Commissioning and Fault Detection of HVAC Systems by Using Simulation Models Based on Characteristic Curves

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In order to reduce the energy demand in the field of heating, ventilation and air conditioning many efforts have been made during the last decades. HVAC-components used nowadays are much more advanced than those used years ago. The success of the energy saving endeavors becomes even more apparent if the controlling devices, and there especially the implementable controlling strategies, are put in the center of view. In former times the controlling appliances in HVAC-systems consisted of analog devices which were relatively inflexible in regard to varying controlling strategies. Nowadays the HVAC-appliances are controlled by digital "systems". These systems enable building operators to run a building - and its HVAC-systems - with sophisticated controlling strategies which can be adapted to the needs of the occupants and to the use of the building. Further on, it is possible to use these devices for monitoring the building performance without much additional efforts.

Commissioning is done to ensure that systems are operating in the way they are designed for. But in opposition to the described improvements on the system level the practice of commissioning has not changed throughout the years. In the following it will be shown that the traditional commissioning methods are overcome. Therefore, a different approach for commissioning will be presented. Further on, a detailed description of the basic tools used in this approach is given. These tools have been developed at the University of Stuttgart.

1 Traditional Commissioning at Advanced HVAC-Systems

Commissioning in the field of HVAC can be defined as a supervising process which has to ensure the proper installation *and* the correct operation of building systems like specified in the planning phase. But ever since the very beginning of using air conditioning systems in buildings commissioning has been done "on-side". In Germany it has been limited mostly to functional checks of single components and to few measurements in order to test the overall performance of a system at full load conditions [1] (see Figure 1). In addition to that usually it is checked if the HVAC systems provide comfortable conditions.

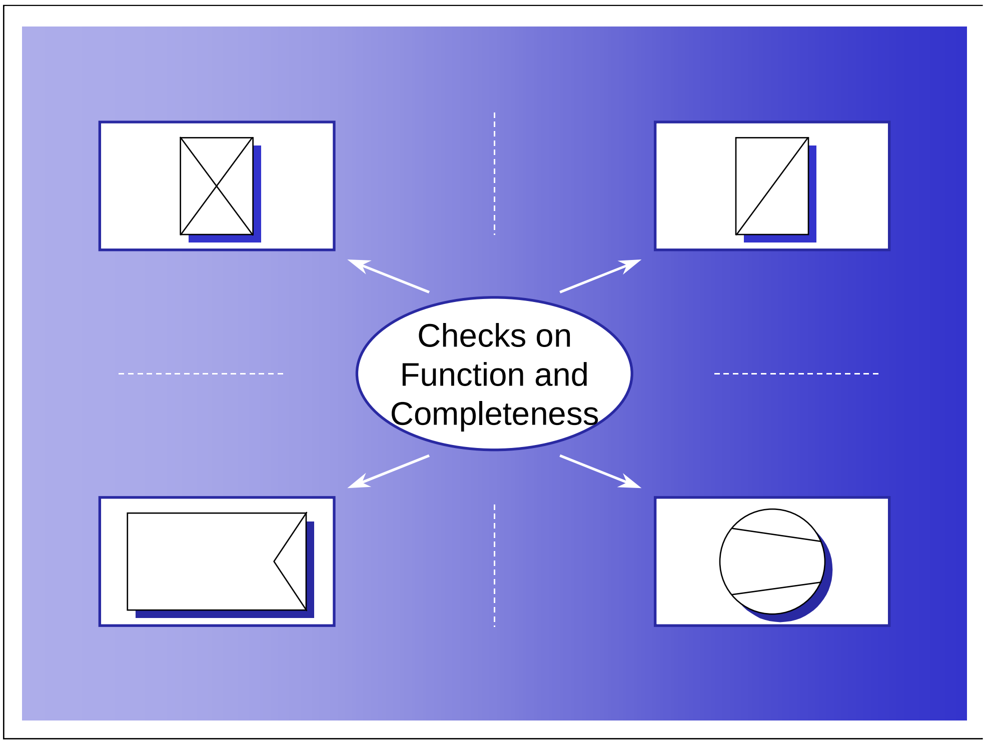


Figure 1 : Traditional commissioning

The methods and procedures of traditional commissioning have shortcomings, especially when they are applied to complex HVAC-systems with sophisticated controlling strategies. First to mention at this, is the fact that HVAC systems are running most of the time under partial load conditions. Therefore, traditional commissioning tools - which are usually applied under full load conditions - can only ensure the correct operation of a system for a small fraction of all possible operating conditions. This implicates in particular that control strategies which are implemented for energy saving purposes cannot be tested.

Another lack of todays commissioning tools is the fact that functional checks are only applied to single components of a HVAC system. But correct operating components do not ensure the proper operation of a whole system. The meaning of this circumstance becomes more obvious if it is taken into account that there are multiple interactions between single components as well as chain reactions in system which are caused by sophisticated controlling strategies used in todays building systems. The term “chain reaction” means that one system figure can be influenced by different control signals and that itself again can affect several other control signals. For example at a VAV-system the room temperature υ_R is a function of the zonal air volume rate V and the zonal supply air temperature υ_{supply} ($\upsilon_R = f(V, \upsilon_{supply})$). The supply air temperature υ_{supply} itself again might depend on the control signals of a heating coil γ_{HC}, a cooling coil γ_{CC}, a heat recovery system γ_{HRS} as well as of an outside air mixing box γ_{MB} ($\upsilon_{supply} = f(\gamma_{HC}, \gamma_{CC}, \gamma_{HRS}, \gamma_{MB})$).

