Model Predictions and Control of Conditions in a CA-Reefer Container

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Abstract

In this paper a concept for energy saving for refrigerated container transport is presented. The concept is based on model-predictive control of the set points of the cooling unit. These models predict energy consumption of the cooling unit, climatic conditions inside the cargo space, and the change in product quality. The objective of the control is to minimize energy consumption while retaining a certain level of product quality. After presenting the concept of the model-predictive control the predictive power of the models used are shown. These models show that we are able to predict energy consumption, temperature, humidity and gas conditions quite accurately. Furthermore, an indication is given for the quality change model to be employed. The impact of the novel control is shown by simulation of a transport of apples.

INTRODUCTION

In a research project we are developing novel ways to control the climate conditions inside a refrigerated sea-container (reefer), equipped with a Controlled Atmosphere (CA) unit. The objective of this new control method is to minimise energy consumption, while retaining a certain (minimal) level of product quality. The control algorithm achieves this objective by making model predictions during shipment. The predictions are based on in-transit measurements of climatic conditions, and available physical models on the energy consumption, climatic conditions, and the product physiology. In order to reach the objective the controller will dynamically change the set points of the container.

In this paper we will present the predictive power of these models, and what is achievable with this Model-Predictive Control (MPC) method (Verdijck, 2000). The model predictions are compared to laboratory experiments. With further simulation for a transport with apples we will give an indication of the impact of the novel control method.

MODEL-PREDICTIVE CONTROL

A schematic diagram visualising the concept of the Model-Predictive Control is shown in figure 1. Based on predictions of future energy consumption and product quality change, the controller dynamically adjusts the set points of the cooling unit of the refrigerated container. The models take the control actions as input, and predict subsequently the climatic conditions of supply air, the air flowing around the pallets with packaged produce, the conditions of the air inside the package, the product quality change, and also the energy consumption of the cooling unit.

COOLING UNIT MODEL

Given the set points this model computes the energy consumption, and also the conditions of the supply air, i.e. its temperature, humidity, and respiratory gas concentrations. Following Jolly et al. (2000), we have built a detailed model of the cooling unit, with modelled components shown in figure 2a. In co-operation with the manufacturer we have built a network model of the steady state heat flows, which are shown in figure 2b. The equations of the model follow by applying Kirchhoff laws (sum of heat flows at each junction is zero), and the constitutive equations delivered by the manufacturer. The model is solved using a modified Newton-Rhapson solver (Broydens method).

This detailed model is part of a larger network model, encompassing other components in the cooling unit, namely the evaporator fan, the heaters, the fresh air intake, and the Controlled Atmosphere unit. The heat flow network representation of the model is depicted in figure 3, where it is shown that it is coupled to the climate models by the heat flow of the supply and return air. Next to the heat flows, a similar network model is used for the flow of water vapour, O_2, CO_2, and N_2. Due to the slow dynamics of the control of respiratory gases, the model also includes the logic for this control.

We have tested the prediction of energy consumption of this model by comparing it to experimental data obtained at our lab and at the manufacturers lab. As shown in figure 4, the model has reasonable accuracy. The tests at the manufacturers lab are according industry standard, performed at specific temperatures given in Fahrenheit. Hence, the test conditions are given in those units in figure 4b.

CLIMATE MODEL

As a function of the conditions of the supply air, the climate model predicts the change in product temperature, humidity and gas conditions in the packaging. The heat flow network is shown in figure 5. Similar models have been built for the mass flows of water vapour and the respiratory gases. The model for the respiratory gas conditions is somewhat simpler, because experiments have shown that there are no gradients in gas concentrations inside the container. The mass flow models are coupled to the heat flow model, due to the heat produced by respiration (P_{resp}) and extracted by evaporation (P_{evap}).

