# A QUALITATIVE MODELING APPROACH FOR FAULT DETECTION AND DIAGNOSIS ON HVAC SYSTEMS

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## ABSTRACT

This paper describes the basics and first test results of a model based approach using qualitative modeling to perform Fault Detection and Diagnostics (FDD) on HVAC&R systems. A quantized system - describing the qualitative behavior of a dynamical system - is established by transforming numerical inputs into qualitative values or states. Then, the qualitative model is used to determine system-states or outputs that may occur in the future. The qualitative model determines the probability that a subsequent condition might occur. The model can then be used for FDD purposes by comparing the expected states of the faultless system with the occurring states of the real process. The paper presents the first results of the model, trained with measurement data of an air handling unit (AHU) heating coil. The authors plan to extend the model to further AHU components and to test them against real data to assess their performance for FDD and their economic viability in terms of engineering efforts and costs by comparing them with a rule-based FDD system. It is then planned to implement and test the models on several large HVAC&R systems operating at two major European airports in the framework of the FP7 European project "CASCADE ICT for Energy Efficient Airports".

## INTRODUCTION

Large amounts of energy up to 30 % are currently wasted in commercial buildings due to insufficient maintenance, faulty equipment, wrong schedules or control loop setups. A significant part of this energy could be saved by the practical implementation of automated Fault Detection and Diagnosis (FDD) to support a condition-based maintenance (Katipamula and Brambley 2005). Although big research efforts have been carried out in the last two decades, there are only very few commercially available FDD tools for heating, ventilation, air conditioning and refrigeration (HVAC&R) systems which are emerging on the market. The aim of the FP7 European project CASCADE is to develop an ISO 50001 Energy Management System (EMS) supported by FDD for HVAC&R systems and to implement and test it in two major European airports Milan Malpensa and Rome Fiumicino. The ISO 50001 EMS enables energy managers to define energy conservation objectives associated with concrete measures, responsibilities and deadlines. Operation and Maintenance (O&M) tasks in airports are particularly challenging due to the building and plant sizes, the system complexity and the high comfort and security requirements. Furthermore, the energy consumption of airports facilities for heating and cooling is very high and cost intensive amounting to several hundreds of GWh yearly. The application of new tools for standardized energy management tasks and for the automated detection and identification of suboptimal plant operation is shown by the authors as a necessity to support airport energy managers. Figure 1 shows an overview of FDD methods using qualitative modeling approaches according to a classification established by (Katipamula and Brambley 2005).

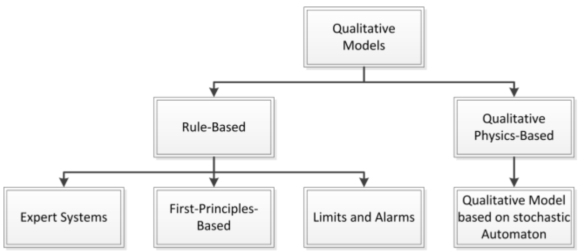


Figure 1: Classification of qualitative modeling approaches, based on (Katipamula and Brambley 2005)

It should be noted, that the classification of qualitative models is not uniform in the literature. Other classifications are described by (Venkatasubramanian et al. 2003a) and (Isermann 2006).

Rule-based FDD systems represent a straightforward method to detect faulty energy operations on simple systems and subsystems. They are based on "If-Then-Else" rules relying on thermodynamic first principles, expert knowledge of the system functions and control strategies and limit checking. Those approaches reach their limits with the raising complexity of the systems that may cause a combinatory explosion of rules. The FDD systems are then difficult to handle and to update when the plants are being modified or retrofitted. As mentioned by (Venkatasubramanian et al. 2003b), rule-based FDD methods do not rely upon a detailed description of the system physics and therefore cannot detect faulty system states if the conditions for their occurrence are not defined in the rule set. The advantage of the qualitative modeling approach is that the model is abstracted from a quantitative physics based model and thus includes the knowledge about the fundamental behavior of the system. This paper presents the principles of a qualitative modeling approach and a concrete implementation case that the authors carried out. The qualitative model is based on a stochastic automaton whose theoretical background has been described by (Lichtenberg 1998) and (Schröder 2003).

## USING A QUALITATIVE MODEL FOR FDD

The qualitative modeling approach can be used for FDD purposes of quantized systems. A quantized system uses quantizers to transform numerical inputs into qualitative values or states. Thus, a quantized system describes the qualitative behavior of a dynamical system (Lichtenberg 1998). Figure 2 shows how a qualitative model can be embedded for FDD.