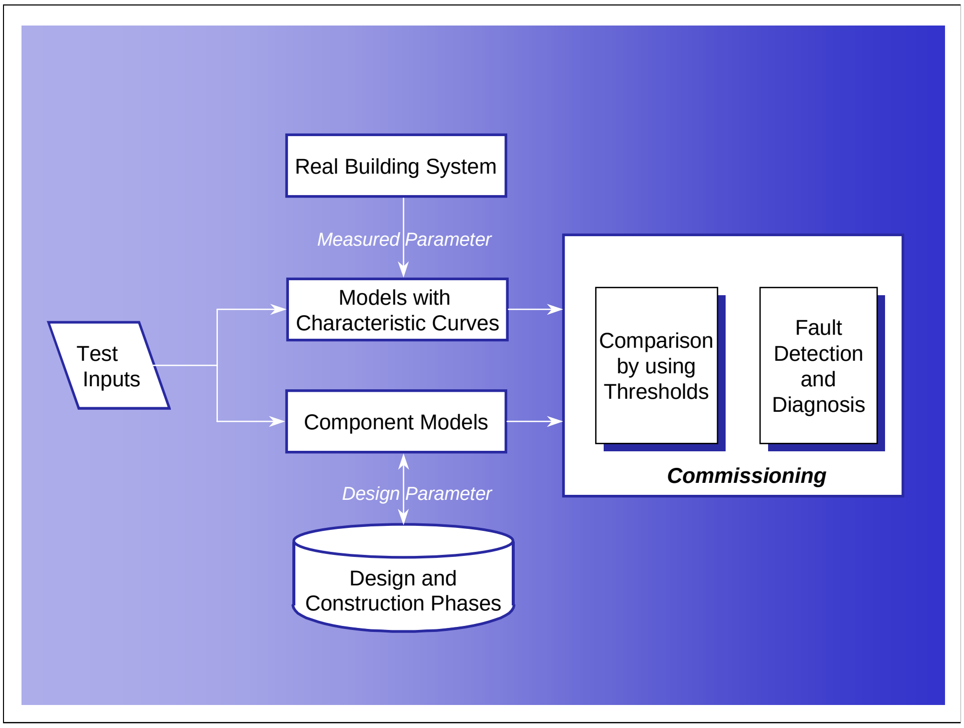
The simple check of comfort conditions can be another drawback since no check on the energy consumption is performed in parallel. Comfortable conditions can be obtained even with controlling systems which don't work in the way they are designed for. Usually this circumstance results in an higher energy usage of the system.

2 New Approach for Commissioning

Because of the above mentioned drawbacks of the traditional commissioning procedures which especially take effect in sophisticated, modern building systems a new approach for commissioning has been developed based on the work in Annex 25 of the IEA [2,3]. One advantage of this approach is that not all of the commissioning work has to be done on-side anymore. It can be done off-side, e.g. in a planning office. The main advantage is the fact that a building system will be commissioned as a whole. The approach is outlined in Figure 2. For the new commissioning method basically two simulation models are used.

The first simulation model is generated interactively during the planning and construction phases of a building. Alternatives in design and construction are tested with this simulation model throughout these phases and kept in there if they are realized at the real building. Therefore this simulation model emerges in parallel to the real building. Basically it consists of previously validated component models which are mostly based on the physical behavior of the correlating real components. In the simulation the physical connections between the single components (ducts, pipes, etc.) and the links in the system due to the controlling devices (e.g. the influence of a sensor on a component) are laid out in a way so that the system topology of the real building

Figure 2: New Commissioning Approach



is represented as exact as possible.

In opposition to that the second simulation model which is needed for the new commissioning approach is generated by using component models which are based on *Characteristic Curves* [4]. One major assumption of the characteristic curves approach is that the processes in HVAC-components are nearly stationary. This means that the real components can be imagined by curves which characterize their behavior in steady state conditions. To generate these models it is assumed that the characteristic curves can be obtained with sufficient accuracy by using the following equation:

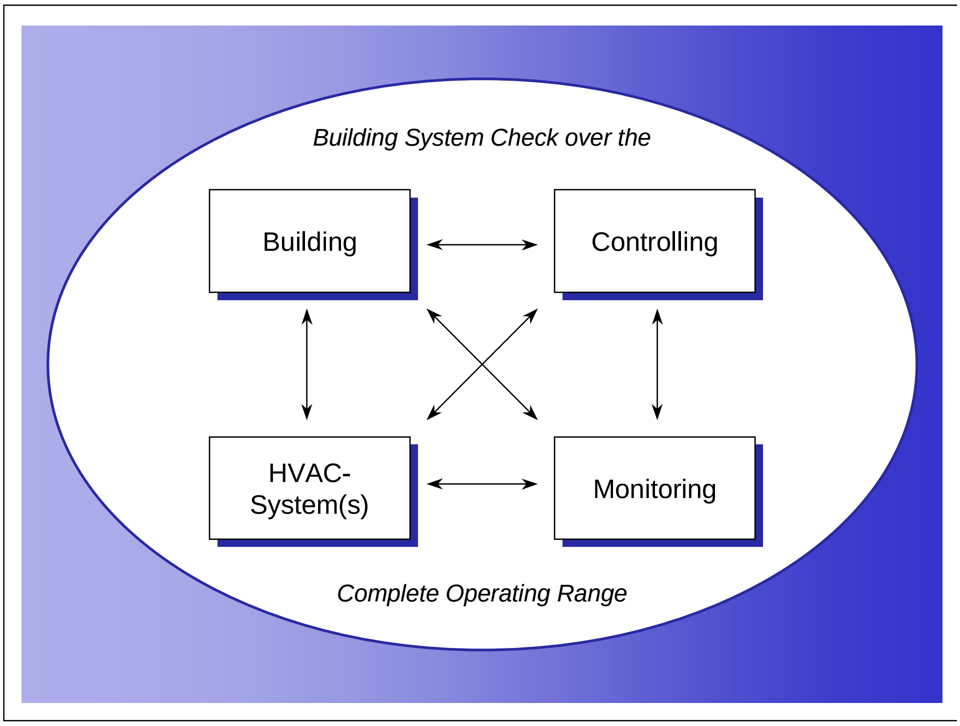
$$z\,(x,y) = c_1 x^2 + c_2\, x + c_3\, x\, y + c_4\, y + c_5\, y^2 + c_6$$

For heat exchanger e.g., the variable z could represent the efficiency whereas *x* and *y* could be replaced by the mass flow rates of the two media running through it. The parameters c_1 to c_6 are the characteristic values of the components. These parameters can be determined by getting measured values for *x*, *y* and *z* at six different operation conditions of the component. Such a set of measurement points provides a linear equation system which can be solved easily. For the measurements it is necessary to make sure that they cover operating conditions over the whole operating range of the considered component. Otherwise the models might perform poorly.