For the production/consumption of the respiratory gases we take a simple respiration model given by Peppelenbos (1996). The aerobic respiration follows a Michaelis-Menten kinetic without inhibition by CO_2, and fermentative CO_2 production does have inhibition by O_2. The model is valid only for low CO_2 levels, a condition valid for refrigerated container transport.

The climate models are solved using Runga-Kutta solvers. The output of the model is fed to the cooling unit model, and the product quality model. We have tested the heat flow network model by comparing it to cooling experiments with a container loaded with 15 tons of apples. From the results in shown figure 6 follows that we can predict quite accurately the average product temperature, which is an important parameter for the product quality. Furthermore, we have tested the mass flow network model for the respiratory gases with CA-experiments on the same container with apples. From the results in figure 7 follows that we are able to predict accurately the change in oxygen.

However, the prediction of CO_2 is a bit off for low oxygen levels, which is probably due to inaccuracy in the parameters for anaerobic respiration. For the purpose of this project this inaccuracy is not very significant, as the product quality is more influenced by temperature, moisture loss, and oxygen consumption (see below). The aim of this paper is to show the potential of the reduction of energy consumption with model predictive control, and hence the improvement of the accuracy of the CO_2 production will be dealt with in a latter part of the research.

PRODUCT QUALITY CHANGE MODEL

Coupling of product temperature, and oxygen consumption to product quality. For apples, which we use in simulations below, the most important quality parameter is firmness. We evaluate the firmness using the model postulated by Tijskens et al. (1999). This model has not been validated fully against experimental data. But, we present it to give the reader an impression of the kinds of models to be used in the MPC-control algorithm.

Tijskens states that firmness related to the abundance of two types of pectines Pc_a and Pc_b, where Pc_a decays under action of PG-enzyme and oxygen, and Pc_b decays in a separate process independent of oxygen. During storage the PG-enzyme level is raised by a first order kinetic. The firmness is linear in the levels of Pc_a and Pc_b. The reaction rates of the pectin decay follow a Arrhenius relation. From the parameter values given by

Tijskens et al.(1999,2001) it follows that the time scale of quality change is much larger than 1 day. Hence, it is expected that daily fluctuations in product temperature or gas conditions around the fruit will not have much influence on the firmness. This finding has been confirmed by experiments performed by Boogaard et al. (2001).

ENERGY REDUCTION

After having validated that the various models have sufficient accuracy, with respect to our project goals, we test the total concept by coupling all models and compute the energy consumption for different scenarios. We apply the model calculation to a 32-day transport of 15 tons of apples from New Zealand to Rotterdam, the main port of Western Europe. The ambient temperature and humidity we take equal to the month-averaged values from the period January to March, which are shown in Table I.

We assume that the MPC control algorithm can change the following set points:

- supply air temperature
- gas conditions (O_2)
- fresh air intake
- air circulation rate

The CA-system of the container operates with a nitrogen membrane system, where the control of CO_2 is indirect. Hence, only the O_2 is taken as a set point. Initial product temperature is 7^0C, and its set point is 4^oC. Under standard conditions, we take fresh air intake is 75 m^3/h, and air circulation is 1 m^3/s.

In figure 8a and 8b we show the results of the simulations using different control algorithms. The graphs indicate 1) the energy consumption, 2) change in firmness, 3) product temperature, 4) gas conditions, 5) moisture loss from product, and 6) R.H. of the air surrounding the product. Moisture loss and R.H. of air around product are also indicative for the product quality. If moisture loss is more than 5%, the peel of apples shrivels, and is unacceptable for sale. If R.H. is 100% condensation occurs, which promotes mould growth.

For the simulation the change of set points is generated by simple rules. In the latter stage of the project the scenarios will be generated an actual MPC Controller. First we have performed calculations for two practical scenarios: 1) transport with constant temperature set point, without CA, and 2) transport with constant temperature, but now with CA. Subsequently, we have calculated two scenarios which allow variations in product temperature and/or gas conditions. These results are shown in figure 8a and 8b.

