ATO-DLO

CEET2005

Half-year Report
1-4-1999 to 1-10-1999

CONFIDENTIAL

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Contents

page

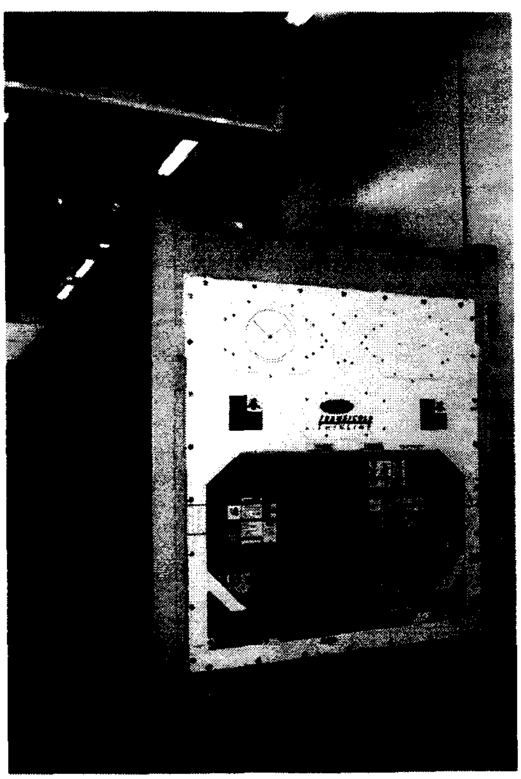
General

Summary

The report gives an overview of activities carried out within the CEET2005 project from April 1999. The half-year period, covered by this report, is the first period in the second phase of the project, the Research and Development phase.

The research activities in this period are summarised per task and per partner in the project in chapter 1 to 7.

Generally, the research shows to yield interesting and fruitful results, emphasising the ideas that led to this project (dynamic advanced control with substantial energy savings). The total input of research-time in the project seems less than planned (this will be reported in more detail within a few months), and as a result certain tasks are lagging partly behind on schedule (see chapter 1 to 7). It is, however, expected that in the coming period this can be compensated for.



In April 1999, a 40 ft. high cube CA reefer container was installed at the research facilities of ATO. The container consists of a CA reefer unit of Carrier Transicold and a 40 ft high cube box of P&O Nedlloyd. The first experiments with the container are described in chapter 1-7. In order to facilitate the experiments, it is planned to have a more flexible and extensive communication protocol with the container within a few weeks.

Introduction

The CEET2005 project is focused to substantially reduce energy within the transport sector, according to EET theme 4. In order to realise this aim for containerised transport of agricultural products, an innovative stand-alone energy-efficient intermodal container will be developed. Key tasks are maintenance of product quality, optimal climate conditioning, energy savings, sustainable energy supply, application of green chemicals, integration of climate and product sensors, logistics and overall system control.

The present report describes the work carried out in the first six months of the second phase. The first research results are presented per task and per partner in the project (chapter 1-7). An exciting part of the project is the multidisciplinary approach and discussions of scientists form plant physiology, biochemistry, microbiology, biophysics, mechanical engineering, thermodynamics, material science and logistics and marketing, activities reflected in the defined tasks. In order to structure the discussions, several meetings have been organised within the project. The total ATO project team has meetings per two weeks. Tasks 2, 3 and 7 have structural meetings with the partners involved ones in about six weeks. Also tasks 6 has joint meetings at the premises of P&O Nedlloyd, where a room for the task 6 project team has been organised.

June 1999, Mr. De Vries and Mr. Sillekens, as co-ordinators of the CEET project, paid a two-day visit to the Carrier Transicold premises in Syracuse, NY, USA.

September 27, 1999, a seminar, consisting of several presentations of the different partners in the project, and a management meeting has been held at ATO. The slides presented at the seminar part are bundled and are a part of this report (Appendix).
For a description of the interaction of the main research issues, the reader is referred to the first progress report of the project (April 1999).