For the commissioning itself the mentioned measurements will be performed on every component of the real heating and ventilation system. Connections between the single components and between the subsystems as well are carried out in the same way as they are found in reality. In this way it is possible to obtain at least the general behavior of the installed system.

For commissioning the same test input data are entered into both simulation models (see Figure 2). The resulting output data of the models will then be compared by using thresholds. This thresholds are necessary since a model can never be as exact as the real component. Additionally there is always a standard deviation in the measurements for the characteristic curve models. The real building system complies with the design if the differences between the two models are within given thresholds. The comparison of the two data flow already takes

Figure 3: Commissioning of a Building System as an Entirety



place in the FDD-tool. In the case that there are faulty components or even faults in the system design the test inputs will produce threshold violations in the output data. In this case the threshold violations will be detected within the FDD-tool. In this tool it will also be checked what kind of fault has occurred. The structure of the FDD-tool is described in the following section in more detail. With the new approach it will be possible to test building systems over their whole operating range since it is not bound to boundary conditions like e.g. the outside temperature or specific load conditions. Therefore, even sophisticated controlling strategies within the systems can be checked. In opposition to the traditional approach, where only single components are tested, it will be possible to test building system as an entirety (see Figure 3).

3 The FDD-Tool Used for Commissioning

The fault detection and diagnosis tool which will be used in the new commissioning approach is a knowledge - and rule -based system. It is built in a modular way in order to keep it as generic - i.e. independent of devices - as possible [5]. Basically, there are two main modules within the FDD-system - one for the fault detection and one for the fault diagnosis.

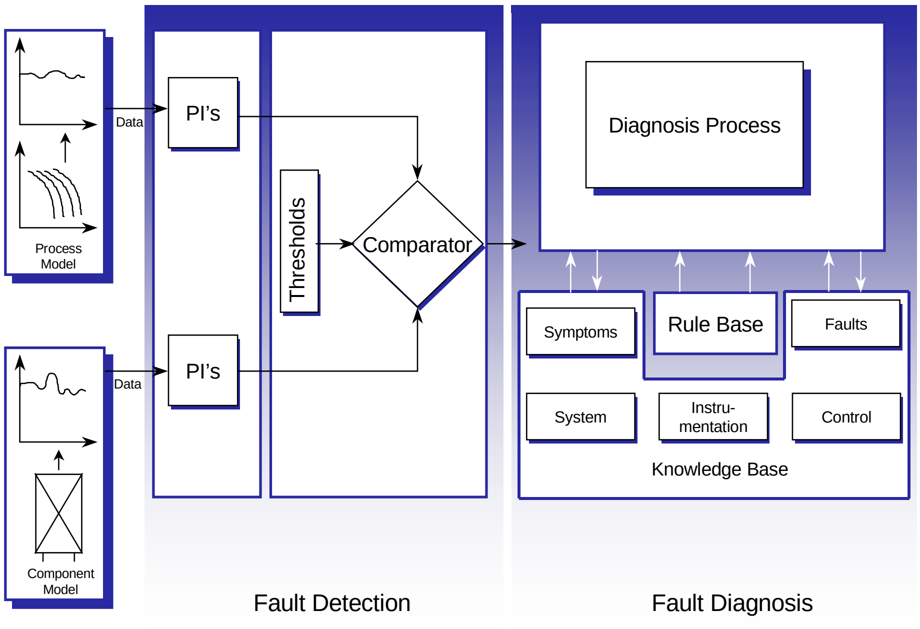


Figure 4: IKE-FDD-Tool for Fault Detection and Diagnosis

The inputs of the fault detection module consist of two data flows (see Figure 4). At first there are the output data of the component model which is generated during the design and construction phase. These data are used as a reference. The second data which enter the fault detection module are the data produced by the process model of the real system (characteristic curves). The information contained in both data flows is “concentrated” by generating so called *Performance Indices* (PI) within this module. PI are characteristic values which are generated out of one or several process variables or out of time series of them. The corresponding PI of both data flows are put into a *Comparator* module. With the comparator it is checked whether the differences between the Pio btained from the two models are within the above mentioned thresholds or not. If a threshold violation is detected the second main module of the FDD-tool - the fault diagnosis module - is activated. There it is determined which kind of fault has occurred and where in the building system it is located.

