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Bayesian Belief Networks (BBN) and Expert Systems for supporting model based sensor fault detection analysis of smart building systems.

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Abstract

The Hague University in Delft uses an advanced climate control system. All sensors and actuators are monitored and deviations from the sensor data are reported daily. The building manager will have to combine the information from the sensor data in order to draw the right conclusions. In this paper, two possible solutions are described for analyzing the data by a computer program. The first solution is by means of a rule-based program, in which predetermined situations have been defined. The data from the sensors are fed into the program and the program checks whether it matches any of the situations. The second solution is to make use of a Bayesian Belief Network. This is a mathematical model that describes the symptoms and causes of a particular problem. With imported sensor data a computer program calculates the likelihood of particular causes of data symptoms.

Keywords: Bayesian Belief Networks, Expert System, HVAC system, sensor fault detection

1. Introduction

Modern smart building systems are equipped with many sensors as information source for the HVAC systems. The combination of data from these sensors can be used for analyzing and detection of faulty sensors. The proposed framework for the sensor fault detection was tested on the building of The Hague University of Applied Science (THUAS) in Delft. This building was selected for the research because this building has a complex HVAC system with an advanced control system and extensive measurement data is available for analyzing the sensor values and the indoor climate. In the rooms of the building cold and heat is delivered by a floor heating system and by ceiling panels in which water is circulated. The ventilation flow rate to the rooms is demand-controlled based on occupancy and the CO_2 level. The building contains mainly classrooms and offices for the lecturers as well as a restaurant. Every room is equipped with a number of sensors: CO2, temperature, humidity, occupancy (PIR), light, ventilation rate, ventilation valve position, window open/close. The sensor data are stored in the production database since the opening of the building in august 2009.

The sensor system was installed by Octalix and the data from the sensors of the building is monitored by software from Octalix [MyBuilding]. The building manager uses MyBuilding for real-time analysis of the sensors, investigation of the current state and adaption of parameters, for instance the temperature setting of an individual room. Additionally a report is produced on a daily basis [MonaVisa] for the building manager with a summary of the outliers in the data. It proves to be difficult to analyze these data in order to find undesirable situations, due to lack of time and knowledge of the HVAC system in detail. In practice action is undertaken when inhabitants complain about the climate or the lights in their rooms.

In this paper we propose an alternative way of analyzing the data and come up with possible causes of the symptoms. One option we investigated was a rule-based program, also called Expert program, because the program tries to mimic the knowledge and reasoning of an expert in the field. The knowledge, in the form of a set of predetermined situations, was the basis of a program written in C++. Data from the building is fed to the program in order to find the undesirable situations. A second solution was developed based on Bayesian Belief Networks (BBN), one of us [1] describes the use of BBN methods for analyzing the energy consumption in the same building.

2. Expert System

The data were retrieved from the historical database for a period a 2 months before and after the occurrence of the investigated case. From an analysis of the data of the first 2 months it is possible to define the 'normal' situation. Each day only those measurements were used during the opening time of the building. The minimum and maximum value of the sensor data are calculated as well as the total occupancy time in hours. The average and standard deviations are calculated, and then the values are normalized to a timeframe of one hour by dividing the standard deviation by 1 + the number of hours of occupancy in the room. When the CO_2 values are above 1400 ppm, this is stored separately, as well as when the temperature is above 22 degrees C. Every following day is added to this list and compared with the 'normal' situation. When deviations are found, the situation is compared with a list of predetermined situations.

In table 1 a number of predetermined situations are given. The sensors which contribute to a situation are marked with a √. A question mark '?' indicates that the sensor is not involved in the definition of that situation. In order to distinguish between an empty room (no occupancy) and a situation where the PIR-sensor is defect, the program uses the data from the nights to define the state of an empty room (see column F in table 1).

Table 1. predetermined situations

	A	B	C	D	E	F
PIR	√	√		√	√	
Air	√	√			√	
Lights	√	√		√	√	
Temp	√		**?**		**?**	√
Temp high		√	**?**	√	**?**	
CO2 normal	√				√	√
CO2 high		√	√	√		
CO2 constant					√	
	normal situation	too many people in the room	PIR sensor defect	ventilation defect	CO2 sensor defect	room not in use

The program was tested on a situation in a small meeting room. As can be seen from figure 1 in the period until 20 April the ventilation was on average 80 m3/h and CO2 levels are around 800 – 1000 ppm. In the next period the ventilation is low (15 m3/h) and the CO2 levels are high (above 1500 ppm). The lights were off in that period, but that is not unusual for a room with a window to the South side of the building. From the analysis of the graph it became clear that in this situation the PIR sensor is not working (situation C).