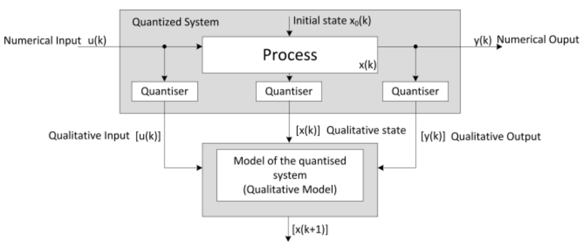


Figure 2: Quantized system, based on (Supavatanakul et al. 2002)

Quantization means reduction of information. Therefore the amount of information that needs to be processed by the qualitative model is reduced (Schröder 2003). Figure 3 shows the quantization of a continuous-time and continuous-variable signal into a quantized signal. The value of the quantized signal can have a symbolic character like "high" or "low".

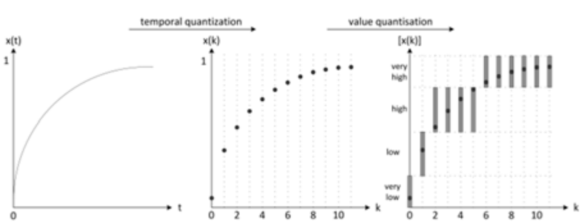


Figure 3: Signal quantization, based on (Schröder 2003)

A qualitative model based on a stochastic automaton can be used to determine system-states or outputs that may occur in the future. This prediction is based on the supervision of the current states, inputs and outputs of the system. The stochastic automaton determines the probability that a subsequent condition occurs. The design of a qualitative model for FDD is realized as follows:

- Construct a quantitative model of the dynamic process that describes the faultless behavior of the system.
- Thereof, abstract a qualitative model based on a stochastic automaton that describes the system "as rough as possible and only as precise as necessary" (Schröder 2003). The qualitative model can also be identified by using the measurement data of the real process (Lichtenberg 2011). The prerequisite therefor is that the system runs in a faultless mode under nominal conditions.
- Use the qualitative model for determining the transition probabilities and successor states of the faultless system.
- A comparison between the occurring states of the real process and the calculated expected states of the faultless system can be used to detect and to diagnose faults in the system.

### Advantages of the Qualitative Modeling Approach

In contrast to other FDD methods the qualitative modeling approach offers some notable advantages:

- Reduction of information: due to the quantizers the information flow is pared down. The amount of data to be processed by the qualitative model is correspondingly lower than by other methods. This affects positively the computational expense and the computing time (Schröder 2003).
- Low complexity in contrast to rule-based approaches: Rule-based methods include a large set of if-then-else clauses and these sets grow rapidly with the behavioral complexity of the system (Venkatasubramanian, Rengaswamy et al. 2003b).
- The qualitative model can be applied to incompletely known systems or to systems whose inputs or initial states can be measured only roughly (Lunze 1998). For example, many values are often not measureable and therefore it is only known whether they are "too high" or "too low". In this case, a precise quantitative model can not be applied because the actual state or the input value of the system is not known (Lichtenberg and Lunze 1996).
- Based on the structure of the qualitative model, the observation algorithm of the process can be applied under real-time conditions (Lichtenberg and Lunze 1995).

However, the approach also has drawbacks as the necessity to develop a model of the system to be supervised which can be time consuming. Furthermore, systems with many physical states lead also to a combinatory explosion of the state space of the automaton. But in contrast to rule based systems it is not necessary to define new rules. Only the computing time will increase. It should be noted that it is necessary to subdivide complex systems into several subsystems. Afterwards a qualitative model of each subsystem has to be abstracted and linked as an automata network that can then be transferred into an equivalent single automaton, describing the qualitative behavior of the whole system (Schröder 2003).

## APPLICATION

In a first step the authors tested the qualitative modeling approach on the heat exchanger (HEX) of an AHU including a heating coil, a pump and a 3-way mixing valve (see Figure 4). A precise model of the HEX has been generated using the simulation environment Modelica®/Dymola®. The algorithms for the qualitative modeling are written in the Python™ language. The model of the HEX takes into account all possible system states that can occur in the real process and describes a faultless operation.

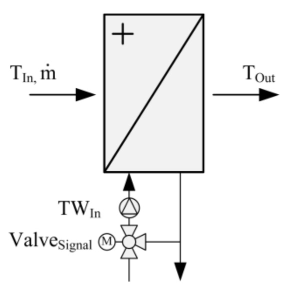


Figure 4: Generic HEX scheme

The qualitative model of the HEX is then abstracted after having established the physical model of the HEX. A preliminary condition is to ensure that the chosen partition boundaries of the state-, input- and output space are precise enough to describe the systems fundamental behavior. In order to reduce the complexity of the system, it is recommended to define the smallest possible number of qualitative states, inputs and outputs.