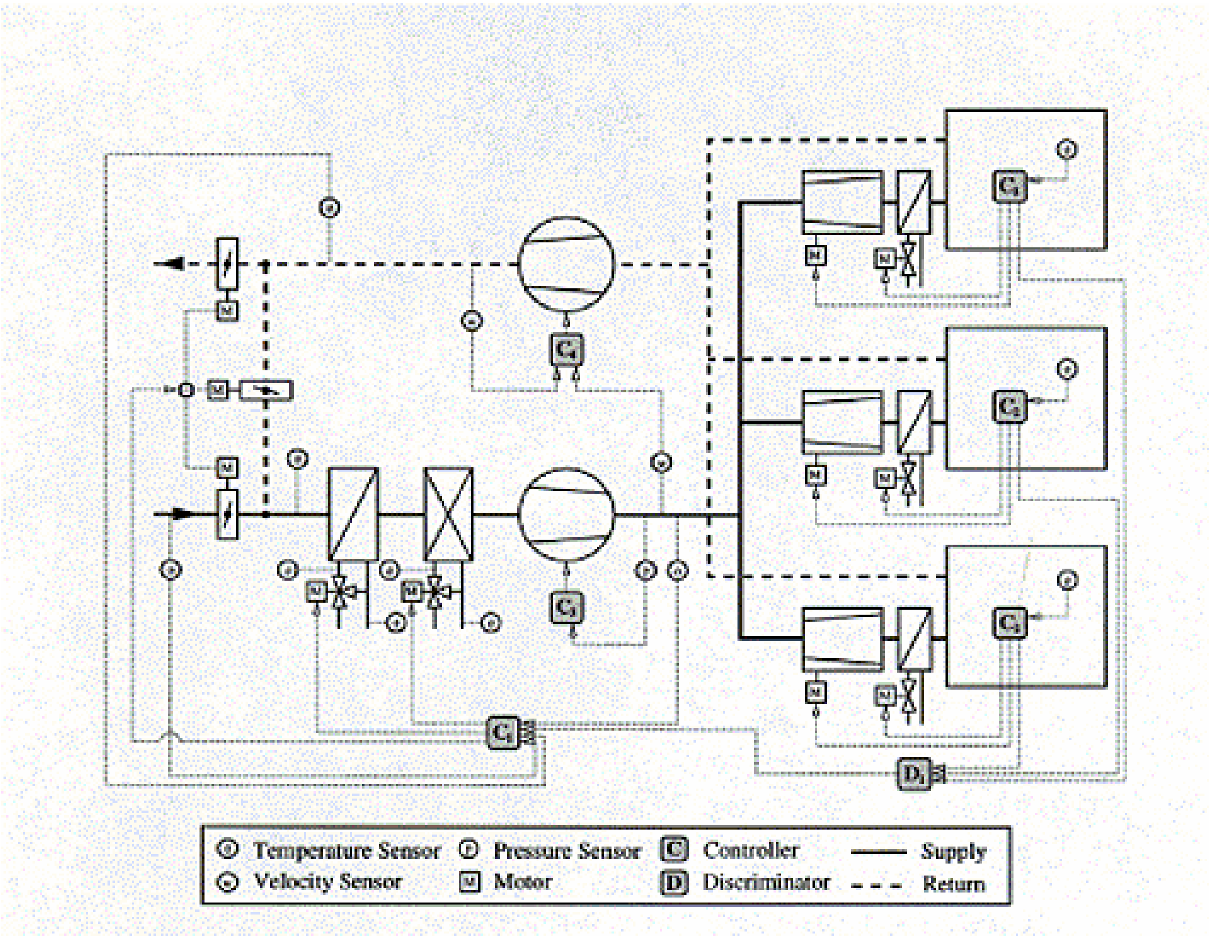


Figure 5: Scheme of the AHU at which the FDD-tool was tested

The diagnosis process within the fault diagnosis module is based on a knowledge base and on a rule base. The knowledge base contains general informations about possible symptoms and how they are related to faults (see Tables 1 - 5). But it also contains more specified information about the topology of the commissioned system, its instrumentation with sensors and especially about the controlling strategies which are used in it. The rules contained in the rule base control the diagnosis process. They can be divided in rules related to the diagnosis process itself, to single components, to faults and to symptoms.

4 Examples for the Application of the FDD-Tool

The FDD-tool has already been tested on an air handling unit in the AHU exercise # 2 of the IEA Annex 25 [6] in order to evaluate and proof its general applicability. In the following this test will be reviewed under the aspect of the new commissioning approach. Certainly this cannot be a validation of the described new commissioning approach, but it will show that the approach will result in a better performance of building systems. To demonstrate the validity of the approach it is needed to do a commissioning on a real building system. After further validation of the FDD-tool this will be the next step.

In the AHU exercise # 2 different data sets of an VAV air handling unit (see Figure 5) were provided. One data set which was defined as fault free served as reference. Therefore, this set can be considered as the so called component model which would be generated during the design and construction phases (see section 2) - in the new commissioning approach. Three other provided data sets contained unknown faults. These sets were used to get the sets of “measurement points” of different operating conditions in order to generate the characteristic curve models.

The pictures in the Figures 7 and 9 are directly taken from the output of the FDD-tool by screen-grab, which unfortunately results in a minor quality. In all pictures the trends of the considered values respectively the PI from the reference model and from the faulty model are shown. Additionally the trend of the difference between both models is included in all pictures but one. The trend of the differences is negative if the values for the faulty conditions are higher than the reference values.

4.1 Case 1: Fouled Cooling Coil

The first data set (Case 1) contained a fouled cooling coil. In Figure 6 the characteristic curves for the coil effectiveness are shown for the unfaulty and the faulty data set. The fouled coiling coil is represented by the lower curve, whereas the upper, smoother curve represents the fault free coil. In order to visualize the faulty conditions the curve for the faulty operation is determined by taking the values of the coil effectiveness $\square_{CC}$, the supply air volume rate V_{supply} and the valve position $C_{cooling}$ at the water circuit of the cooling coil at six different operating points. Therewith the characteristic values of the above mentioned characteristic equation are obtained for the faulty conditions. The values shown in Figure 6 are related to maximum possible values and therefore in percent. The difference between desired and actual operation can clearly be seen. In regard to commissioning it can be said that it is probably most unlikely that a built in cooling or heating coil is already fouled. But it is quite possible that an installed coil does not meet the design requirements (e.g. by too low performance). Faults of this kind will be become visible with the new approach in the same way. An insufficient coil performance for example can only be detected under full load conditions with traditional commissioning methods if there are no other devices which can compensate the lack of performance.

