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ENERGY SAVINGS POTENTIAL USING THE THERMAL INERTIA OF A LOW TEMPERATURE STORAGE

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ABSTRACT

50% of the energy consumed in food cold chain are for chilling, freezing and storage steps. For cold storage facilities, refrigeration is the main source of energy consumption with an average of 50 kWh/m³/year. A possible strategy to reduce their energy consumption is to take advantage of the variation of performance of the refrigeration systems during a day due to external and internal temperature variations. Electricity cost can also widely change during a day, depending on the local production. This strategy can be based on additional storage capacities to delay the refrigeration running period, but also on the use of the thermal inertia provided by the storage warehouse itself and the products stored. An experimental test has been performed in a frozen warehouse storage facility to evaluate the potential energy savings of such a strategy. Using coupled models of the building, products and refrigeration system, using weather forecasts and products flux statistics, a predictive control algorithm was developed and applied to determine periodically the optimal set-points of the storage warehouse. Technical implementation of the control system is presented. Energy savings potential and impact on products of the temperature fluctuations are also discussed.

1. INTRODUCTION

Electricity cost for a storage warehouse related to refrigeration is evaluated to 20% of the total cost. Reducing this consumption may be achieved through innovative, more efficient but often more expensive new systems or technologies. Low investment solutions also exist, like control strategies to improve the efficiency of the system, for example taking advantage of the large performance variation of vapour compression systems due to external (and internal) temperature fluctuations. Forcing the systems to run preferentially during night in this case is a first step, but an optimal implementation of this strategy has to integrate the occurrence of every source of heat loads: products input, door openings, ventilation... Weather is only a part of the heat loads even if it is a factor of large variation: a rainy day will decrease drastically the energy consumption, but wall sun exposure will increase it.

Information and control technologies now give the possibility to integrate every source of information available through connected devices, internet protocols and computing power. Monitoring systems are often already existing and a global predictive controller that could communicate with these systems and the existing controllers has the potential to reduce energy consumption by defining for example the best time to run or to stop the system, the refrigerating capacity needed and the best settings for fans, pumps and motors. By being able to predict the energy consumption, and knowing the events that will occur in the future, it becomes possible to compute the future state of the system. Therefore, various scenarios can be assessed. An objective function can be defined to compare these scenarios with a set of criteria (product quality, energy consumption and environmental impact), and an appropriate algorithm should choose the best.

The principle of such a predictive controller has been presented in [1]. This paper presents an experimental test of this controller performed in a frozen warehouse storage facility to evaluate the potential energy savings.

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2. MATERIAL AND METHODS

2.1 Storage warehouse

The warehouse selected is a new and modern frozen storage warehouse in Germany (Neuenkirchen-Vorden) and is mainly used for long term meat storage. It can be considered as a medium size modern freeze storage, with 2700 pallet positions.

The energy performance of the refrigerating system have been analyzed during 12 months. The measurement system consisted in an extension of the existing control system, and provided information about temperatures, pressures, energy consumption and mass flow rates of the refrigeration system components and the cold room.

These measurements have stated that:

1. The heat losses due to the transmission through the walls is only 25% of the total heat losses.
2. There is no significant relation between the energy use and the load (number of pallets)
3. The energy use is highly correlated to the temperature of the incoming pallets. The impact can be negative if the pallets have been placed in the shock freezer (-45°C) before being stored in the warehouse.
4. There is a correlation between the coefficient of performance of the refrigerating system and the outside temperature, but it is not a linear function
5. Ventilation losses are an important part of the heat losses
6. There is already a high thermal inertia of the freeze storage due to the mass of products (an average of 5000 tons of frozen products)

2.2 Predictive controller implementation

Based on MPC control approach [3-4], this advanced controller concept for cold chain applications has been developed through the successive tasks of the Frisbee project. The main characteristics of this controller are:

- An optimal control strategy computed periodically based on the measured state and a predictive model of the system (MPC approach)
- The possibility to take advantage of heat storage capacities and weather forecast
- The possibility to use the cold chain models from the Frisbee tool
- Its integration in a low cost hardware unit

MPC makes use of a model of the process to be controlled. Measurements and modelling lead to knowledge of the state of the system and allow to forecast its evolution given future control variables input (Figure 1). Therefore, the values of the future control variables can be optimised to obtain the desired behaviour of the system. Thus the objective of the algorithm is to minimise a cost function while satisfying constraints. The cost function is a measure of the user's satisfaction; it combines in one equation the various objectives (process output) and in some cases includes a measure of the satisfaction of the constraints.