Project layout

The work plan is described at the end of this report. The following persons have made contributions to the work carried out and this report:

Carrier Transicold:	T. Gaubatz	
P&O Nedlloyd:	P. Eekel, E. v.d. Heuvel, M. Wildemans	
Eteca	K. Govaert	
The Greenery International:	J. Smits	
Ecofys:	H. Opdam, J. Schoonderbeek, R. Jonker	
Shell Solar Energy B.V.:	J.W. Hendriks, J. van Vlerken	
ATO-DLO:	H. de Vries	G. Otten
	J. Sillekens	J. Ruijsch van Dugteren
	R. v.d. Boogaard	M. Sanders
	W. v.d. Broek	R. v.d. Sman
	J. Harbinson	E. Smid
	S. Hoogerwerf	M. Strous
	E. de Jonge	S. Tromp
	P. de Leeuw	G. Verdijck
	L. Lukasse	J. Verschoor
	M. van Ooijen	

Publications and PR actions

- Transportkrant (June 99): - interview J. Sillekens (ATO)
- TransAsia conference (August 99): - oral presentation H. de Vries (ATO)
- Fluent User Seminar, UK (Sept 99): - oral presentation and paper R. vd Sman (ATO)
- Reefer conference, UK (Sept 99): - oral presentation T. Gaubatz (Carrier Transicold)

Progress versus project planning

Chapter 1 to 7 present the results, which are in accordance with the project proposal. Since the CA reefer container has been present at ATO since April 1999, the experiments with the container (which had been planned for next year) have been partly shifted. Although it has taken some time for the container to be operational, at present the container is fit for experimental work.

Realisation project aims

So far, there are no indications that the project aims will not be met, on the contrary. First DCS results have demonstrated the improved quality of e.g. apples and thus strengthen the here chosen approach (instead of more or less static CA conditioning). The controllable ventilation unit of Carrier Transicold is the first step in realisation of DCS in containers. Further practical results in phase 2 will elucidate the application possibilities of CEET. See also chapter 1 to 7.

Bottlenecks

The withdrawal of NDX Intermodal from the CEET project, as described in for instance the previous progress report, has not become a bottleneck. P&O Nedlloyd has integrally taken over the task form NDX Intermodal.

Milestones

Milestones are identified later on in the project (end of phase 3). A set of deliverables is identified for each task.

Evaluation parameters

The reader is referred to chapters 1-7.

Project layout

The work plan for each individual task is described including interrelations with other tasks in the chapters 1-7. Within each task, the work is described for the various partners.

1 Task 1: Optimisation of product quality under varying conditions

1.1 Contribution of ATO

Introduction

The main focus of task 1 is to assess quality of fresh products in a changing environment. Until now research on assessing quality has nearly always been based on static systems (constant T, O_2, CO_2, RH, etc.).

Changing from a steady state controlled atmosphere to a dynamic controlled system requires knowledge of product dynamics (or adaptation behaviour). This is one of the reasons why we have been focusing on the product response to temporarily changing climate conditions. A second reason is that during transport energy levels might become to low, resulting in variations in conditions and not optimal storage conditions.

To describe changes in fruit and vegetables it is necessary to monitor quality and physiological state. To characterise the physiological state of a product, important tools are: CO_2 production, the oxygen consumption, ethylene production, diffusion of ethanol and acetaldehyde, heat production, and water loss.

Results

In this period we focused on two different ways of climate control:

- Control of solely temperature
- Controlled atmosphere (CA) conditions (T, CO_2, O_2, RH).

Effects of temperature changes

In figure 1 the effect on ethylene production is shown when tomatoes are switched between 10 and 20 °C at 21 % O_2. The tomatoes were first measured (t=0) after 3 days storage at the desired conditions.

