A METHOD FOR ANALYSIS OF CONTROLLABILITY OF DUCT SYSTEMS DESIGNED FOR VARIABLE VENTILATION FLOW RATES

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ABSTRACT

This paper presents a tool, based on a method using IDA for simulation of duct systems and MATLAB as a pre- and post-processor, to study the controllability of VAV-systems. The focus of this paper is on how the data created during the simulations are analysed and how criteria matrices are used to determine the grade of controllability of the systems. The method is tested on a set of different system configurations and the result shows that it, as a whole, appears to be viable. Furthermore, there is a discussion about how MATLAB and IDA are used as an integrated part of the method.

INTRODUCTION

This paper is about a tailored tool, developed to study controllability of duct systems designed for variable ventilation flow rates. When studying a problem using simulation, a lot of data is created. It is important to develop tailored tools to be used together with the simulation environments to administrate and analyse all that data. Today, a number of simulation environments such as TRNSYS, HVACSIM+, and IDA are available, suitable for performing simulations of various aspects of ventilation duct systems.

A few studies about the use of simulation in the study of controllability of VAV-systems can be found in the literature. Haves (1994), presents a detailed description of models usable for the study of different aspects of controllability. In a more recent paper (Haves 1995) he presents a simulation environment developed to support the study of control algorithms. The paper indicates the use of a utility program to create boundary files. The use of MATLAB as an analysis tool is also suggested. ASHRAE 825-RP (1997) presents a testbed for evaluation of control strategies. This report describes models useful for simulation and briefly discusses some measures of controllability.
All three papers indicate a need for a more straightforward method for studying the controllability and they all indicate some parts that will be needed in such a method.

The method suggested in this paper is based on four parts: building a model of the duct system to be analysed, simulation of the performance of the duct system using different kinds of events, analysis of the data created through the simulations, and finally evaluation of the degree of controllability.
The focus of this paper is on the analysis and evaluation parts of the method, since it is the discussion and conclusions from these parts that determine how the simulations must be performed. This discussion is supported by a number of simulations of different duct systems. The models of the systems are built using IDA Modeller (Sahlin, P, 1993) to connect individual components found in a library. The library consists of models written in the Neutral Model Format (NMF) (Sahlin, P, 1996), (Sahlin, P, Bring, A, Sowell, E.F, 1996). The simulations are performed, by using IDA Solver (Sahlin, P, Bring, A, 1991). To be able to automatize the process from modelling to evaluation, a simple MATLAB (Math Works 1996) program was developed. When using the program the administration and analysis of all created data is simplified.

METHOD

To analyse the controllability of VAV-systems, a clear and straightforward method is needed and requested. If such a method is based on simulations of the air distribution system, it must be structured to handle the large amount of data collected. To support such a method, a tool was developed consisting of following four parts.

1. Project set up (To support the collection of information needed to understand the project a long time after its completion).
2. Modelling and simulating different kind of events (Using the IDA simulation environment).
3. Analysis (Calculation of key numbers to be used during the valuation).
4. Valuation (Supported by criteria matrices).

The frame program to handle these parts of the method is based on the graphical interface of MATLAB.
For this specific project controllability is defined as *Ability to keep the controlled variable within a specific interval without more wear of the equipment, or consumption of resources, than is needed to fulfil the desired control activity*.
When using this definition, four questions become evident:

1. To what extent is the VAV system able to keep the room temperature in a given range?
2. To what extent do disturbances originating in one part of the system propagate to other parts?
3. How great is the wear of the components?
4. How much energy does the fan consume?

A VAV-system used for temperature control of a room must be able to handle the following three events:

1. Change of internal heat gain.
2. Change of room temperature set point.
3. Change of supply air temperature.

Data collected from simulations involving changes in these three events must be analysed using a method that provides answers to the four questions raised. The instructions for calculation of each criterion used are:

1. To what extent is the VAV system able to keep the room temperature within a given range?
- Study the data collected during the simulations of the events “Change of internal heat gain” and “Supply air temperature”. Calculate the mean difference between room air setpoint and actual temperature over the simulated period (Criterion: temperature 1).
- Study the data collected during the simulations of the event “Change of room temperature set point”. Calculate the settling time (Criterion: temperature 2).
- Study the data collected during the simulations of the event “Change of room temperature set point”. Calculate the rise time (Criterion: temperature 3).