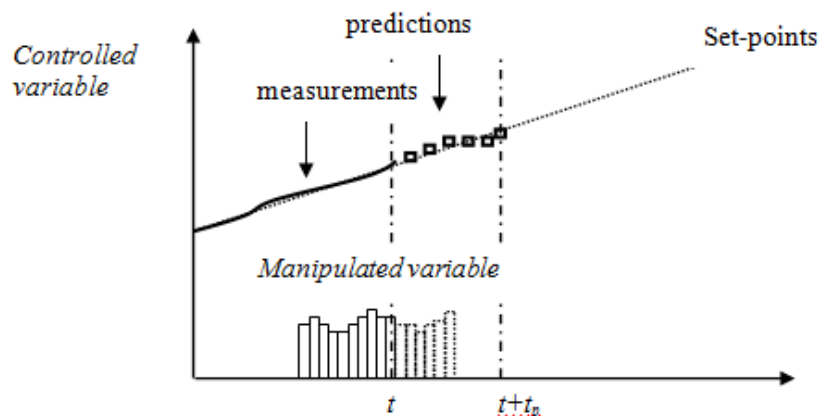


Figure 1 : Predictive control principle

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MPC can be used at three levels : actuators, control setpoints or supervision[2]. When used to define setpoints, existing controllers are in charge of tracking these setpoints. In case of failure of one of these controllers, the process can still be operated manually. The advantage of this approach is that the current controllers of a given factory need not be changed. This enhances end-users acceptance and allows for a modular approach.

The advanced controller is a closed loop controller, and then requires measurements on the controlled system to be operated. The existing controller is connected to a front end that provides an access to the measurements by a web interface. This appeared as the most convenient way to access the data for the advanced controller. A development based on web client automation has been performed to enable a two way communication (measurements and control actions) between the advanced controller and the existing controller. Measurements were based on existing sensors (pressure, temperature, flow rate, electrical consumption) and additional thermocouples placed inside the warehouse, with a 5 minutes acquisition period.

2.3 Protocol

The experiment started by a 3 weeks observation period. During this time, we modelled and validated a model of the warehouse. This model includes:

- Heat losses through the walls
- Heat load due to air infiltration by opening doors
- Heat load due to fans
- Heat load due to product inputs
- A model of the refrigerating system based on manufacturer data of the compressors

Figure 2 shows a comparison of the measured and simulated temperature inside the warehouse. The main source of differences between measurements and simulation is the air infiltration related to door openings, related itself to the products input/output that is not a constant and continuous process, and difficult to anticipate using only the available data and sensors. Despite these difficulties, it was stated that the temperature evolution is predicted by the model with a satisfying accuracy.