4.2 Case 2: Stuck damper of a mixing system

With the second case of exercise # 2 it can be shown that it is possible with the new approach to detect faults which don't affect comfort but cause energy waste. In this case a damper of the mixing system at the inlet of the AHU got stuck. In Figure 7 the trends of control signals of the mixing system C_{mixing} and the cooling coil $C_{cooling}$ as well as of the return air temperature T_{return} are shown.

There is almost no difference between the return air temperatures between both models despite of the faulty mixing system as it can be seen in the picture on the right hand of Figure 7. The pictures in the middle and on the left hand side of the same figure indicate that there are exactly then differences at the cooling coil when the demand at the mixing box is higher than under normal conditions. The AHU therefore maintains comfortable conditions in the zones as required but it uses more energy than needed.

4.3 Case 3: Degradation of a temperature sensor

The fault which occurred in the third case is a degradation of the supply air temperature sensor which measures too high. It is very difficult to detect this kind of fault since it is not directly related to any component. That means checking the single components will not show the defect of the sensor. Even observing the whole system during operation does not lead to the faulty sensor because the VAV-boxes at the zones compensate the wrong supply air temperature. Therefore the required zone conditions are still reached. This facts can be seen in the pictures of Figure 8. Therein it is shown that the zone temperature $T_{zone,1}$ only differs within a very small range compared to the reference case. The differences of the control signal for the reheat coil $C_{reheat,1}$ and of the zonal supply air volume rate $V_{supply,1}$ become effective almost exactly in opposite direction as the differences of the measured supply air temperature T_{supply} (see Figure 9). Therefore energy is wasted similar to case 2.

In this case the fault could only be detected by the fault diagnosis system. Within this tool the observed symptoms like increased cooling demand, different settings for the mixing system (see Figure 9) or the already mentioned differences at the VAV-boxes were connected to the fault. For this connection process the controlling strategies were considered as well. This would not have been possible with traditional commissioning methods.

5 Conclusion and Perspectives

The work presented in this paper shows that fault detection and diagnosis techniques based on characteristic curves will be very useful in the described new commissioning approach. Tests with the FDD-tool of the University of Stuttgart indicate that using FDD-methods will improve commissioning. Especially faults which don't have an effect on the provided comfort but cause an increased energy consumption will be detected. The new commissioning approach will give the possibility to test a system over its whole operating range and at critical operating conditions independent of actual boundary conditions (e.g loads, outside temperature, etc.). Therefore, the new commissioning approach will help to ensure an energy efficient operation of new buildings.

Simulations are applied more and more during the design and planning process. These simulations can be used as the reference models for the commissioning if they are adjusted to the real building during the construction phases. At integral planning processes this this is done anyway which means that there's not much additional work needed in order to get the reference models for the new commissioning approach. Further on it is possible to use the FDD-tool during operation as well.

References

[1] VDI-Richtlinie 2079, Abnahmeprüfung an RLT-Anlagen, VDI-Verlag GmbH, Düsseldorf, March 1983

[2] Hyvärinen, J. \& Kärki S. (eds.), Source Book IEA Annex 25: Building Optimisation and Fault Diagnosis, Technical Research Centre of Finland, Espoo, Finland, August 1996

[3] Bauer, M. \& Madjidi, M., IKE Objectives for a New IEA Annex, Working Paper at the IEA Annex 25 Meeting in Paris, April 1996

[4] Madjidi, M., Beitrag zur modellbasierten Überwachung und Optimierung des Betriebes heiz- und raumlufttechnischer Anlagen, Universität Stuttgart, Dissertation, 1996

[5] Bach, H. et al., Entwicklung eines Systems zur Erkennung und Diagnose von Fehlern beim Betrieb von HLK-Anlagen, IKE, Universität Stuttgart, December 1995

[6] Grob, R.F., Anwendung des IKE-Systems zur Erkennung und Diagnose von Fehlern beim Betrieb von HLK Anlagen, Diplomarbeit, Universität Stuttgart, 1996

