Simulation of the Climate System Performance of a Museum in Case of Failure

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ABSTRACT

The paper presents the evaluation of the current HVAC components and indoor climate of a high tech Naval Depot in case of failure events. The methodology of the research was: First, implementation of the heat, air & moisture models of the building and HVAC components in SimuLink. Second, validation of the models using measured data from the present 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, it is 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 contains sufficient thermal inertia to maintain a stable indoor climate for a longer period in which the system fault can be repaired. A further improvement of the design could be to control the indoor climate surrounding the depots instead of inside the depots itself. In this case, even if the system would not detect a fault and thus supplying uncontrolled air at the surroundings of the depot, the indoor climate in the depot would remain stable. Furthermore it is concluded that the approach presented in this paper appears to be wider applicable than this single case study.

KEYWORDS

Modeling, Simulation, HVAC, failure, Indoor climate

1. INTRODUCTION

The indoor climate plays a key-role in preserving artifacts in museums. Most of the time, a lot of effort has been put in the realization of a steady indoor climate. Furthermore, the design of climate control should also be robust, in case of temporary partial system faults. The 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, the reliability of this specific HVAC system is investigated in this project. The main research questions are: 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 and is it wider applicable than this single case study. The outline is 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 Section 4, the simulation of respectively 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 (Scheepvaartmuseum 2006), located at Amsterdam, gives housing to one of Dutch most valuable collections of artifacts. The Depot of the Dutch Naval Museum 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.

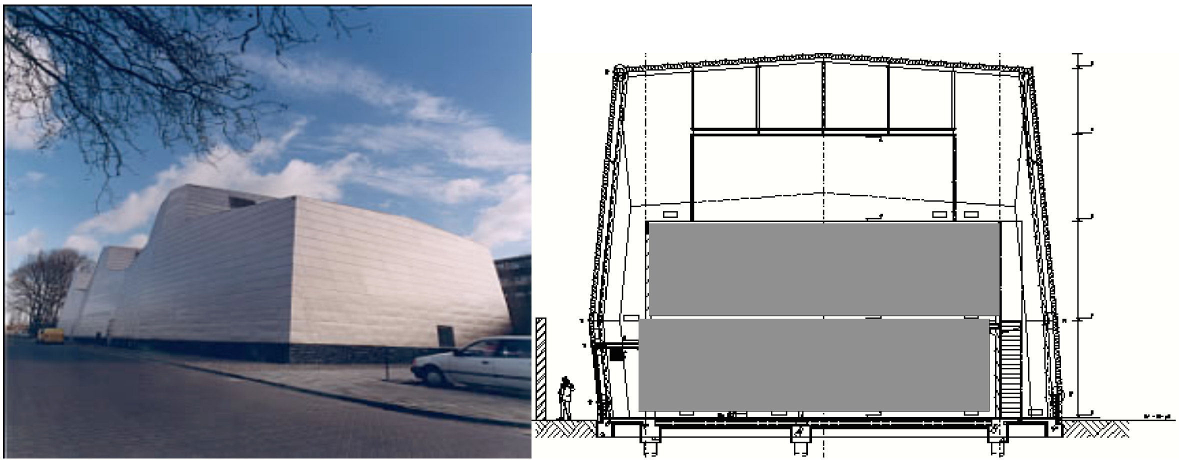
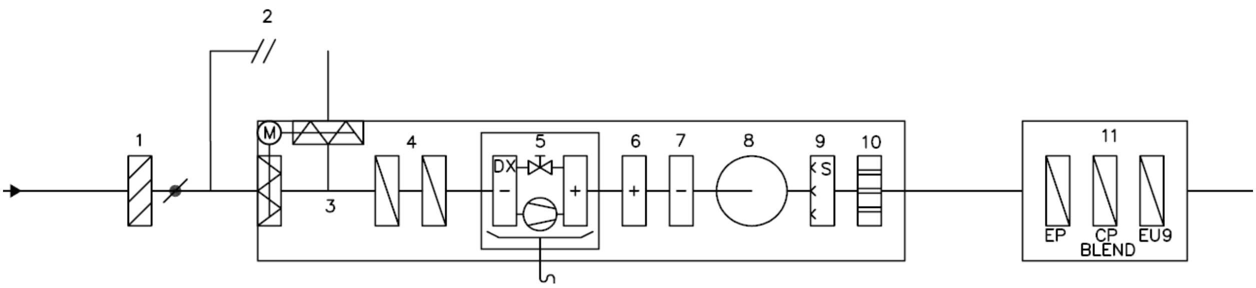