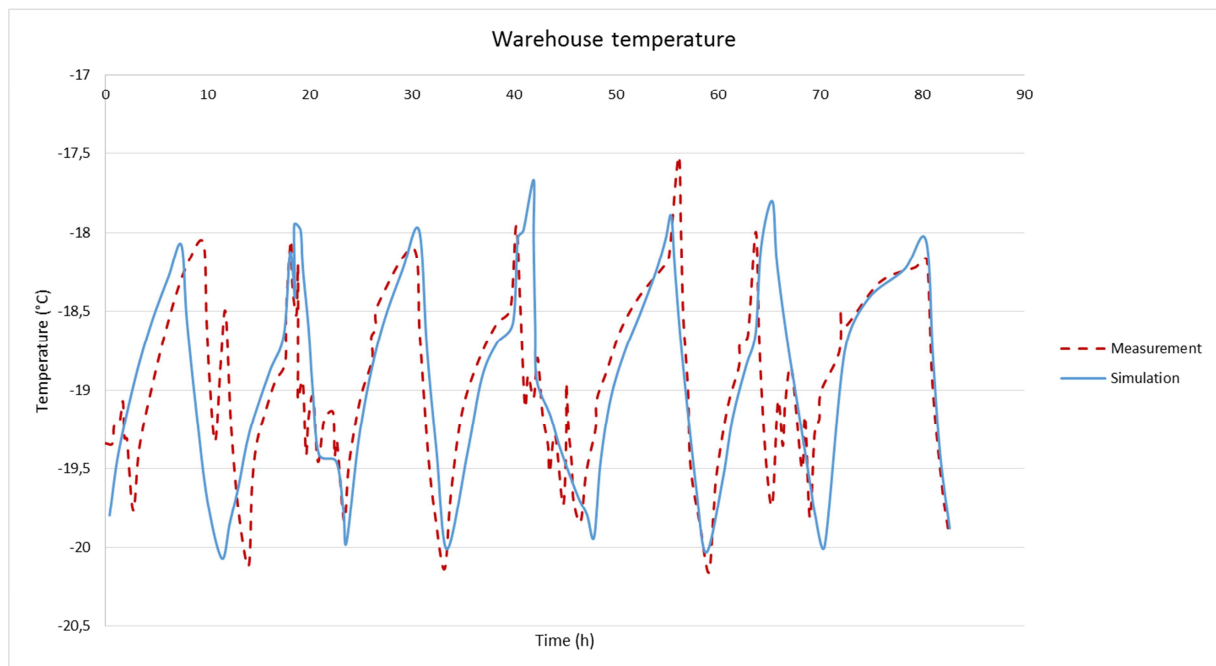


Figure 2 : Comparison between measurements and simulation results of the warehouse model

For the predictions, data weather forecasts from www.worldweatheronline.com were used. An XML file is retrieved every 10 minutes and the next 48 h forecasts are used by the controller. The controller software and

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the optimization have been developed under the Labview environment. A graphic interface has been designed in order to display the available measurements.

To limit the risks related to failure of the controller, the agreement with the owner of the storage was to only modify the lower on/off temperature (when the compressor is shut down). Another constraint was related to a technical limit of the compressor that prevents to have a condensation temperature lower than 20°C. For this reason, it was decided to limit the testing period to summer (July, August and the first weeks of September).

Every ten minutes, the controller checks the weather forecast, then looks for the best set-points to apply during the next 24 hours. The best scenario takes only a few seconds to be computed on a notebook, exploring the performance variation as a function of the temperature inside the warehouse and the outside temperature as shown in Figure 3. Dotted lines in this figure are the predicted values of coefficient of performance for different temperatures inside the storage warehouse.

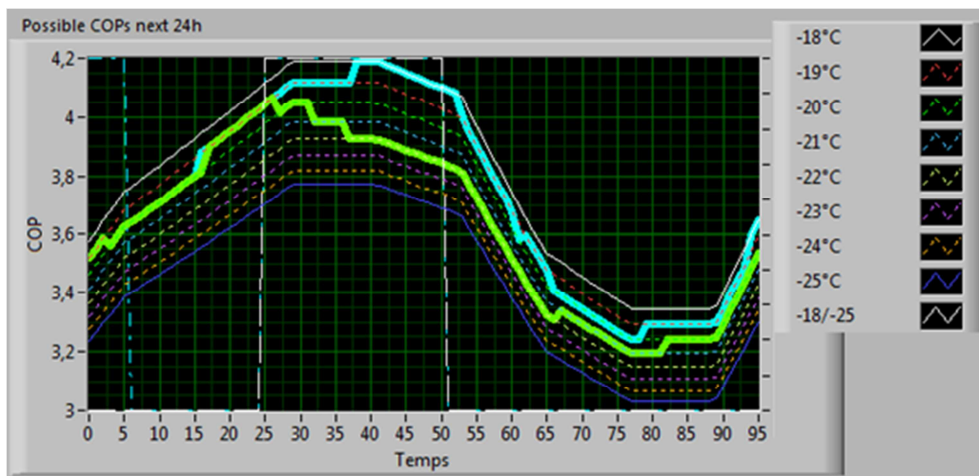


Figure 3 : Predicted coefficient of performance of usual and optimal scenarios for the next 24h

3. RESULTS AND DISCUSSION

Figure 4 shows an example of the temperature evolution inside the warehouse when the controller is activated. Usual set-point used before the controller was -18/-20°C. It can be seen that the temperature could reach -22°C during night. The result is a system running mostly during night with a higher COP (Figure 5) and early in the morning, usually stopping around 10AM depending on the weather forecast. When the outside temperature is high, from 150h to 160h for example, the temperature rises quickly during the morning, due to the activity in the warehouse; in this case, the refrigerating system has to restart during noon to keep a temperature under -18°C. Nevertheless, it runs only a short time.

