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Simulation of the climate system performance of a museum in case of failure events

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ABSTRACT

The paper presents the evaluation of the current HVAC components and indoor climate of a high tech Naval Depot when the system fails. The methodology of the research was: first, implementation of the heat, air & moisture models of the building and HVAC components. Second, validation of the models using measured data from the existing building control system. Third, simulation of the current and new HVAC systems designs. Fourth, discussion of the usability of the approach. For this specific case, we concluded that the current system design performs well if, in case of a fault, the air supply to the depots is switched off automatically. The construction of the depots has sufficient thermal inertia to maintain a stable indoor climate for a period long enough to allow it to be repaired. The design could be further improved by controlling the indoor climate surrounding the depots instead of inside the depots itself. In such a case, even if the system did not detect a fault and continued supplying uncontrolled air to the surroundings of the depot, the indoor climate in the depot would remain stable. We conclude that the approach presented in this paper has a wider application than this single case study.

1. Introduction

The indoor climate plays a key-role in preserving artifacts in museums [1–5]. Usually, considerable effort is put in to realize a steady indoor climate. The design of the climate control system needs to be robust, in case of temporary partial system faults [6–15]. Our study concerns the HVAC system of the Dutch National Naval Depot located at Amsterdam, which should have a high reliability. However, during the year, a seemingly harmless HVAC fault almost caused a serious problem for the preservation of the artifacts. Due to this incident, a project was under taken to investigate the reliability of this specific HVAC system. Four research questions were formulated: What is the performance of this high tech installation in case of failures? Is it possible to improve the current climate control concept in such a case? What are the drawbacks and benefits of the approach used and does it have wider application than this single case study.

The aim of the paper is to answer these key questions. The article is organized as follows: Section 2 provides a short description of the National Naval Depot building and systems. Section 3 presents the implementation of the heat, air & moisture (HAM) models of the building and installation components into SimuLink. In addition, data from both the present building control system and additional measurements were used for validation purposes. In Section 4, the simulation of the current design and alternative design options in case of system failure events, are presented. In Section 5 we discuss the drawbacks and benefits of the approach and the possibilities of extracting some general rules for other applications.

2. The Dutch National Naval Depot

The Dutch Naval Depot [16], part of the Dutch Naval Museum, located at Amsterdam, houses one of the Netherlands most valuable collections of artifacts. The Depot is an advanced building with an advanced HVAC system. The building consists of a box-in-a-box construction. The inner concrete boxes (depots) of this building are used for storing the artifacts. See Fig. 1. The collection of artifacts is divers, including paintings, prints, manuscripts, and various marine tools such as telescopes, compasses, etc. The concrete storage boxes are air-conditioned with a high reliability HVAC plant. Abrupt changes of the indoor climate can damage the artifacts. Therefore storage must meet the tight demands of control class ASHRAE AA [17]. There are five independently operating, nearly identical HVAC systems for conditioning the different depots and ateliers. Because the depot cases are analogue the research focuses only on the depot with the most sensitive objects. This is the HVAC system, responsible for controlling the indoor climate of the depot located on the first floor. This depot is used specifically for the storage of highly sensitive, organic materials. Fig. 2 shows this HVAC system. The main reason for introducing a second DX cooling coil,

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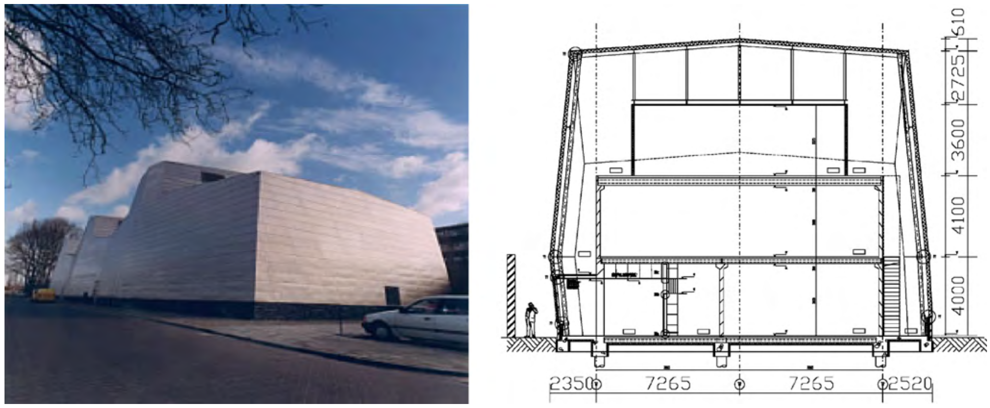