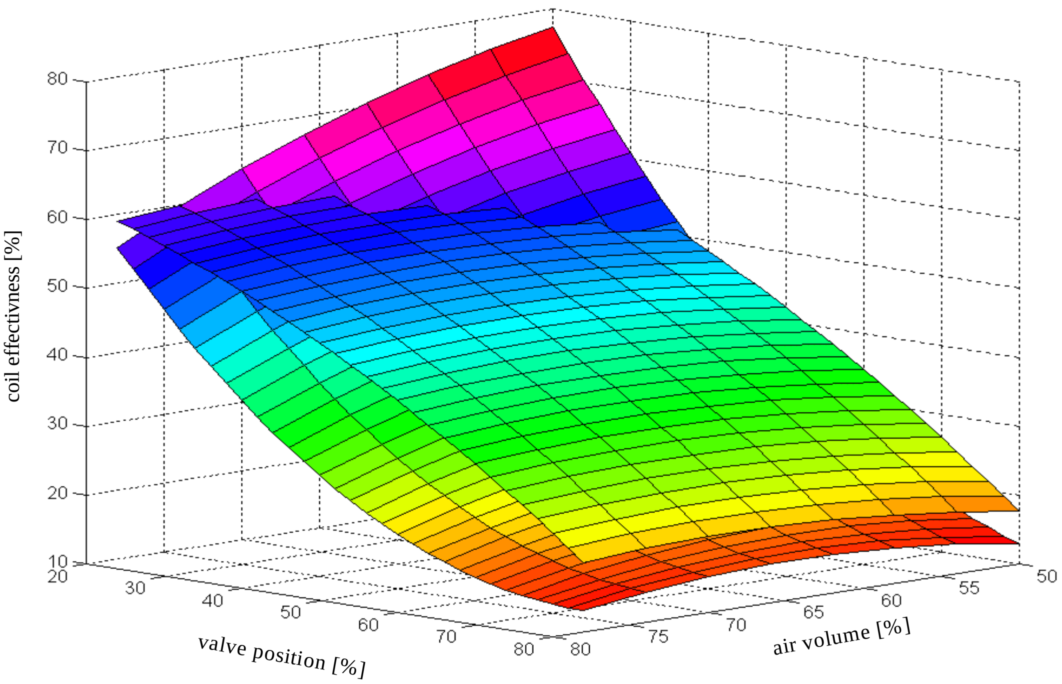


Figure 6: Characteristic Curves of the coiling coil in case 1

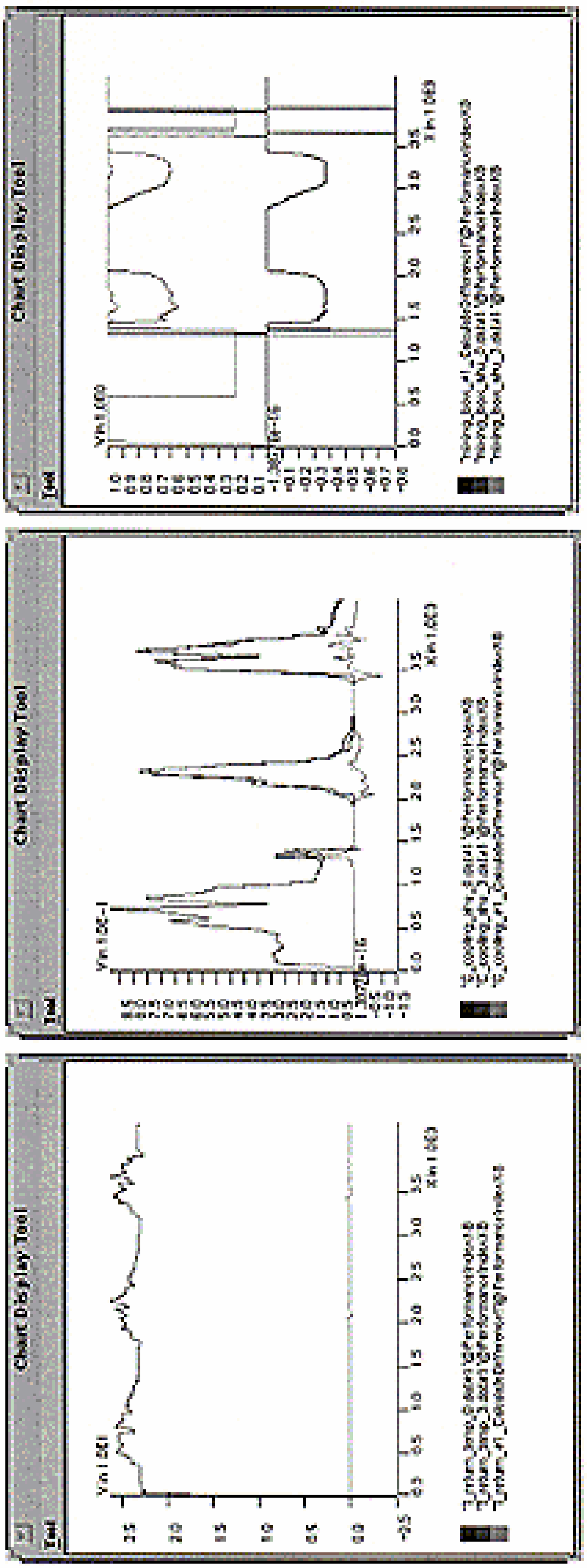


Figure 7: Trends for C_{mix}, $C_{cooling}$ and T_{return} in Case 2

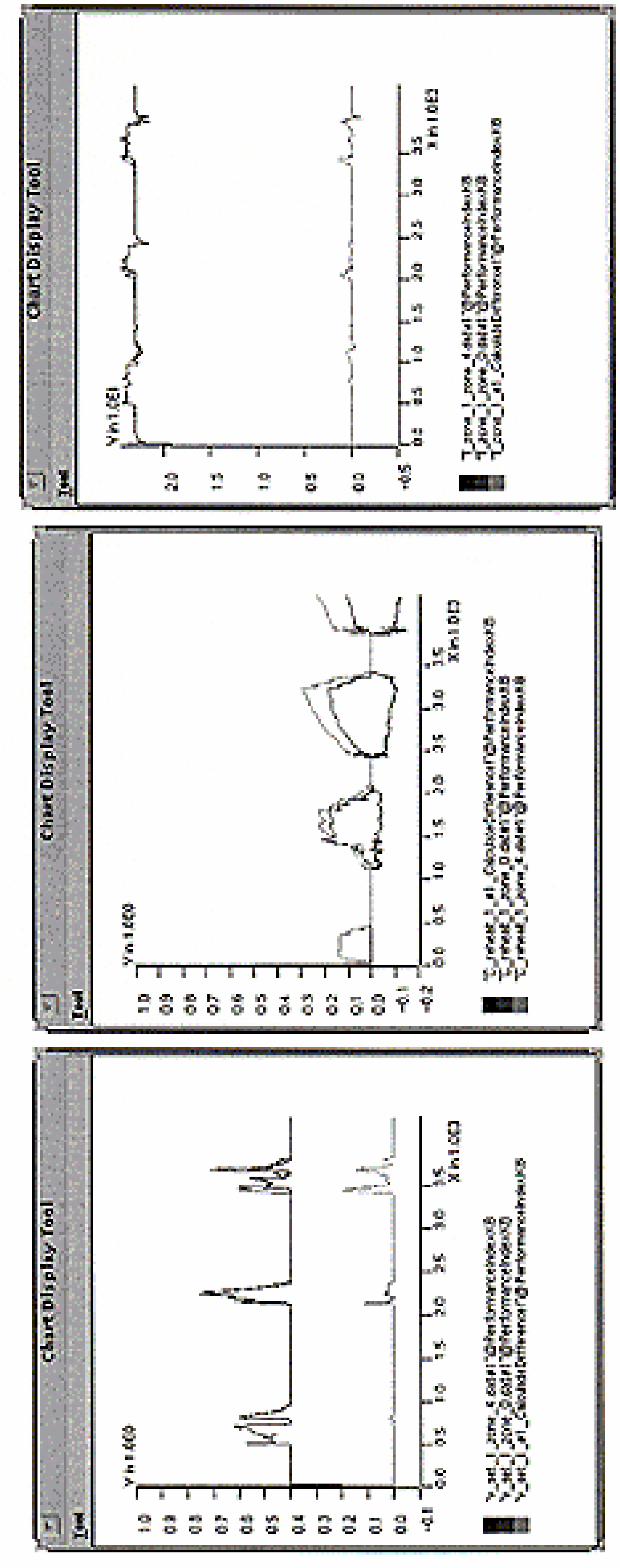


Figure 8: Trends for $T_{zone,1}$, $C_{reheat,1}$ and $V_{supply,1}$ in Case 3

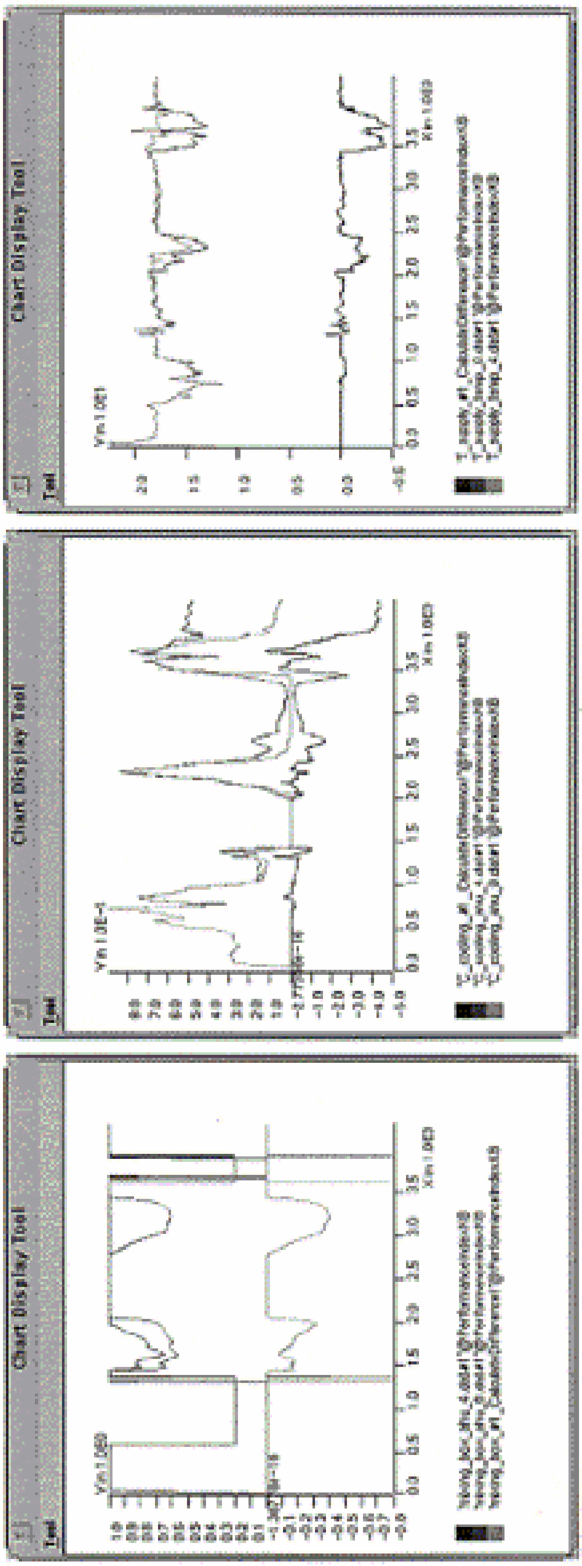


Figure 9: Trends for T_{supply}, $C_{cooling}$ and C_{mix} in Case 3

Table 1: Symptom-Fault Relations for the PI C_{mix}, $T_{mix,cal}$ and $C_{cooling}$

	Faults	1. AHU cooling coil fouled	2. One of the VAV box dampers stuck in fully open position	3. AHU fresh air temperature sensor degradation		4. AHU cooling coil water valve stuck at a position		5. AHU supply air temperature sensor degradation		6. AHU fresh air damper stuck at a position		7. Drifting of the supply pressure sensor	
Devices	**Symptoms**			measures to low	measures to high	below reference position	above reference position	measures to low	measures to high	below reference position	above reference position	measures to low	measures to high
C_mixing	too low during mixing mode				X			X			X		
	too high during mixing mode			X			X		X	X			
	decreasing during mixing mode												
	increasing during mixing mode												
	constant during mixing mode	X										X	X
	changing during mixing mode												
	delays in switching mixing and cooling modes			X	X			X	X				
ΔC_mixing	decreasing												
	increasing			X	X			X	X				
	constant												
	changing						X			X	X		
T_mix,calc	too low				X						X		
(compared to T_mix,measured)	too high			X						X			
	decreasing												
	increasing												
	constant												
	changing												
ΔT_mix,calc	decreasing												
	increasing			X	X								
	constant												
	changing									X	X		
C_cooling	too low in non-mixing mode				X		X	X			X		
	too high in non-mixing mode	X		X		X			X	X			
	decreasing												
	increasing	X											
	constant												
	changing												
ΔC_cooling	decreasing												
	increasing	X		X	X			X	X				
	constant												
	changing					X	X			X	X		

