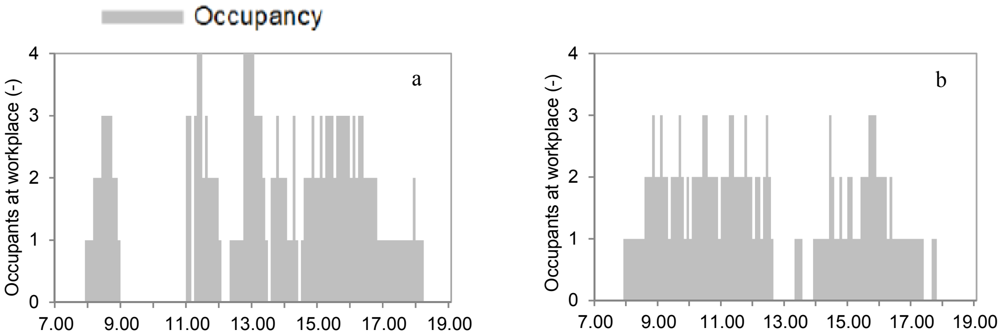


Figure 5: Occupancy of 4 CAD workplaces and electrical load, time step = 5 min

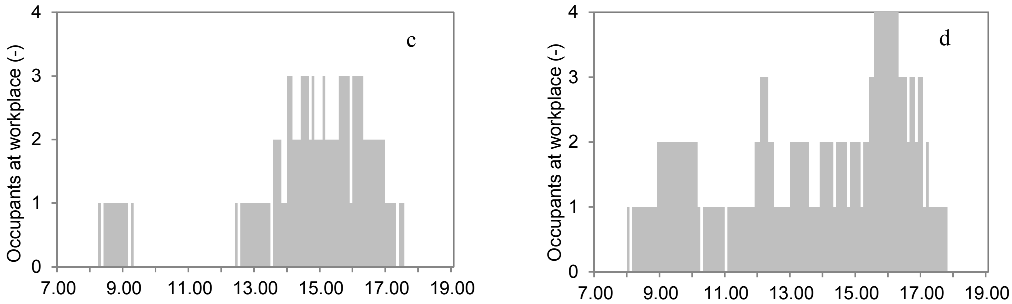


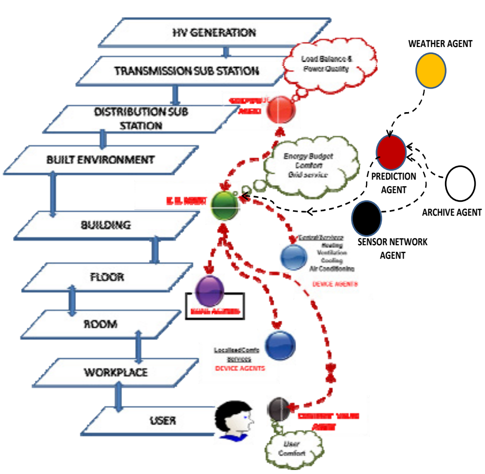
Fig. 6. Occupancy of 4 office workplaces time step = 5 min.

5.2. Multi-agents framework

Yielding a real benefit both in terms of comfort and energy efficiency in buildings is a process that either requires a great amount of human involvement or an intelligent system. The latter should be capable of executing routine (and yet complex) tasks autonomously and on behalf of a user, but without requiring user interaction. This demand for an intelligent, autonomous system is another indicator that points into the direction of agent oriented designs**.** The MAS framework depicted in figure 7 is idealized for implementation in an ongoing study of an office building in Breda, Netherlands. This paper has been written as part of supplementary studies aimed at realizing design of multi-agent based building energy management system. This system will be based on a proprietary traditional BECM system that is currently in use in the building. Ten agents that are hierarchically structured are suggested for the case building. The agents identification and roles are also outlined in Figure 7.The Building Manager Agent makes decision on the basis of a scoring rule. This is set such that any decision that promotes comfort is rewarded for all agents. This borrows greatly from the design structure developed by the authors in[43], which uses a similar system for decision-making in a demand side management scenario for households in a smart grid. Also, the maintenance of operations in a manner that does not go beyond power quantity budgets and conformance to power quality requirements is rewarded. This encourages value based on both comfort and energy performance. The proposed multi-agent framework is largely hierarchical but allows for minimal localised decisions to improve performance.

6. Conclusions and future work

We have presented the concept of value as a basis of negotiating the conflict between comfort demand and optimal energy management in buildings and the local grid. The paper has outlined the multi-agent system framework for use in negotiating value in the interaction between building and the smart grid. Preparation is currently underway to practically operationalize the agents.



Agent	Role
Building Manager	This is the super-agent. It undertakes overall coordination of activities of agents, it's the ultimate enforcer of order. Also tasked with ultimate decision making for comfort & energy management. It's the ultimate value enforcer.
Grid Value	Communicates the effect of building operations on the local grid to the Building Manager Agent. Also communicates quantitative energy and production to the grid SCADA.
Comfort Value	Communicates user comfort preferences to the Building Manager Agent.
Device Manager Local	Coordinates & communicates actual settings of locally installed services installations, such as lighting, radiator panels and plug load activities to the Building Manager Agent.
Device Manager Central	Coordinates, communicates actual settings & load profiles of centralised installed services installations, such as lighting, boilers, HVAC Controls, Humidifiers to the Building Manager Agent. Also coordinates & communicates energy generation profiles to the Building Manager Agent.
Zone	Communicates zonal environmental conditions to the Building Manager. Aggregates energy requirements at workplace, room and floor level installation to the Building Manager Agent.
Prediction	Predicts energy production and load profiles in several time frames (10 minutes, 1 hour, 3 hours, 1 day, 3 days) then communicates the results to Building Manager Agent.
Sensor Network	Communicates measurements on equipment set-points, operation conditions and ambient environment to the Building Manager Agent and Prediction Agent.
Archive	Communicates archive data from sensor network to the Prediction Agent to improve accuracy of prediction.
Weather	Undertakes basic analysis of prevailing weather parameters and communicates them to the Building Manager Agent.

Fig. 7. Agent Framework.

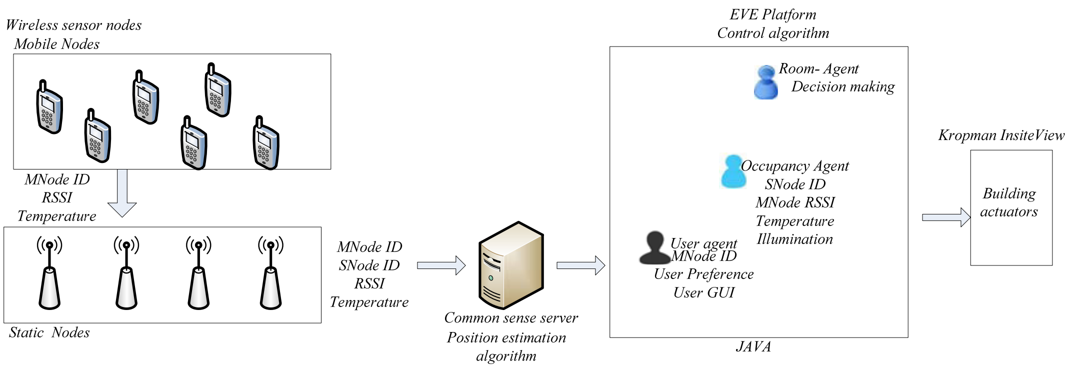


Fig. 8. Concept future test setting Kropman Breda.

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