Figure 1. Left: Impression of the Depot. Right: The box in a box construction.

The indoor air of the concrete storage boxes is conditioned with a high reliability HVAC plant. Abruptly changes of this indoor climate can be harmful for the artifacts. The artifacts that are stored therefore require the tight demands of control class ASHRAE AA (ASHRAE 2003). There are five independently operating HVAC systems for conditioning the depots. The research only focuses on one system responsible for controlling the indoor climate of the depot located at the first floor. In figure 2 the HVAC system is presented:



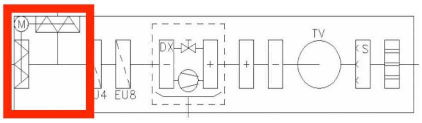
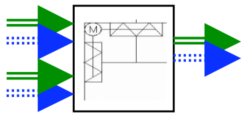
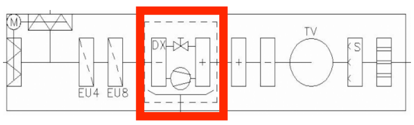
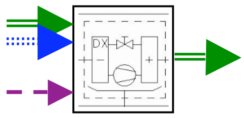
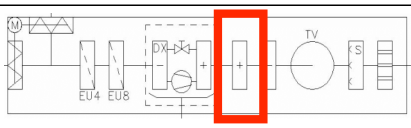
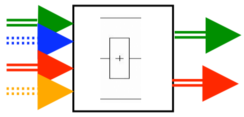
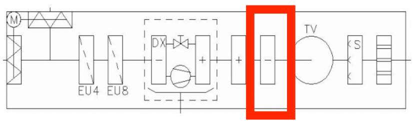
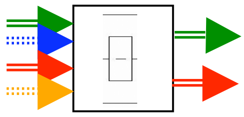
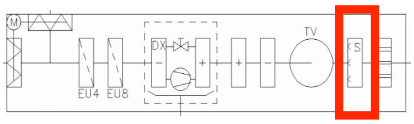
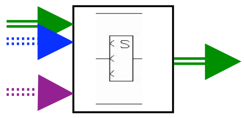
1. grid
2. exhaust air
3. mixed air section
4. filters
5. direct expansion cooling coil (dehumidification)
6. heating coil
7. cooling coil
8. supply fan
9. steam humidification
10. water drop catching
11. filters

Figure 2. The HVAC system

This depot is specifically used for the storage of organic materials. 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 depot is completely surrounded by a 'cavity' zone, heated by radiators.

3. MODELING

Figure 3 presents an overview of the HVAC components. The Heat Air & Moisture Laboratory (HAMLab 2006) is used for implementation and simulation of all models.

Component	Location	Input & output	Parameters
mixed air			- none
dx cooling coil			- T cooling coil - bypass airflow - efficiency
heating coil			- AU - heat capacities
cooling coil			- AU - heat capacities
steam humidification			- humidification

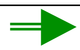
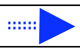
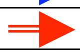
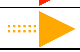
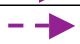
Vector	Arrow	Description	Unit
air		Temperature	°C
		Air humidity	kg/kg
		Mass flow	kg/s
water		Temperature	°C
		Mass flow	kg/s
control signal		Humidification	-
power		Electric	W