Table 2: Symptom-Fault Relations for the PI Q_{cool}, $T_{W,2}$ and Φ_1

Faults		1. AHU cooling coil fouled	2. One of the VAV box dampers stuck in fully open position	3. AHU fresh air temperature sensor degradation		4. AHU cooling coil water valve stuck at a position		5. AHU supply air temperature sensor degradation		6. AHU fresh air damper stuck at a position		7. Drifting of the supply pressure sensor	
Devices	**Symptoms**			measures to low	measures to high	below reference position	above reference position	measures to low	measures to high	below reference position	above reference position	measures to low	measures to high
Q_cool	too low	X			X	X		X			X		
	too high			X			X		X	X			
	decreasing	X											
	increasing												
	constant					X	X						
	changing			X	X			X	X				
ΔQ_cool	decreasing												
	increasing	X		X	X			X	X				
	constant												
	changing					X	X			X	X		
T_water,2	too low			X		X			X	X			
	too high	X			X		X	X			X		
	decreasing												
	increasing												
	constant					X	X						
	changing												
ΔT_water,2	decreasing												
	increasing			X*	X*			X*	X*				
	constant												
	changing									X	X		
Φ	too low	X											
	too high												
	decreasing	X											
	increasing												
	constant												
	changing												
ΔΦ	decreasing												
	increasing	X											
	constant												
	changing												

Table 3: Symptom-Fault Relations for the PI v_{supl} and T_{supl}

Devices	Symptoms / Faults	1. AHU cooling coil fouled	2. One of the VAV box dampers stuck in fully open position	3. AHU fresh air temperature sensor degradation: measures to low	3. measures to high	4. AHU cooling coil water valve stuck at a position: below reference position	4. above reference position	5. AHU supply air temperature sensor degradation: measures to low	5. measures to high	6. AHU fresh air damper stuck at a position: below reference position	6. above reference position	7. Drifting of the supply pressure sensor: measures to low	7. measures to high
T_supply,set	too low					X		X					X
	too high						X		X			X	
	decreasing												
	increasing												
	constant												
	changing												
ΔT_supply,set	decreasing												
	increasing							X	X				
	constant												
	changing					X	X						
C_damper	too low						X		X			X	
(all zones)	too high					X		X					X
	decreasing												
	increasing												
	constant												
	changing												
ΔC_damper	decreasing												
(all zones)	increasing							X	X				
	constant												
	changing					X	X					X	X
C_reheat	too low					X		X					X
(all zones)	too high						X		X			X	
	decreasing												
	increasing												
	constant												
	changing											X	X
ΔC_reheat	decreasing												
(all zones)	increasing							X	X				
	constant												
	changing					X	X						
C_damper	too low		X				X		X			X	
(one single zone)	too high					X		X					X
	decreasing												
	increasing												
	constant												
	changing												
ΔC_damper	decreasing												
(one single zone)	increasing							X	X				
	constant												
	changing					X	X					X	X

Table 4: Symptom-Fault Relations for the PI $T_{supl,set}$ and C_{damper}

Faults		1. AHU cooling	2. One of the VAV box	3. AHU fresh air temperature sensor degradation		4. AHU cooling coil water valve stuck at a position		5. AHU supply air temperature sensor degradation		6. AHU fresh air damper stuck at a position		7. Drifting of the supply pressure sensor	
Devices	**Symptoms**	coil fouled	dampers stuck in fully open position	measures to low	measures to high	below reference position	above reference position	measures to low	measures to high	below reference position	above reference position	measures to low	measures to high
C_reheat	too low					X		X					X
(one single zone)	too high		X				X		X			X	
	decreasing												
	increasing												
	constant												
	changing												
ΔC_reheat	decreasing												
(one single zone)	increasing							X	X				
	constant												
	changing					X	X					X	X
T_zone	too low												
(all zones)	too high												
	decreasing												
	increasing												
	constant												
	changing												
ΔT_zone	decreasing												
(all zones)	increasing												
	constant												
	changing												
T_zone	too low												
(one single zone)	too high												
	decreasing												
	increasing												
	constant												
	changing												
ΔT_zone	decreasing												
(one single zone)	increasing												
	constant												
	changing												
Zones	one zone has a different behaviour than the other ones regarding damper and reheat valve settings		X										
	all zones have the similar different behaviour regarding damper and reheat valve settings							X	X			X	X

Table 5: Symptom-Fault Relations for the PI C_{reheat} and *Zones*

Devices	Symptoms / Faults	1. AHU cooling coil fouled	2. One of the VAV box dampers stuck in fully open position	3. AHU fresh air temperature sensor degradation		4. AHU cooling coil water valve stuck at a position		5. AHU supply air temperature sensor degradation		6. AHU fresh air damper stuck at a position		7. Drifting of the supply pressure sensor	
Devices	**Symptoms**			measures to low	measures to high	below reference position	above reference position	measures to low	measures to high	below reference position	above reference position	measures to low	measures to high
v_supply	too low						X		X				X
	too high		X			X		X				X	
	decreasing												
	increasing												
	constant												
	changing					X	X						
Δv_supply	decreasing												
	increasing							X	X				
	constant												
	changing					X	X					X	X
T_supply	too low						X						
in non-mixing mode	too high					X							
	decreasing												
	increasing												
	constant												
	changing												
ΔT_supply	decreasing												
in non-mixing mode	increasing												
	constant												
	changing					X	X						
in mixing mode	too low						X						
	too high					X							
	decreasing												
	increasing												
	constant												
	changing												
	follows T_supply,set							X	X				
ΔT_supply	decreasing												
in mixing mode	increasing												
	constant												
	changing					X	X						