The average power consumption in the various scenarios described above, is listed in Table II. One can observe from the results in figure 9 that short time variations in product temperature and gas conditions does not have much influence on quality parameters as firmness, weight loss, and risk of condensation (leading to spoilage). But allowing temperature variation means that energy consuming compressors in cooling unit and CA system can be periodically be shut down, leading to significant energy reduction (See Table II).

CONCLUSION

We have shown that by means of Model Predictive Control significant energy reduction in refrigerated container transport of perishables can be obtained without unacceptable loss of product quality. We continue the research by coupling the model to a MPC-controller. Furthermore, we add more detail to the climate model, indicating conditions in bulk and cold and hot spot areas. These details are necessary in order give an accurate estimation of the risk of condensation, which are likely to occur in cold spots. Furthermore, we think our approach has potentials for incorporation of postharvest treatments during transport, such as delayed storage (for prevention of chilling injury) or fruit ripening.

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Literature Cited

Boogaard, H.A.G.M., et al., 2001. Acta Hort proceedings CA2001, Rotterdam.
Jolly, P.G., et al. 2000. Simulation and measurement on the full-load performance of a refrigeration system in a shipping container. Int. J. Refr. 23(2): 112-126.
Peppelenbos, H.W. 1996. The use of gas exchange characteristic to optimize CA storage and MA packaging of fruits and vegetables. Ph.D. Thesis Univ. Wageningen, the Netherlands.
Tijskens, L.W. et al. 1999. Modelling the firmness of 'Elstar' apples during storage and transport.Acta Hort. 485: 363-.
Tijskens, L.W. 2001. personal communication.
Verdijck, G.J.C., Lukasse, L.J.S., and Sillekens J.J.M. 2000. Aspects of Control Structure Selection in Post-Harvest Processes. Proc. Agri-Control 2000, Wageningen, the Netherlands.

Tables

Table 1. Ambient conditions during transport from New Zealand to Rotterdam

Days of travel	Temperature	RH
16	20	85
24	21	95
28	13	85
32	6	85

Table 2. Energy consumption according to various control algorithms

Control Algorithm	Average Consumed Power (kW)
Standard Temperature Control – No CA	4.6
Standard Temperature Control with CA	7.6
Cooling unit compressor cycling , No CA	1.8
Standard Temperature Control, CA cycling	6.1

Figures

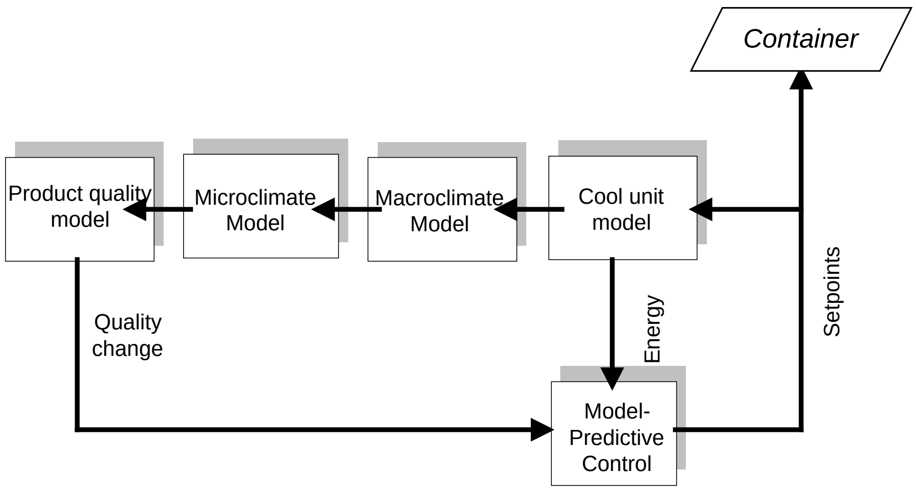
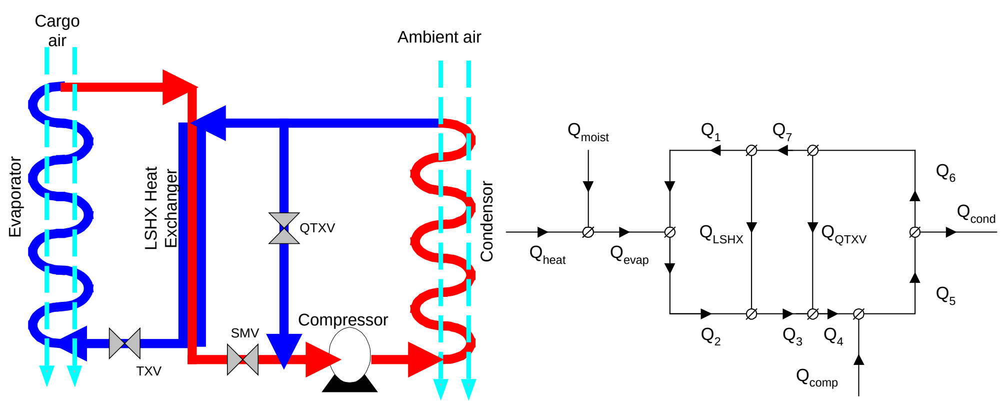