Figure 3. Overview of the components of the HVAC system including input, output & parameters structure
(please note that unfortunately the arrows in this figure depend on color)

All components are modeled based on the approach of (van Schijndel and de Wit 2003). The application of this approach is demonstrated for the cooling coil and presented below. The other components are modeled in a similar way. Often, the cooling coil is (also) used for dehumidification purposes. However, in this HVAC system, dehumidification is exclusively done by the DX cooling coil. The mathematical model is represented by:

$$Ca\frac{dTa\_out}{dt} = qm\_a \cdot 1000 \cdot (Ta\_in - Ta\_out) + AU \cdot (\frac{Tw\_in + Tw\_out}{2} - \frac{Ta\_in + Ta\_out}{2})$$

$$Cw\frac{dTw\_out}{dt} = qm\_w \cdot 4120 \cdot (Tw\_in - Tw\_out) - AU \cdot (\frac{Tw\_in + Tw\_out}{2} - \frac{Ta\_in + Ta\_out}{2})$$

$$Xout = Xin$$

Where: Ca and Cw are the characteristic heat capacities of respectively air-duct mass and water-pipe mass [J/kg]; Tw_out is the temperature of the exhaust water [^oC]; AU is the characteristic heat conduction of the heat exchanger [W/K]. Our goal was to use data from the building automation system for validation purposes. The indoor climate of the depot and the surrounding zone (cavity) are modeled using HAMBase (de Wit 2006). A 2-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. All models were implemented and connected using SimuLink. The reader should notice that although the single modeling components are quite simple, this is certainly not the case for the complete model. A validation of the complete model is practically impossible. Due to the large amount of signals this would be too time consuming. Furthermore, a lot of signals neither are measured, nor stored in the HVAC control system. In order to check the performance of the model, we simulated the indoor climate in the depot using the complete model subjected to the external climate. In figure 4 these results are provided.

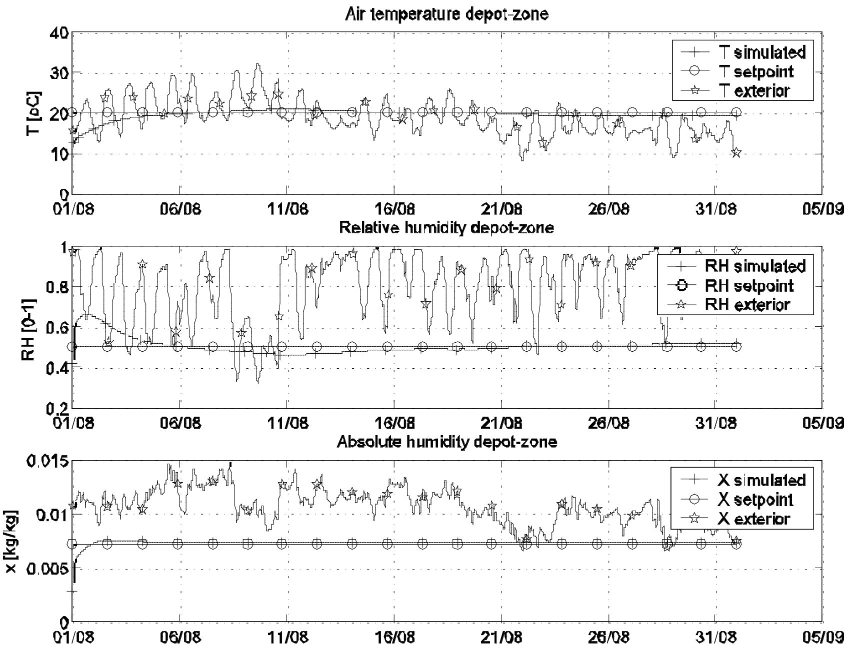


Figure 4. The measured and simulated indoor climate in the depot.

From figure 4 it can be seen that the climate control works appropriate. To illustrate the potentials of this modeling approach, we proceed with applications of the complete model for simulating system failure scenarios and alternative design options.