Fig. 1. (Top left) Impression of the Depot. (Top right) The box-in-a-box construction.

together with a cooling coil in the same HVAC system, is that the DX cooling coil is mainly used for dehumidification. The indoor climate demands for this depot are: Mean relative humidity (RH) equals 51%; short fluctuations allowed ±2%; temperature (T) equals 18 °C during the winter and 20 °C during the summer; short fluctuations allowed ±2 °C. The mixed air characteristics of the depot are 10% fresh air and 90% recirculated return air. The depot is completely surrounded by a 'cavity' zone, heated only by radiators with temperature control settings identical to the depot winter setting of 18 °C. There is no cavity cooling system for the summer season.

3. Modeling

3.1. Background on the modeling environment

The modeling environment consists of three main components:

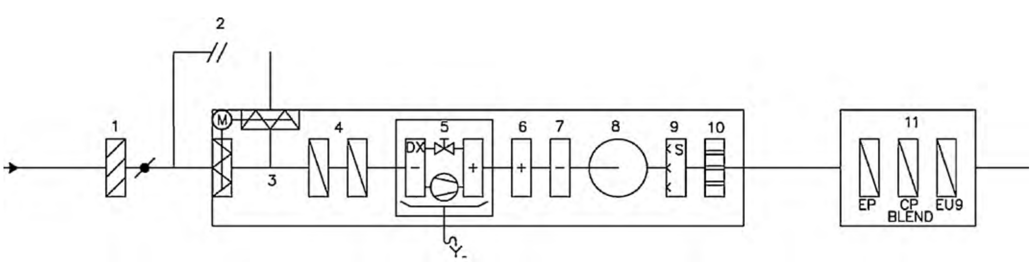
(a) a whole building (global) modeling facility, for the simulation of the indoor climates and energy amounts;
(b) an ordinary differential equation (ODE) solving facility, for the accurate simulation of HVAC systems and controllers;
(c) a partial differential equation (PDE) solving facility, for the simulation of 2D/3D HAM responses of building constructions and 2D internal/external airflow. This feature is not used in this work.

(a)

The whole building model originates from the thermal indoor climate model ELAN which was already published in 1987 [18]. Separately a model for simulating the indoor air humidity (AHUM) was developed. In 1992 the two models were combined (WAVO) and programmed in the MATLAB environment [19]. Since that time, the model has constantly been improved using newest techniques provided by recent MATLAB versions [20]. Currently, the hourly-based model, named HAMBase [21], is capable of simulating the indoor temperature, the indoor air humidity and energy use for heating and cooling of a multi-zone building. The physics of this model is extensively described [21]. The HAMBase model was implemented in SimuLink [20] by splitting the energy and vapour flows into two parts. First, a discrete part was developed for modeling 'slow responses', i.e. the transmittance through walls. Second, a continuous part was developed for the 'fast responses', i.e. admittance, ventilation, heat gains, etc. There are three main advantages: First, the dynamics of the building systems where small time scales play an important role (for example on/off switching) are accurately simulated; Second, the model becomes time efficient because the computation of the 'slow response' part of the model only takes place at hourly intervals and not at every (much smaller) time step of the 'fast response' part of the model; Third, the moisture (vapour) transport is also included. With this feature, the (de-) humidification of HVAC systems can also be simulated.

(b)

ODE based models have been integrated into SimuLink using the continuous states part of an S-Function [22]. The following steps can be used to build models: The first step is to develop a mathematical model of the heat pump, based on first principles, in the form of ODEs. The second step is to prepare the input–output definition of the model. The third step is to build the input–output structure con-



1.	grid	7.	cooling coil
2.	air to other systems	8.	supply fan
3.	mixed air section	9.	steam humidification
4.	filters	10.	water drop catching
5.	direct expansion cooling coil (dehumidification)	11.	filters
6.	heating coil		

Fig. 2. The HVAC system.