2. To what extent do disturbances originating in one part of the system propagate to other parts?
- Study the data collected during the simulations of the events “Change of internal heat gain” and “Room temperature set point”. Calculate the maximum amplitude of the signals to the controllers. Summarise the results for all controllers, excluding the controller of the room in which the event takes place (Criterion: interaction 1).
- Study the data collected during the simulations of the events “Change of internal heat gain” and “Room temperature set point”. Calculate the mean difference between the end value, and actual value of the signals to the controllers during the simulated period. Summarise the results for all controllers except the signal to the controller of the room in which the event takes place (Criterion: interaction 2).

3. How great is the wear of the components?
- Study the data collected during the simulations of all three events. Calculate the total distance travelled for all dampers in the system (Criterion: distance).

4. How much energy does the fan consume?
- Study the data collected during the simulations of all three events. Calculate the energy consumption (Criterion: energy).

The use of these criteria for evaluation of control performance is discussed in ASHRAE 825-RP (ASHRAE 1997). The report indicates that the performance of individual control loops can be studied using criteria such as overshoot and integral error squared. Wear of equipment can be evaluated using the total distance travelled.

The large number of events and criteria studied leads to a large amount of data to be analysed. This implies full automation of the analysis. It is necessary to condense the results to a few descriptive numbers, which will be discussed in the next section.

A frame program serving as a pre- and post-processor has been developed to administrate the simulations. The text files describing different events are created using the frame program, "MATLAB-IDA VAV Control Analysis tool". Each button and submenu on the graphical interface shown in figure 1 calls a single MATLAB function. This makes it easy to change the individual parts of the program. Modelling and simulation are performed in the IDA simulation environment, using a library of components developed for this application (Eriksson 1998). All the models in the library are formulated in the NMF format, which makes them compatible with other simulation environments. Models of duct systems are built using IDA-Modeller, which is also used for the initial simulations. The intermediate IDA file containing the model of the system is modified using the project handler of the "MATLAB-IDA VAV Control Analysis tool". The actual simulations are run from the frame program, using IDA Solver as standalone.

Criteria matrices (figure 2) are useful for condensing the values of each criterion to one number that can be used when comparing the different systems. The final valuation value is calculated as the sum of the three events. The values of the different criteria are calculated according to an assessment description.

The assessment is then multiplied by the weight allocated to the criterion. It is also possible to allocate weights to the different events. The valuation is subjective since the same set of systems can be ranked differently when looking at results from different valuations. The result depends on the performer of the valuation and what aspects are most important in a certain situation. The assessment description used in this study is quite uncomplicated. The total range of observed values is converted to grades in the interval, 1 to 9. The mean value for each criterion was calculated and used as grade (*G*) number 5. The minimum value was set as grade number 1 and the maximum value as grade number 9. The grades between 1 and 5 are calculated using formula 1a, and the grades between 5 and 9 using formula 1b.