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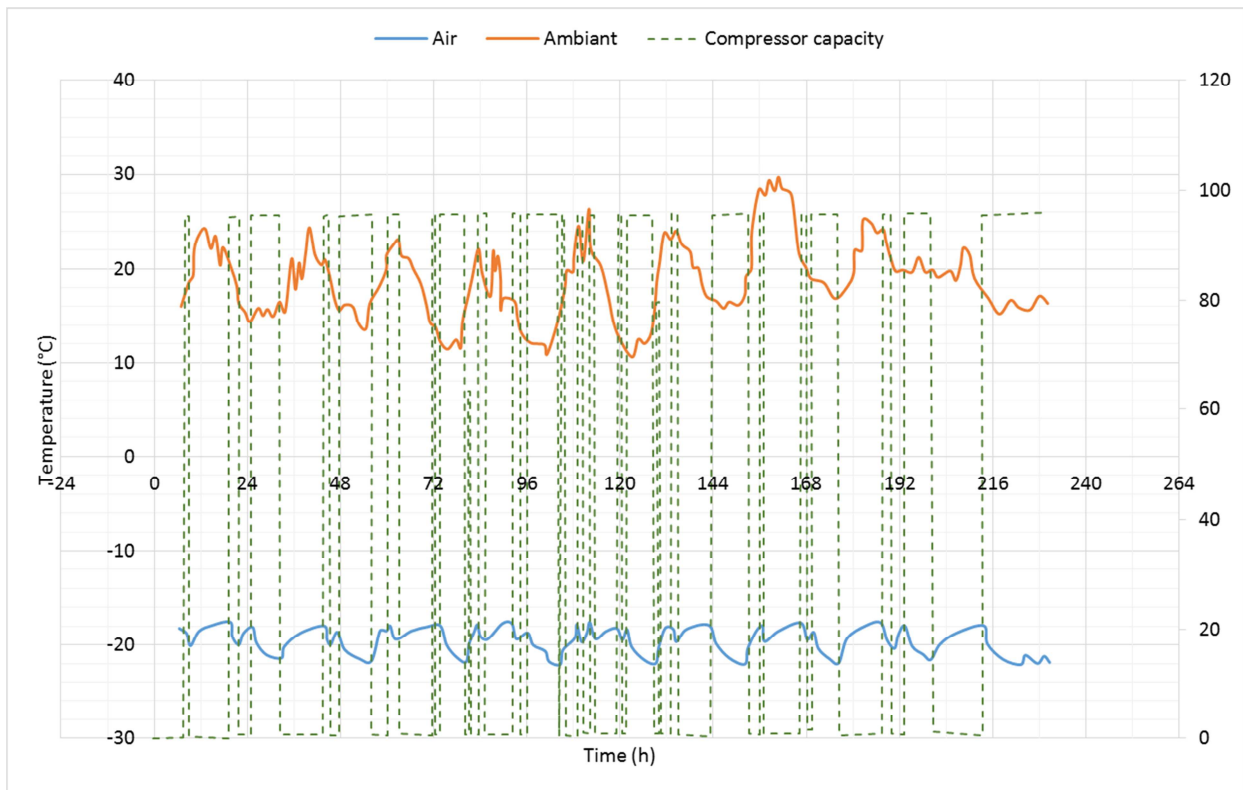


Figure 4 : Outside and inside temperature behavior with the controller activated

Figure 5 shows an evolution of the coefficient of performance during the same period presented in Figure 4. The best performance is obtained if the system only operates in the green zone and the worst performance in the red zone (or below). It can be seen that most of the running time occurs when the coefficient of performance is more than 2.6, mainly in the orange and green zones. Since the air temperature can rise very quickly when the doors are opened, it may happen that the system has to restart in the orange or red zones, but only briefly.