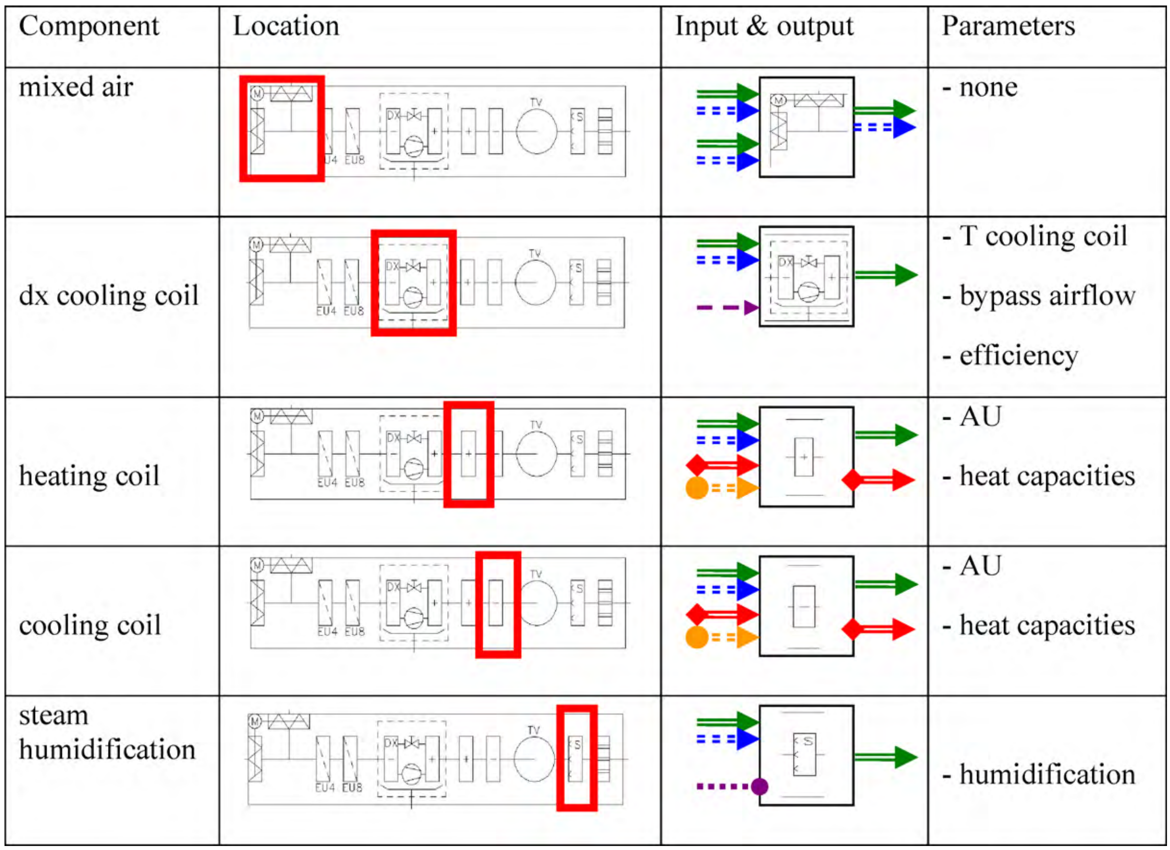


Fig. 3. Overview of the components of the HVAC system including input, output and parameters structure.

nected with the S-function block. The fourth step is to write code into an S-function. Note that possible time scale problems (i.e. the lowest time constant present in the dynamic system is an order of magnitude 5 lower than the highest one) seem less relevant in the case of ODE based models because of specially designed solvers for this case. So-called stiff solvers can handle such a problem accurately and time efficiently [23]. On the other hand, simulating controllers, for example (rapid) on/off switching, can generate small time steps during simulation. Although accurate results are obtained in this case, it could still lead to relatively long simulation duration times.

The final step of the integration of all models using a single simulation environment (SimuLink) is presented in [24].

3.2. The HVAC system

Fig. 3 and Table 1 present an overview of the HVAC components. The application of this approach is demonstrated for the cooling coil and presented below. The other components are modeled in a similar way.

Table 1
Description of the vectors of Fig. 3.

Vector	Arrow	Description	Unit
Air		Temperature Air humidity	°C kg/kg
		Mass flow	kg/s
Water		Temperature	°C
		Mass flow	kg/s
Control signal		Humidification	–
Power		Electric	W

3.3. The cooling coil as an example of the modeling approach

Fig. 4 and Table 2 provide the input/output structure of the cooling coil, implemented in SimuLink. Often, the cooling coil is (also) used for dehumidification purposes. However, in this HVAC system, dehumidification is done exclusively by the DX cooling coil.