Fig. 1. Schematic diagram of Model-Predictive Controller driving the set points of a refrigerated container. Controller accepts input on energy consumption and product quality change from models.



a) b)

Fig. 2a) Schematic diagram of components in the model of the refrigeration unit, and b) Network diagram of heat flows in model of refrigeration unit. (Q)TXV are thermostatic expansion valves, and SMV modulates the refrigerant flow.

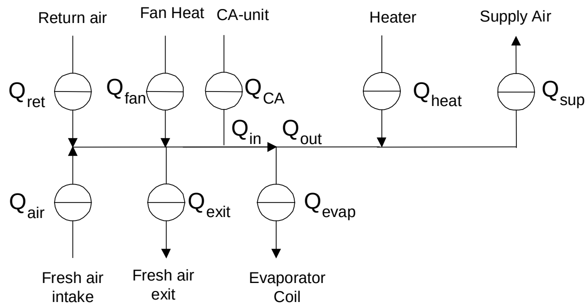


Fig. 3. Network model of heat flows inside the cooling unit, with Q_{evap} given by the model depicted in figure 2.

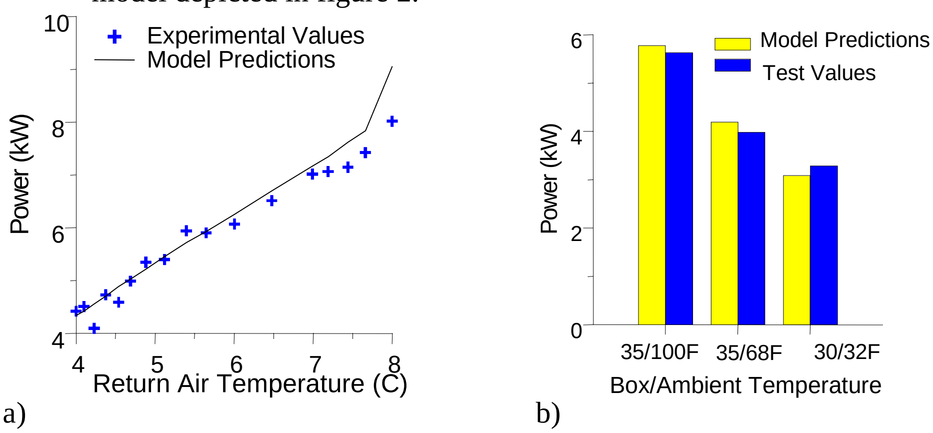


Fig. 4. Comparison of results from the energy model with a) experimental data from our lab, and b) standard test data from the manufacturer.