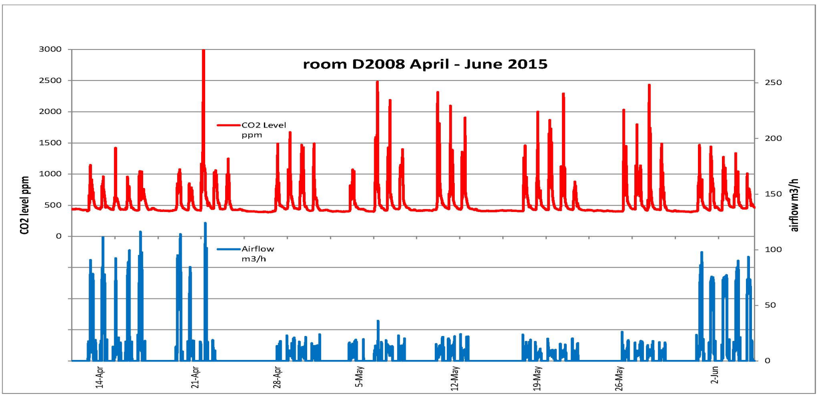

Figure 1. room D2.008 April – June 2015

The same data were fed into the Expert program, the results are summarized in table 2.

Table 2. results Expert system

Room D2.008					
Day	1	2	3	4	5
	13-apr	14-apr	15-apr	28-apr	night
CO_2 ppm:					
Max.	1143	962	1418	1490	480
Min.	405	433	424	400	400
Average	620	585	564	634	440
Stdev.	168,0	145,1	167,4	257,3	19,0
Occupancy (hour)	10,0	9,0	7,4	0,0	0,0
Normalized result.	15,3	14,5	19,9	257,3	19,0

Days 1, 2 and 3 are examples of the 'normal' situation, the figure 'Normalized result' is between 15 and 20. For comparison the night situation is also given in table 2 with the same normalized result. On day 4, April 28, one can see that the min, max and average values do not distinguish this situation, but the calculation of the standard deviation shows an indication that this is an extraordinary situation, as is the normalized result. This result combined with the other sensor values indicates situation C from table 1, PIR sensor probably broken, see figure 2.

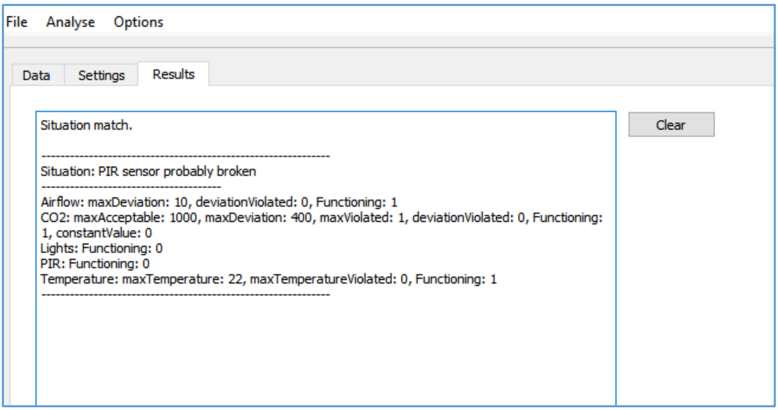

Figure 2. output of the Expert system for situation C

As an example of situation B from table 1: 'too many people in the room' the next graph is given (figure 3)