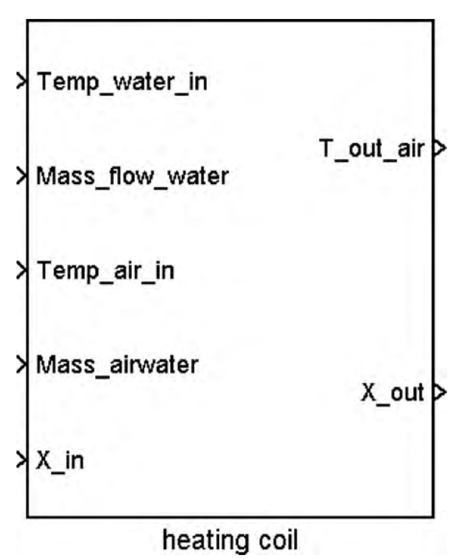


Fig. 4. The input output structure of the cooling coil, implemented in SimuLink.

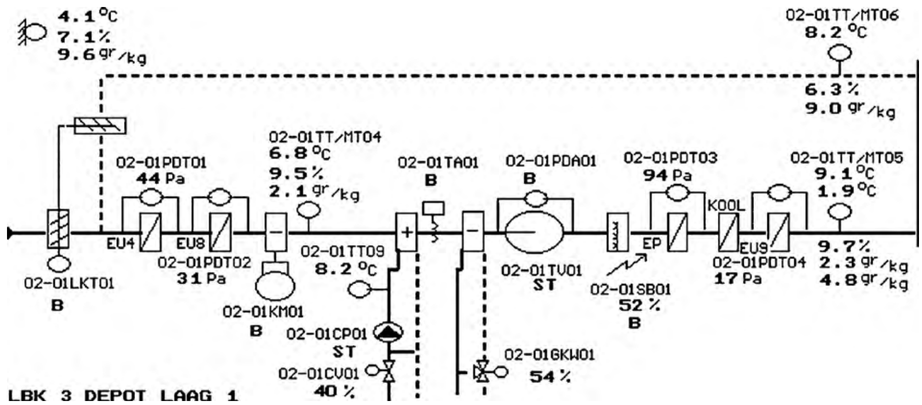


Fig. 5. Overview of the location and typical output of the sensors present in the system.

The mathematical model of the cooling coil is represented by:

$$C_a \frac{dT_{aout}}{dt} = q_{ma} \cdot 1000 \cdot (T_{ain} - T_{aout}) + AU \cdot \left(\frac{T_{win} + T_{wout}}{2} - \frac{T_{ain} + T_{aout}}{2} \right) \quad (1)$$

$$C_w \frac{dT_{wout}}{dt} = q_{mw} \cdot 4120 \cdot (T_{win} - T_{wout}) - AU \cdot \left(\frac{T_{win} + T_{wout}}{2} - \frac{T_{ain} + T_{aout}}{2} \right) \quad (2)$$

$$x_{out} = x_{in} \quad (3)$$

where C_a and C_w are the characteristic heat capacities of air-duct mass and water-pipe mass [J/kg], respectively; T_{wout} is the temperature of the exhaust water [°C] (not used as output); AU is the characteristic heat conduction of the heat exchanger [W/K], that can be calculated using, for example, the NTU method. Our goal was to use data from the building automation system for validation purposes. A typical overview is provided in Fig. 5. Fig. 6 presents the measured air temperature before the cooling coil and the measured and simulated air temperature after the cooling coil.

The cooling capacity is controlled by a mass flow control. The water supply temperature (T_{win}) is constant. The valve characteristics are linearized. A (slave) PI controller controls the T_{aout} using a (master) controlled set point.

3.4. The depot

The indoor climate of the depot and the surrounding zone (cavity) are modeled. We refer to [24] for modeling and implementation details. The two-zone building model is exported to SimuLink. In order to validate this model, measured data of the external climate and the supply air are used as input for the building model. The measured and simulated indoor climate conditions in the depot within a 55-day period are presented in Figs. 7 and 8. Both Figs. 7 and 8 show that the results are quite satisfactory except at the beginning due to the initialization influence.

Table 2
Description of the input and output of Fig. 4.