4. FAILURE SCENARIOS AND ALTERNATIVE DESIGN OPTIONS

In a *first* case we simulate the effect of a failure (dehumidification stop) at the DX cooling coil starting at August, 8^{TH} with and without a recirculation failure. In figure 11, four simulation results are presented: The reference situation with no failures ('no faults'). The current design in case of a detected failure ('dx fault') where the HVAC system switches to 100% recirculation and an undetected failure ('dx fault, recirc fault') where the HVAC system does not switch to 100% recirculation. Furthermore, an alternative design is presented, where in case of a detected failure, the complete HVAC system is switch off, causing a free floating indoor climate at the depot ('all off'). This case shows that a failure of the dehumidification should be detected within 2 hours (time to reach the allowed 2% RH change). Within this period the HVAC system should be either switched to 100% percent recirculation or completely shut down. The latter has the advantage that it is more robust solution for all kinds of 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.

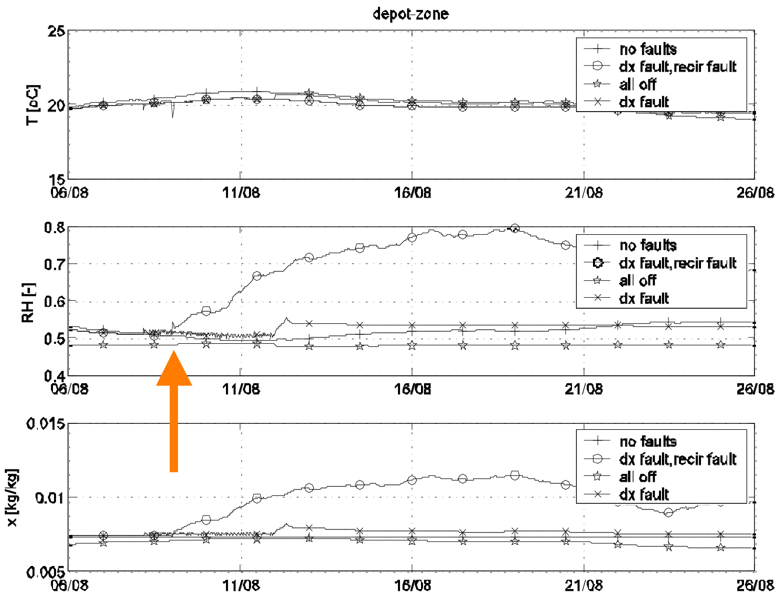


Figure 5. Evaluation of dehumidification failures (arrow: time of failure).

In a *second* case we simulate the effect of a failure at the steam humidifier during the winter. Furthermore we want to investigate the indoor climate in the depot in case the 'cavity' zone surrounding the depot is controlled (alternative) instead of the depot itself. This case shows again that this type of failure should be detected within 2 hours (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 not directly controlled anymore. This means that (unexpected) disturbances of the indoor climate in the depot for example visiting people and leakages are virtual uncontrollable.

5. DISCUSSION

The current strategy 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 it is possible that within 2 hours the indoor climate of the depot approaches the allowed 2% RH change. A complete shut down of the HVAC system in case of a detected failure provides also a stable indoor climate in the depot for a period of at least a week. This solution seems to be more robust in case of multiple failures than the current design assuming that initialization of the whole HVAC system causes no extra problems. 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 virtual uncontrollable. So this seems no appropriate solution. The relative large air supply is designed to create a uniform indoor climate in the depot. However, in case of a failure this air supply mainly causes the relative short time of 2 hours 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 decreased of 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 is left over for future research. *Drawbacks of the approach:* (1) The heat air & moisture modeling of new HVAC system components is time consuming. (2) Validation is a major problem. We were able to use the data from the building automation system to calibrate our models. 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. *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 which already a lot of useful models are available. (3) The approach may also be used for design purposes. *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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