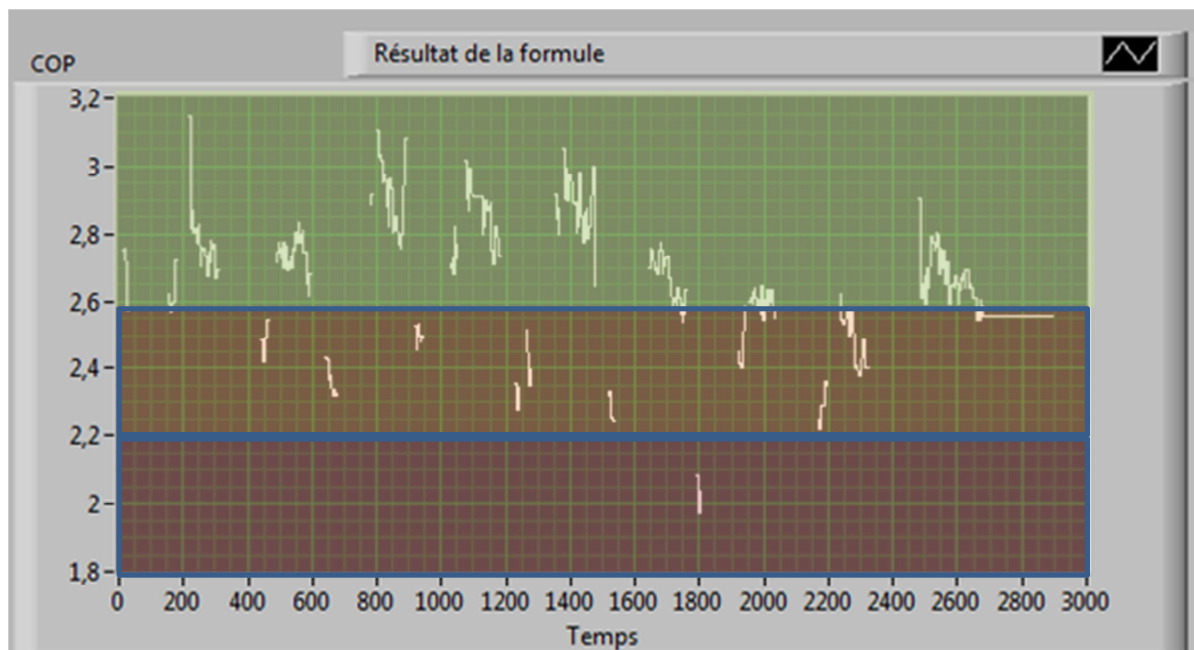


Figure 5 : Coefficient of performance with the controller activated

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Energy use from end of June to the end of September is presented in the Figure 6. This energy use is obtained from 3 energy meters related to the refrigeration systems. The values include the electrical consumption of the evaporator and condenser fans. Controller was active only from end of July to the first week of September. Outside temperature is also presented in the figure. Comparison between “normal” scenarios and optimized scenarios show a 5 to 15% average reduction of the energy consumption, mostly depending of the amplitude of weather temperature fluctuation.

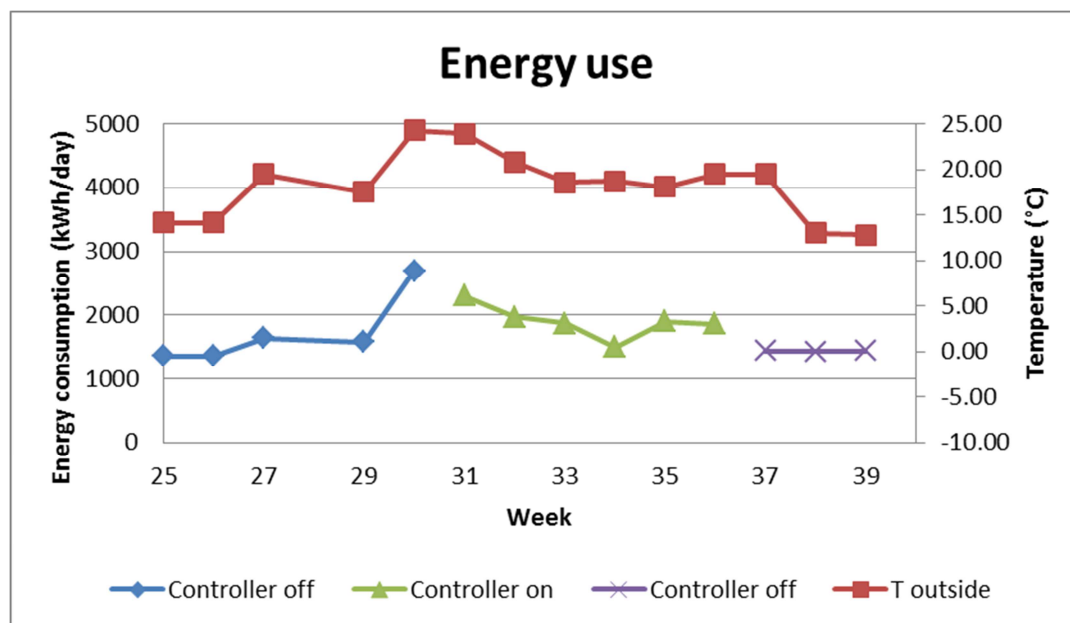


Figure 6 : Energy use related to refrigeration systems with controller on and off

4. CONCLUSION

This experimental test showed that the implementation of a predictive controller is feasible for an existing system and can be combined with an existing controller. The implementation was relatively transparent for the staff working in the warehouse. The constraints due to the compressor technology didn't allow a significant evaluation of the energy performance, but the average energy savings potential when the controller is running, based on daily simulations, is evaluated at 10%. It has to be noted that this kind of strategy causes larger temperature fluctuations and should be not be used with sensitive products. The implementation in a real low temperature cold store was initially challenging but helped the FRISBEE project to give a clear demonstration of the potential of the applied technology shift implemented on purpose. The control technique, though limited by the constraints on the impact allowed in a real production plant, demonstrates a high potential for exploitation of the technology in industry.

5. ACKNOWLEDGEMENTS

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