	Name	Symbol	Unit	Description
Input	Temp water in	T_{win}	°C	Temperature of the supply water
	Mass flow water	q_{mw}	kg/s	Mass flow of the supply and exhaust water
	Temp air in	T_{ain}	°C	Temperature of the supply air
	Mass flow air	q_{ma}	kg/s	Mass flow of the supply and exhaust air
	X in	x_{in}	kg/kg	Humidity of the supply air
Output	Temp air out	T_{aout}	°C	Temperature of the exhaust air
	X out	x_{out}	kg/kg	Humidity of the exhaust air (=xin)

3.5. The complete depot, HVAC systems and controllers

All models were implemented and connected using SimuLink. The reader should note that although the single modeling components are quite simple, this is certainly not the case for the complete model. This has consequences for the validation of the whole model. Although each component is verified separately, a validation of the complete model is very difficult. Due to the large number of signals, this would be also very time consuming. Furthermore, a lot of signals are neither measured, nor stored in the HVAC control system. In order to check whether the model is trustful, we simulated the indoor climate in the depot using the complete model subjected to the external climate. These results are provided in Fig. 9. From Fig. 9, it can be seen that the climate control works appropriately. To illustrate the potential of this modeling approach, we proceed with applications of the complete model for simulating system failure scenarios and alternative design options.

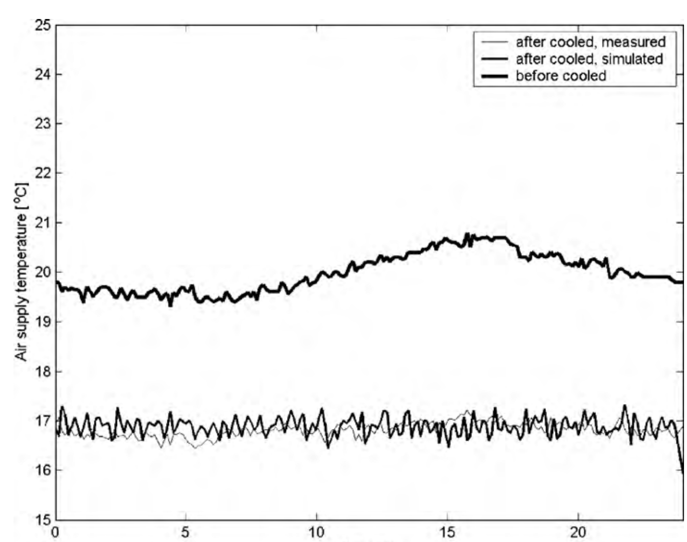


Fig. 6. Air temperature before and after the cooling coil.

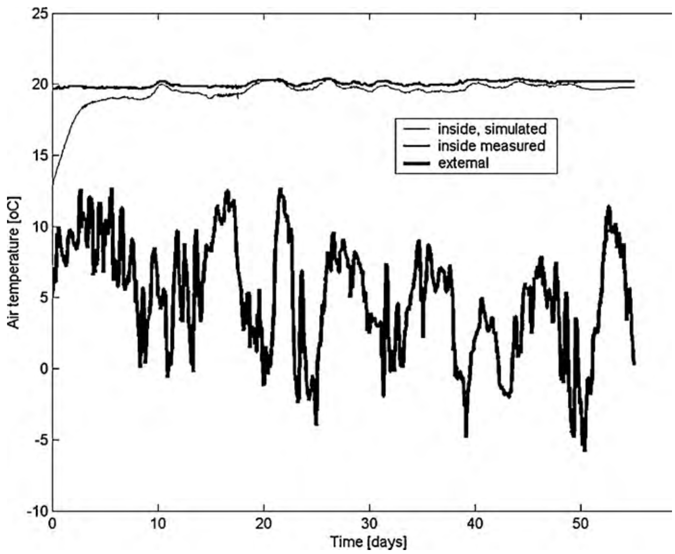


Fig. 7. Measured external and indoor air temperature and simulate indoor air temperature.

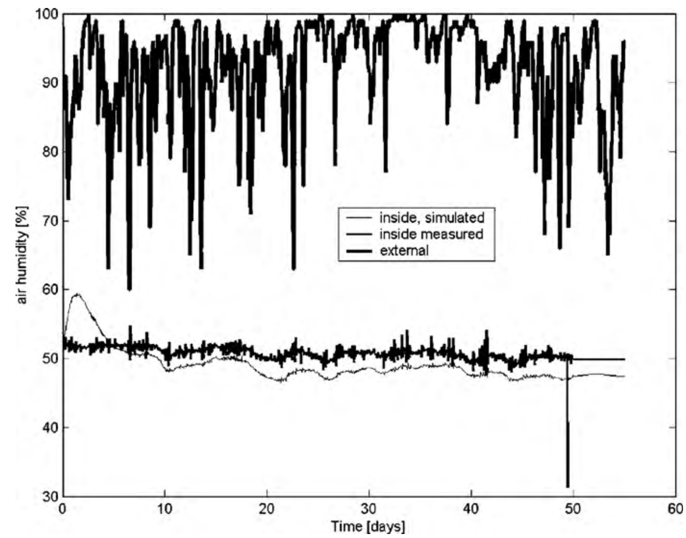


Fig. 8. Measured external and indoor relative humidity and simulate indoor relative humidity.