The first FDD tests carried out with the qualitative model are aiming to identify potential weaknesses of the HEX and to diagnose following faults that might occur:

- Too low or too high air outlet temperature
- Too low or too high temperature spreads
- Faulty valve positions or valve-leakage
- Faulty operating state of the pump
- Wrong operation times

## FIRST RESULTS

With regard to figure 4, the air outlet temperature $T_{Out}$ of the HEX was defined as a state value. The other values like air inlet temperature $T_{In}$, air mass flow rate $\dot{m}$, water inlet temperature $TW_{In}$, and the valve signal were defined as inputs or outputs. The state space was divided into four partitions, the input and output space into two partitions.

Figure 5 shows the four partitions of the state space over a chosen time period of three days. Each partition represents one automaton state. Thereby, the partition with the number "1" means that the air outlet temperature of the HEX has a high value. Partition 4 means, that the temperature is low. The different gray shades represent the probabilities. A dark color means that there is a high probability that the temperature is in the respective qualitative state.

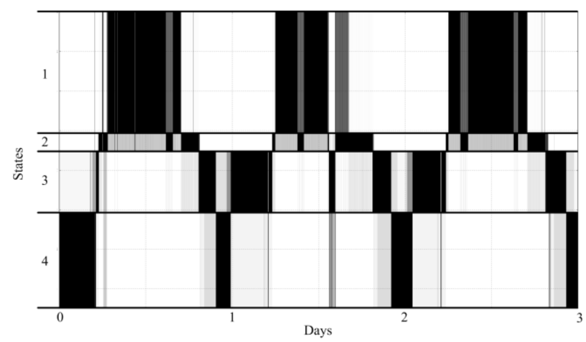


Figure 5: Result of the qualitative model

Figure 6 shows a graphical combination of the result of the qualitative model and the numerical output of the quantitative model. The occurrence probabilities of system states predicted by the qualitative model match very well the numerical output of the quantitative model.

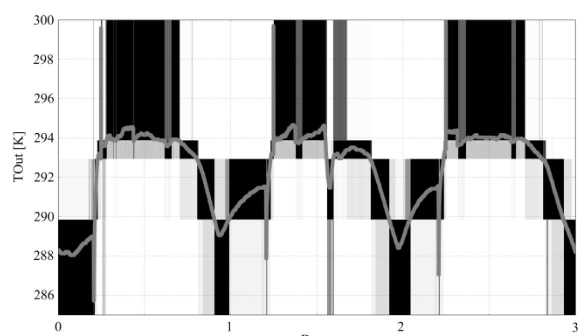


Figure 6: From the qualitative model predicted probabilities and quantitative simulation output of $T_{Out}$.

The results shown in Figure 5 and 6 are based on the simulated faultless behavior of the HEX. This information about the faultless system can then be used to detect a faulty operation. Thus, the probabilities, which include all possible combinations of states, inputs and outputs of the faultless system, can be compared with the measurement data of the real system as shown in in Figure 7. One can see that from time stamp 0.7 on the abscissa axis the temperature profile does not coincide with the states which are predicted by the qualitative model with a high probability. This suggests that the heater is in a faulty condition.

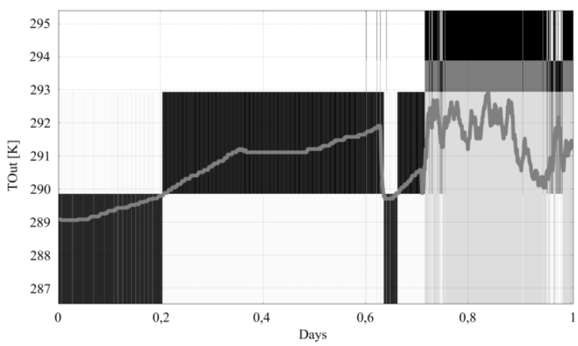


Figure 7: Faulty condition of the HEX

In the treated case, the qualitative model only allows for the detection of a wrong operation of the heater but not the diagnosis of the fault. The faulty condition shown in Figure 7 is based on a wrong operation time: the ventilator of the AHU was turned off while a hot water mass flow supplied the heating coil due to a faulty position of the heating coil valve. This fault was diagnosed by analyzing the quantitative data manually. It must be noted that the diagnosis of a fault by the qualitative model requires additional investigations.

## FURTHER INVESTIGATIONS

The authors aim to extend the qualitative modeling of the heater to further subsystems like the pump, the valve and water loop system temperatures to allow automated diagnostics of subsystems involved in a faulty operation. In general, the qualitative modeling approach can also be extended to many HVAC&R systems like chillers, AHUs or water loops. The authors pretend to extend the implementation to different HVAC&R systems put at their disposal by the CASCADE project. To this end, heating circuits and AHU's of selected zones at the Milan Malpensa and the Fiumicino airports will be selected.

Finally, both qualitative modeling and rule-based approach will be compared in terms of implementation and development efforts, accuracy of the FDD results and the transferability to further building services.

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