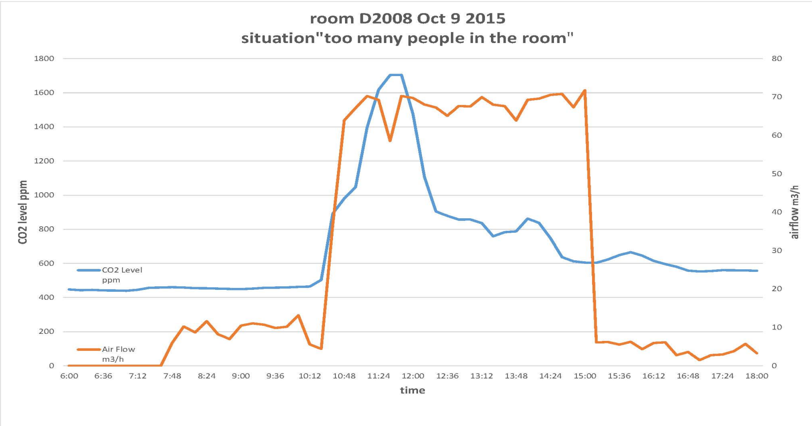

Figure 3. room D2.008 October 9 2015

Situation B (figure3) with too many people in the room (CO2 high above 1400 ppm, ventilation working 75 m3/h, temperature above 23 degrees C, lights on, PIR signal ok). The maximum ventilation in this small meeting room is approximately 75 m3/h, which is enough for an occupancy of 2 or 3 persons. In this case probably 4 or 5 persons were present in the room.

3. Bayesian Belief Networks

Another way to tackle this problem is the use of a Bayesian Belief Network (BBN) [3]. If there is an unwanted comfort situation in a room in the building we must try to find the cause of the problem. The symptoms we observe can be related to different causes. A BBN is a mathematical model which can handle all the causes and symptoms of system. Bayesian theorem is used for calculating conditional probabilities. As an example for the relation between the probability of a defect ventilation V and the probability of a high CO2 signal C can be given as:

$$P(V|C) = \frac{P(C|V)P(V)}{P(C)} \tag{1}$$

The probability of a non-functioning ventilation, given a high CO2 value equals the probability of a high CO2 value given a non-functioning ventilation, multiplied by the probability of a non-functioning ventilation and divided by the probability of a high CO2 signal. A further extension can be made when we introduce a temperature sensor.

A high temperature can be a symptom of a non-functioning ventilation, but a high CO2 value can also be a symptom. The probability of a non-functioning ventilation given a high CO2 value and a high temperature is given by:

$$P(V|CT) = \frac{P(C|V)*P(T|V)*P(V)}{P(CT)} \quad (2)$$

Table 3. probabilities

	V	C	T	Total
	P(V)	P(C|V)	P(T|V)	V*C*T
V	0.3	0.9	0.7	**0.189**
!V	0.7	0.3	0.1	**0.021**
Combined probability: high CO2 value and high temperature P(CT) =				**0.21**

According to Bayes theorem P(V|CT) can be calculated: 0.189 / 0.21 = 0.9. In other words there is a chance of 90% of a non-functioning ventilation in case there is a high CO2 value and a high temperature, see situation D in table 1. The BBN definition of the system at the THUAS we used in this work is given in figure 4.

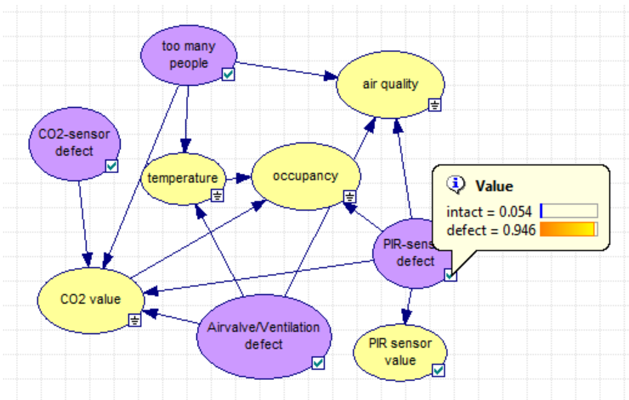

Figure 4. Bayesian Belief Network

In figure 4 the GeNIe program has calculated that the probability of a defect PR-sensor equals 0.946, given the situation: poor air quality, high temperature, high CO2 and no occupancy in the room.

The different probabilities were defined in meetings with HVAC experts of the building of THUAS. The sensor data were input to a Bayesian belief system of the building, and is built in the GeNIe software environment.

4. Results

Both the Expert System and the BBN systems were used to investigate a number of cases of malfunctioning sensor systems in the building by using the historical data. The Expert system was able to find disturbances in several rooms, and could indicate the most plausible cause. The same data were fed to the Bayesian system, and analysis results in early detection of anomalies in the functioning of the HVAC system.

5. Discussion

BBN methods are based on rules and expert reviews and also require fine tuning with data, which is often a challenge. The rules for the Expert System (the predetermined situations) are based on the same rules as for the BBN system. The statistical analysis of the data as done with the Expert system seems to be comparable with the results of the BBN system.

6. Conclusion

The Expert system and the BBN system give comparable results with the historic data. The methods described in this article are now being used to analyze and learn from the historical (5 years) database.

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