4. Failure scenarios and alternative design options

4.1. Case 1: dehumidification failure in summer

For this case, we simulate the effect of a failure (dehumidification stop) at the DX cooling coil starting on 8 August with and without a recirculation failure. In Fig. 10, four simulation results are presented: First, the reference situation with no failures ('no faults'). Second, the current design in case of a detected failure ('dx fault') where the HVAC system switches from 90% to 100% recirculation. Third, an undetected failure is shown ('dx fault, recirc fault') where the HVAC system does not switch to 100% recirculation. The fourth is an alternative design, where in case of a detected failure, the complete HVAC system switches off, causing a free floating indoor climate at the depot ('all off'). This case shows that a failure of the dehumidification must be detected within 2 h (time to reach the allowed 2% RH change). Within this period the HVAC system

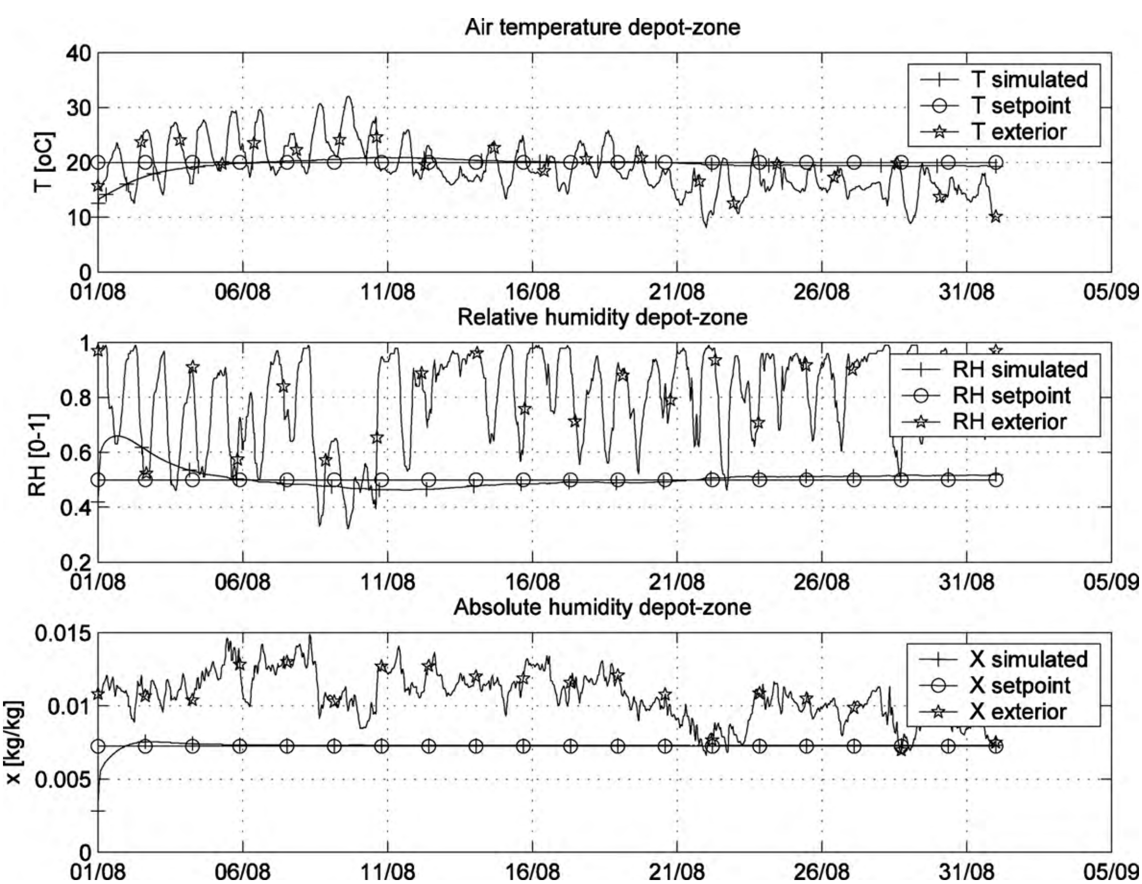


Fig. 9. The measured and simulated indoor climate in the depot.