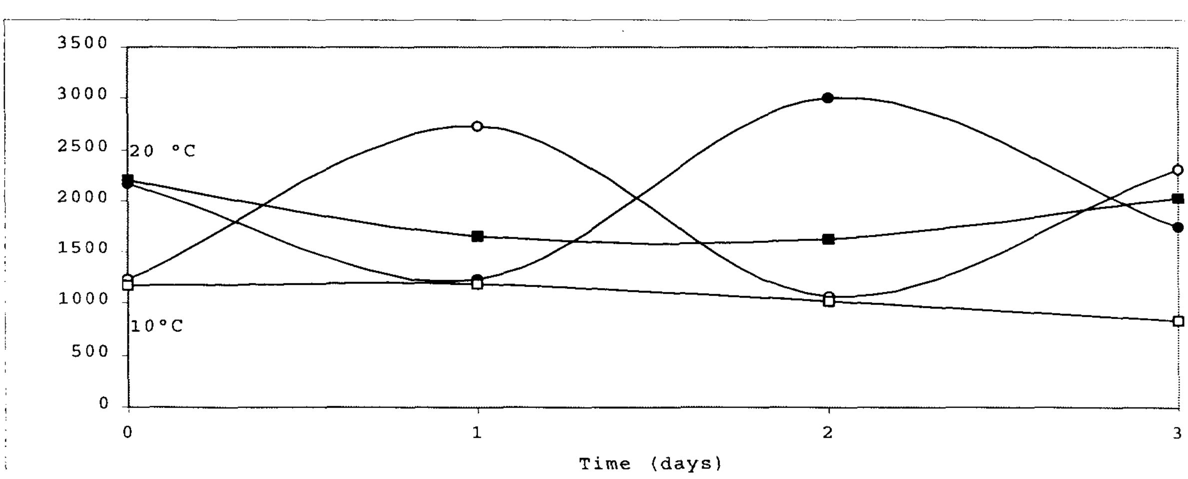


Fig 1.Effect of temperature on ethylene production (nL/kg.h) at 21% oxygen (tomato).
Symbols: □ constant 10 °C; ■ constant 20 °C; ○10-20-10-20°C; ● 20-10-20-10 °C.

Ethylene production was enhanced when tomatoes were transferred from 10 to 20 °C, whereas at transferring tomatoes from 20 to 10 °C the same ethylene production level was reached.

CO_2 production or O_2 consumption was measured directly after closing the sample flask and after 2 hrs. From the difference in concentration in the headspace the CO_2 production or O_2 consumption was calculated. The effect of O_2 consumption and CO_2 production follows the same pattern as the ethylene production. The response time for ethylene production, CO_2 production and O_2 consumption to change in temperature of 10 °C is less then 24 hrs.

Effects of changing gasconditions

Figure 2 shows the CO_2 production of tomatoes at 10 °C. CO_2 production at 21 % oxygen decreases to a steady state level, whereas at 0 % there seems to be a linear decrease in CO_2 production. An interesting question is does a steady state CO_2 level indicate that the product is adapted to the condition?