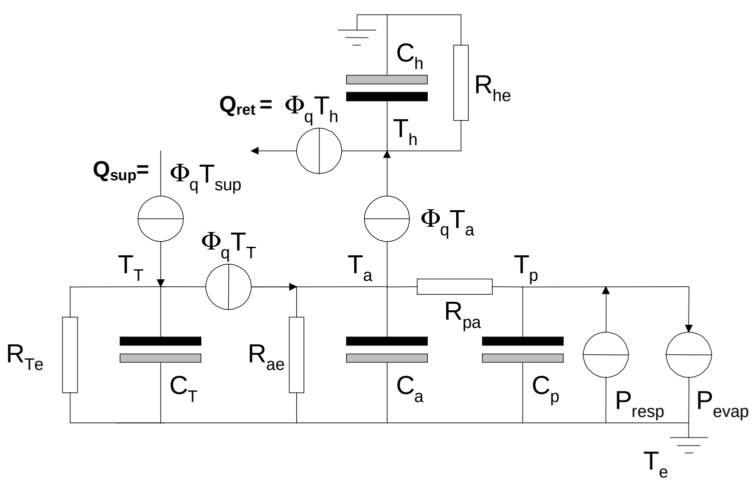


Fig. 5. Network of heat flows inside the cargo space. Coupling to energy model is by Q_{sup} and Q_{ret}. Heat current sources are driven by the airflow forced by the evaporator fan, with $\Phi_q = \rho_a c_{p,a} \Phi_v$, and Φ_v the volumetric flow rate of the fan.

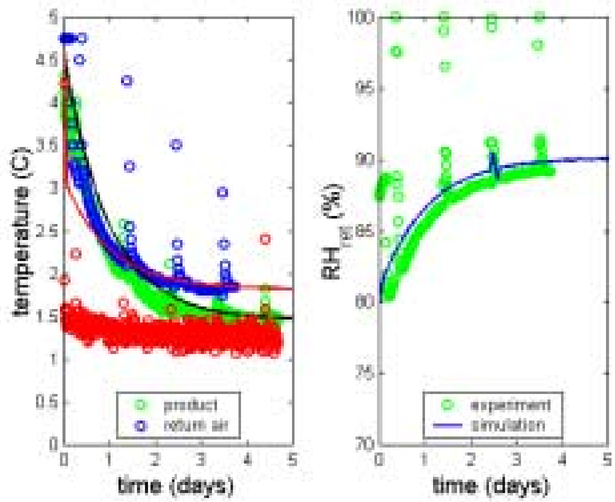


Fig. 6. Comparison of climate model with lab experiment of cooling 15 tons of apples from 5^{o}C to 1^{o}C. Shown are the average product temperature, temperature and relative humidity of return air.

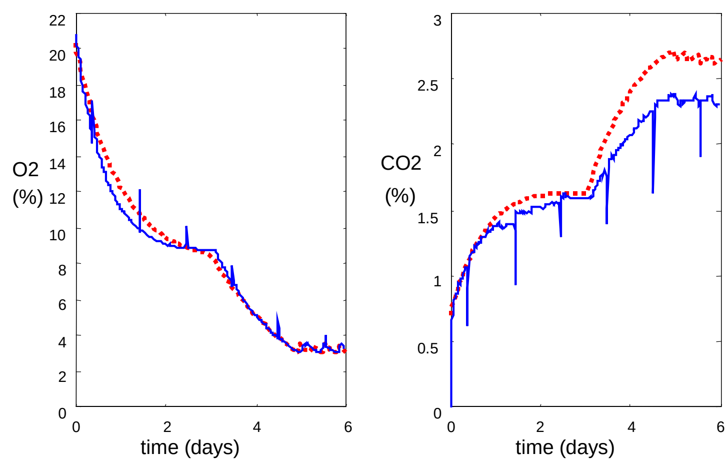


Fig. 7. Comparison of results from the model (dashed line) and CA-experiment (solid line).