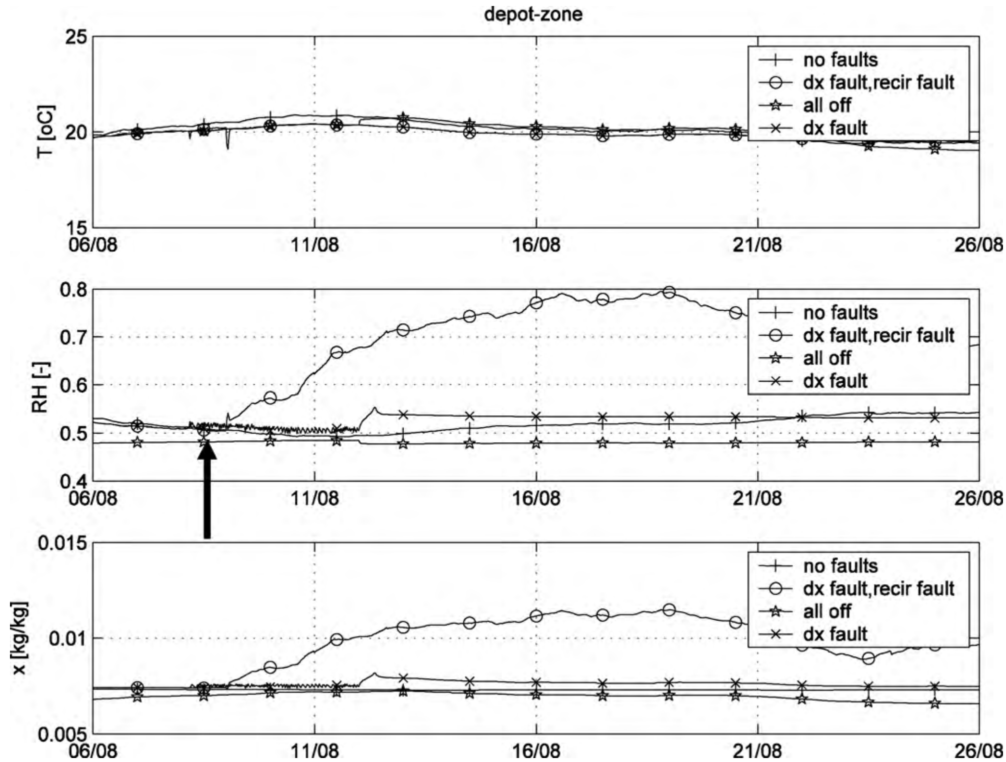


Fig. 10. Evaluation of dehumidification failures (arrow: time of failure).

should be switched either to 100% recirculation or completely shut down. The latter has the advantage that it is a more robust solution for various other possible failures occurring at the same time (for example, a failure of the recirculation detection or controller). A disadvantage is that after a failure event, the whole HVAC system has to be initialized instead of the part(s) of the HVAC system that caused the problem.

4.2. Case 2: humidification failure in winter

For this case we simulate the effect of a failure at the steam humidifier during the winter starting from 12 December. Furthermore we want to investigate the indoor climate in the depot when the 'cavity' zone surrounding the depot is controlled (alternative) instead of the depot itself. Four simulation results are