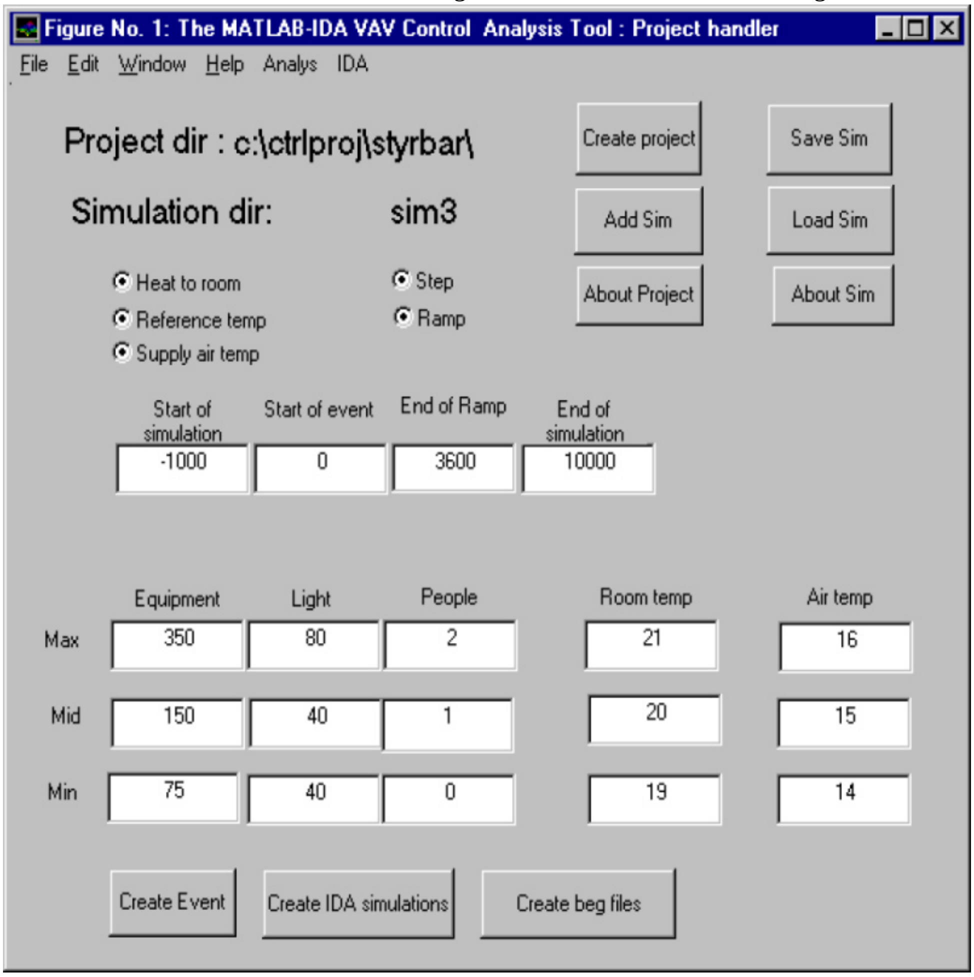

Figure 1: The project handler of the MATLAB-IDA VAV Control Analysis tool

$$G(i) = \bar{v} - (5-i)\cdot\left[\bar{v} - min(v)\right]/4 \qquad (1a)$$

$$G(i) = \bar{v} + (i-5)\cdot\left[max(v) - \bar{v}\right]/4 \qquad (1b)$$

EVALUATION OF THE METHOD

To support the method, a relatively large number of simulations of different VAV-systems must be performed. It is important that the number of zones to be controlled is equal for all systems simulated. The systems compared in this study are all designed for a maximum load of 350 W from the equipment, 80 W of light and two persons in each of the twelve rooms. The supply air temperature is 16 ºC and the room temperature set point is 19 ºC. The system characteristics that have been varied are listed below and all simulations are summarised in Table 1.

- The second column shows if the fan is PI or P controlled. If the fan is PI controlled, the first value is the gain used and the second one is the integration time. Otherwise the value is the gain used
- The third column shows the loss of pressure over the zone dampers at design conditions.
- The fourth column shows if the zone damper is PI controlled or not controlled at all. If the fan is PI controlled, the first value is the gain used and the second value is the integration time.
- The fifth column shows the pressure loss over each terminal unit at design condition and if the terminal units are pressure-independent (pi) or pressure-dependent (pd)

Criteria matrix for event:____________		value	assessment	weight	assessment x weight
Temperature	temperature 1				
	temperature 2				
	temperature 3				
Interaction	interact 1				
	interact 2				
Wear	distance				
Fan energy	energy				
				Total for event:	