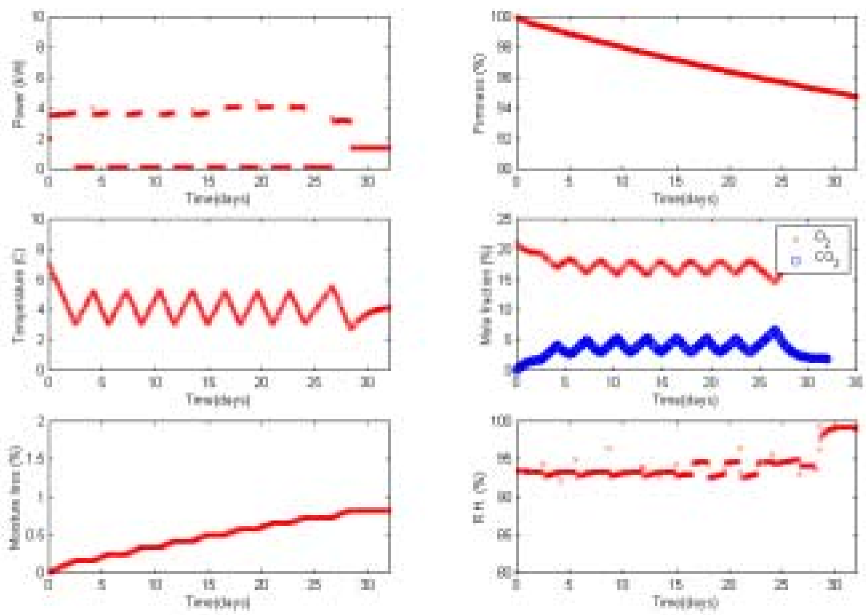


Fig. 8. a. Simulation with control where compressor is cycled on and off, and furthermore Temperature set point and fresh air intake are changed dynamically. CA-system is off and air circulation is 0.5 m^3/s.

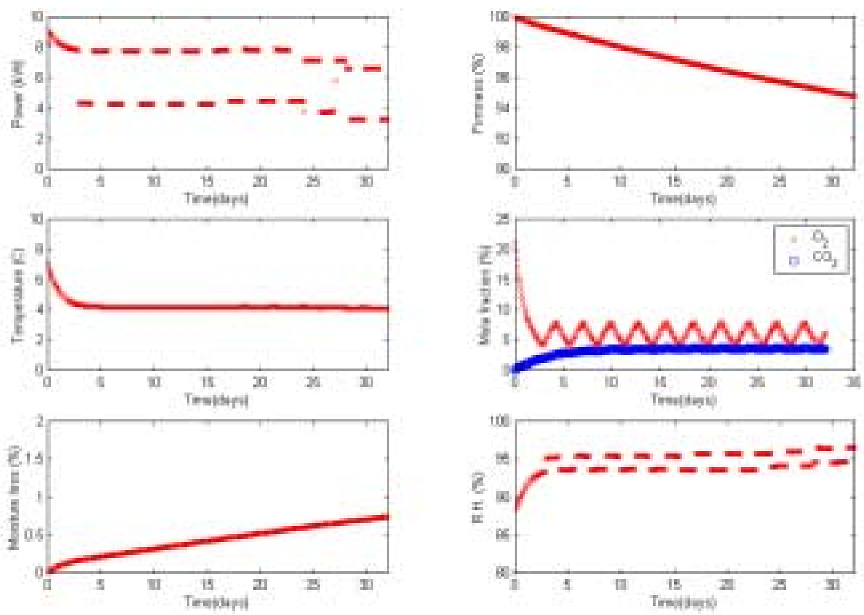


Fig. 8.b. Constant temperature set point (4^oC), but with variable O_2 – set point and fresh air intake control. Average O_2 set point is taken 6%. CO_2 is at about 2%. Air circulation is $0.5\ m^3/s$.