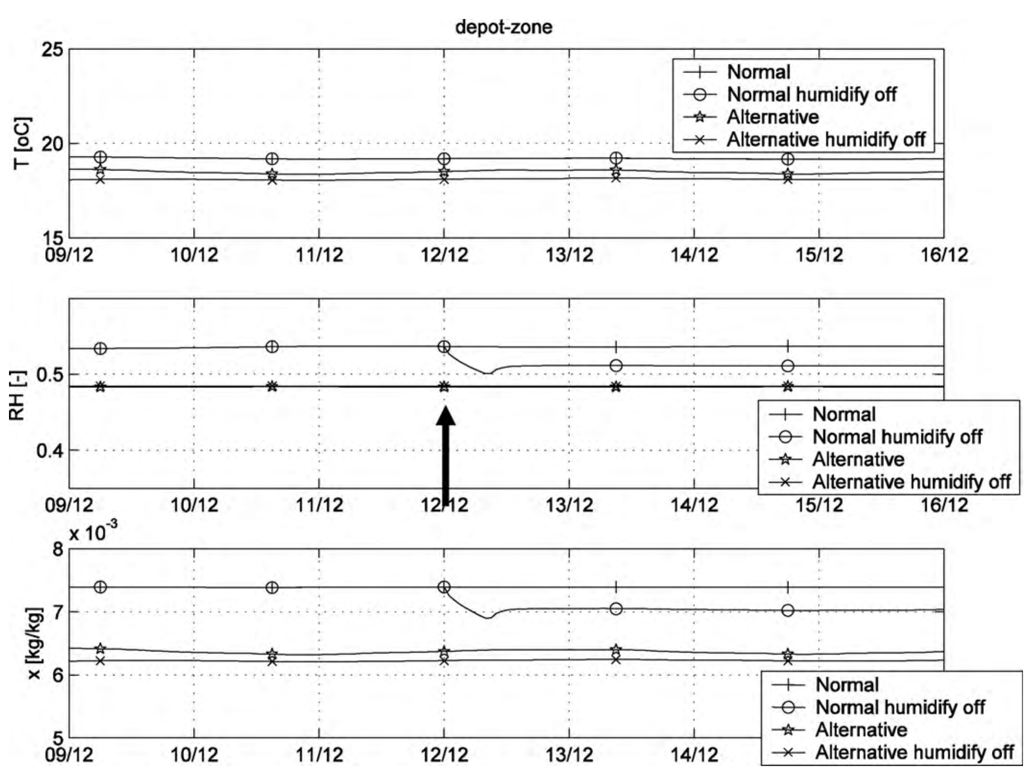


Fig. 11. Evaluation of humidification faults (arrow: time of failure).

presented in Fig. 11: The reference situation with no failures ('Normal'). The current design in case of an undetected failure at the humidifier, i.e. no 100% recirculation ('Normal humidify off'). The alternative control with no failures ('Alternative') and in case of a undetected failure at the humidifier ('Alternative humidify off'). This case shows once again that this type of failure should be detected within 2 h (time to reach the allowed 2% RH change). Controlling the indoor climate in the cavity zone instead of the depot itself seems to provide a stable indoor climate in the depot even when a failure is not detected for a long time (week). This seems a very good alternative. However, in this case the indoor climate in the depot is no longer directly controlled. This means that (unexpected) disturbances of the indoor climate in the depot such as people visiting and leakages, are virtually uncontrollable.

5. Discussion

5.1. Performance of the current system control in case of failures

The current strategy of switching to 100% recirculation in case of a detected failure provides a stable indoor climate in the depot for a period of at least a week. However, if the failure is not detected or detected without switching to 100% recirculation, simulation results show that within 2 h the indoor climate of the depot may approach the allowed 2% RH change.

5.2. Possible improvements of the control concept

(1) A complete shut down of the HVAC system in case of a detected failure also provides a stable indoor climate in the depot for a period of at least a week. This solution seems to be more robust in the case of multiple failures than the current design, assuming that initialization of the whole HVAC system causes no extra problems.
(2) Controlling the indoor climate in the cavity zone instead of the depot itself has the disadvantage that (unexpected) disturbances of the indoor climate in the depot for example visiting people and leakages are virtually uncontrollable. So this does not seem an appropriate solution.
(3) The relatively large air supply ($3\,m^3/s$) is designed to create a uniform indoor climate in the depot. However, in case of a failure, this air supply is responsible for the relatively short time of 2 h where the indoor climate approaches the allowed 2% RH change. Furthermore, in the current HVAC system the amount of air recirculation is about 90%. Preliminary simulation results show that a significant decrease in the air supply would provide a longer reaction time. Further research of this effect on the uniformity of the indoor climate in the depot using CFD is needed and will be handled in future research.

5.3. Drawbacks of the approach

(1) The heat, air & moisture (HAM) modeling of *new* HVAC system components is time consuming (the model development by an MSc student took about 3 months).
(2) Validation is a major problem. We used the data from the building automation system to calibrate our models. Unfortunately, validation was not possible due to the absence of required sensors or due to badly placed sensors. The characteristics of the PI controllers could not be verified because we were not allowed to experiment with the current HVAC system.

5.4. Benefits of the approach

(1) Simulation is perhaps the only option if experimenting is not possible.
(2) The presented models in this paper are public domain and implemented in the Matlab/SimuLink environment. In this simulation environment a lot of useful models are already available.
(3) The approach can also be used for design purposes.

5.5. Recommendations to improve the approach

(1) For new HVAC systems, it is recommended to measure the impact of several failure scenarios after the HVAC system is operational but before people and/or valuable objects are situated in the building.
(2) For current HVAC systems and when it is allowed to do some experiments it is recommended to change some set points by small allowable steps in order to verify the overall dynamics and the characteristics of the present controllers.

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