Event	Heat gain	Set point	Supply air temperature	Sum:
assessment x weight				

Figure 2: Criteria matrix and summary of the three events

Table 1: Simulations performed

Sim nr	Fan	Zone damper		Terminal-unit	
	Control algorithm	Nominal pressure loss	Control algorithm	Nominal pressure loss; type of unit	Control algorithm
1	PI-0.155;1	150	PI-0.15;10	200;pi	Tstat 2 deg
2	PI-0.155;1	150	PI-0.15;10	200;pd	PI-12.6;417
3	PI-0.155;1	150	PI-0.15;10	200;pd	PI-6.3;417
4	PI-0.155;1	150	No	200;pi	Tstat 2 deg
5	PI-0.155;1	150	No	200;pd	PI-6.3;417
The simulations above this point are designed for a case with 70% of the heat loads, a supply air temperature of 15 º C and a room temperature set point of 20 ºC.					
6	PI-0.155;1	250	PI-0.15;10	100;pi	Tstat 2 deg
7	PI-0.155;1	250	PI-0.15;10	100;pd	PI-6.3;417
10	P-200	150	PI-0.15;10	200;pi	Tstat 2 deg
11	P-50	150	PI-0.15;10	200;pd	PI-6.3;417
14	PI-0.155;1	150	PI-0.15;10	200;pi	Tstat 1 deg
15	PI-0.155;1	150	PI-0.15;10	200;pd	P-20

- The sixth column shows if the terminal unit is PI controlled or controlled by a room thermostat. If the damper is PI controlled the first value is the gain used and the second one is the integration time. If a room thermostat controls the terminal unit, the value presented is the control range. In one case, the unit is P controlled, and then the value is the gain used.

To evaluate the method, the spread of the values for each criterion is highlighted. If the diversity is wide enough the criterion is assumed to be useful for the assessment of the systems. The significance of each event is analysed in the same way

RESULTS

The diagrams in figure 3 show the values of one criterion of each type calculated for each event (Temperature 1, interaction 2, distance and energy). Low values are desired for all criteria. The values of the first three criteria (temperature 1 to 3) are spread in a wide range, which can be considered as fairly good. The results from criterion "temperature 2" and "temperature 3" are similar to "temperature 1". It is, however, evident that the simulations can be divided into two groups. The group with the highest values represents systems having a pressure independent terminal unit and the other group represents systems having a pressure dependent terminal unit. When looking at the next two criteria (interaction 1 and 2) the results of the two groups show the opposite tendency. This deviation between the two groups can also be seen when observing the wear criterion (distance). The last, energy, shows only small dispersion of the values and no splitting of the systems into two groups.

The values calculated from the criteria can be used to rank the systems without using the criteria matrix. In the table below (table 2), a mean value of all criteria for each system at each event is presented. The range of the mean values is not very wide, which is evident from the diagrams above. The ranking of the systems is presented in the table, for each event separately, and for all events together.

Figure 4 shows the result from the valuation using criteria matrices. The results are presented for each event separately, and for the sum of all events. When comparing the results from each event, it becomes evident that the relative order of the systems varies. The total result varies between 298 and 496, which is wide enough for detecting differences between the systems.

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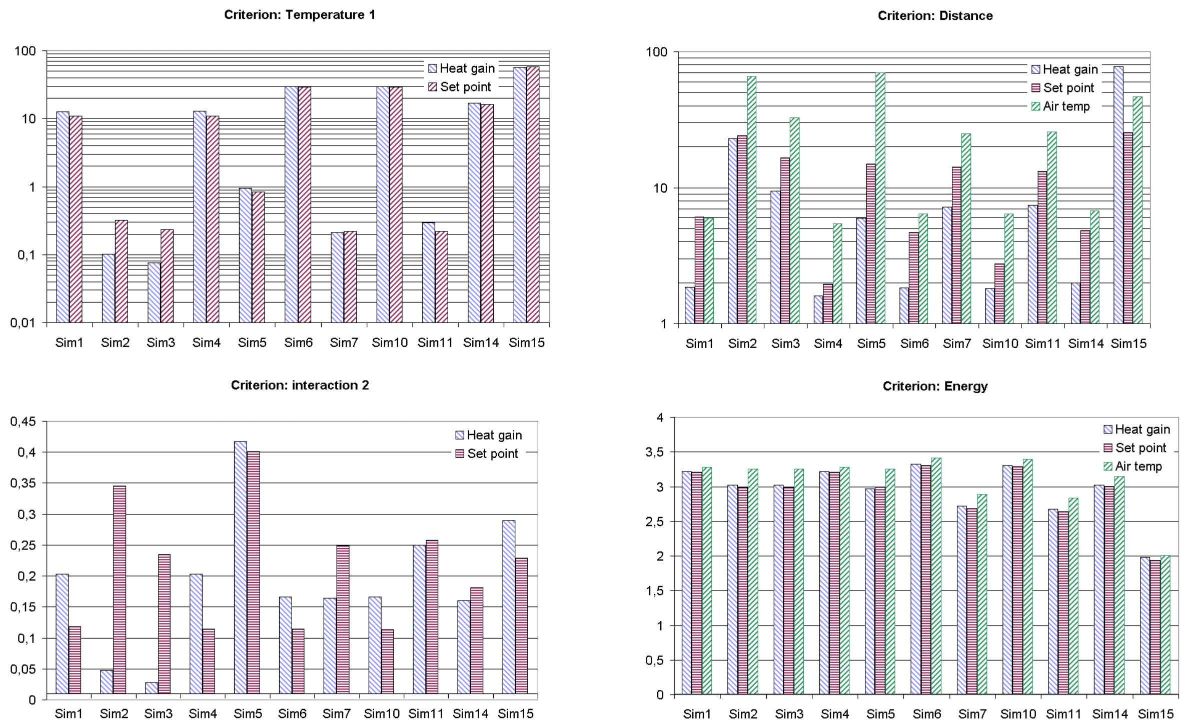

Figure 3: The values for one criterion of each type for all events

DISCUSSION

The results show differences in the ranking between the systems for the three events. The usefulness of these events is thus supported.

The values of each criterion, except for the energy criterion, show good dispersion, which supports their applicability. The energy criterion will presumably have more influence when studying systems designed for different pressure levels.

The importance of using some kind of weighting during the valuation becomes evident when the results from the ranking of the systems without criteria matrices are studied. The mean ranking shows small differences between the systems. This difference can, however, be increased if the significance of the different criteria is highlighted, using criteria matrices and weighting factors. Equally important is the assessment description, which can be made in a wide variety of ways. In this paper, the assessment description is quite simple, but more complex descriptions can be implemented.

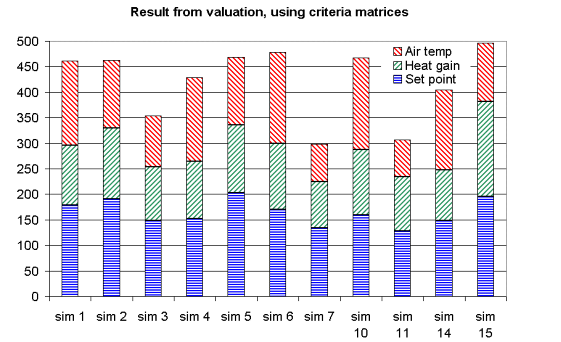

Figure 4: Result from valuation using criteria matrices

CONCLUSION

The method as a whole appears to be viable. Using MATLAB to handle analysis of IDA simulations is effective. The modularity of each program allows a change of different criteria or of the assessment descriptions without changing the method. The next step from here is to test the method in a real case and to validate the models used in the simulations.

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Table 2: Mean ranking of the systems for each event.

Simulation nr	Events						Total	
	Heat gain		Set point		Air temp			
	Mean ranking	order	Mean ranking	order	Mean ranking	order	Mean ranking	order
1	6	5	6,7	8	7,8	9	6,8	9
2	6,2	7	6,3	8	6,2	5	6,2	6
3	5,2	4	5,5	4	4,4	3	5,0	3
4	4,8	3	5,3	3	7,2	8	5,8	5
5	7	10	7,2	10	6,8	7	7,0	10
6	6,6	9	5,8	6	8	11	6,8	8
7	4,6	1	5,2	1	2,6	1	4,1	1
10	6,4	8	5,5	4	7,8	9	6,6	7
11	6	5	5,2	1	2,8	2	4,6	2
14	4,6	1	5,8	6	6,6	6	5,7	4
15	8,6	11	7,5	11	5,8	4	7,3	11