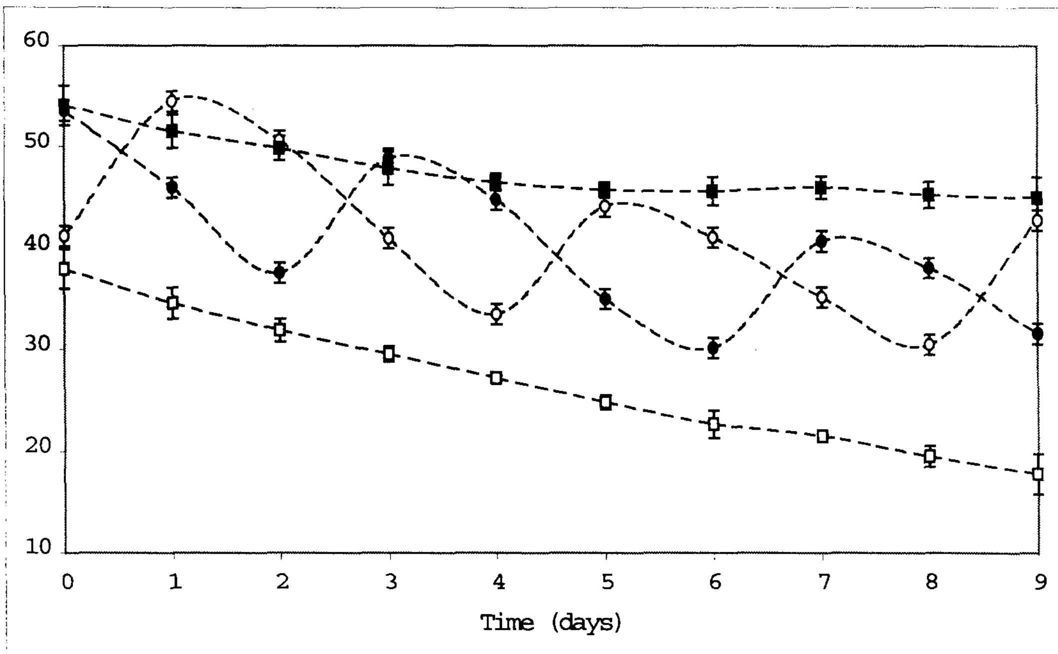


Figure 2. Effect of oxygen on CO_2 production (nmol/kg.h) at 10 °C (tomato). Symbols : □ constant 0% O_2;■ constant 21 % O_2; ○ 0-21-0-21% O_2 ● 21-0-21-0% O_2. Conditions were changed directly after measurements on day 0,2,4,6 and 8.

Adaptation to lower O_2 levels at 10 °C requires a longer response time (3-4 days) compared to the adaptation time to higher O_2 levels.

One way to produce energy at low oxygen concentrations is a pathway in which pyruvate is metabolised to acetaldehyde. In a second step acetaldehyde is enzymatically converted to ethanol, which accumulates in the tissue. Because of the difference in diffusion rates (acetaldehyde diffuses faster than ethanol) the amounts which are measured in the gas flow are not exact production rates. Ethanol and acetaldehyde diffusion to the headspace can be measured directly in the gas flow (figure 3).

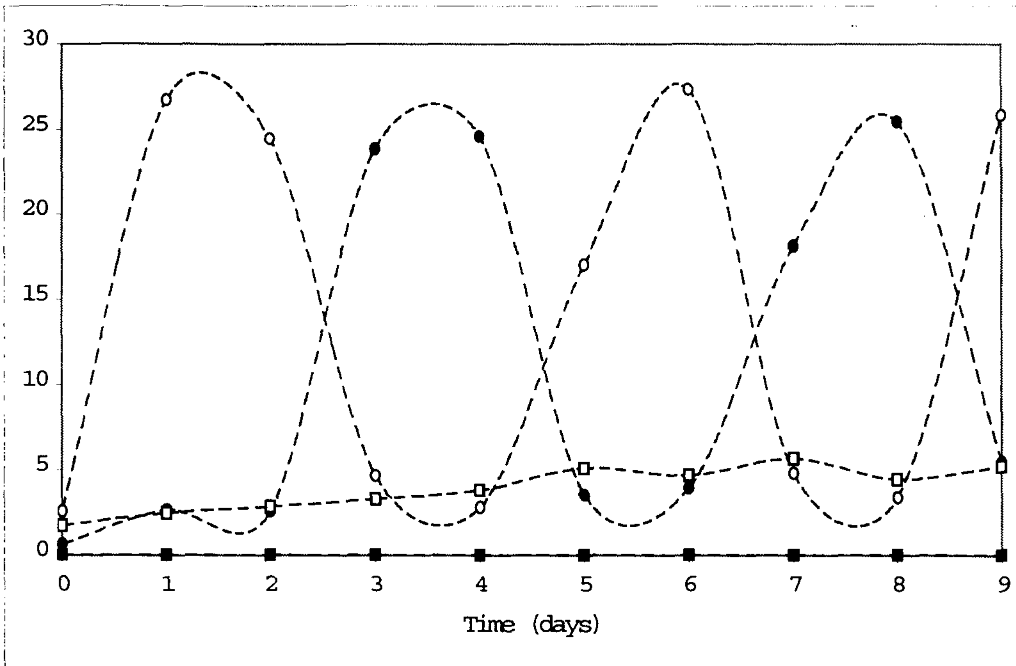


Figure 3. Effect of oxygen on acetaldehyde concentrations (μL/kg.h) in the headspace at 10 °C (tomato). Symbols : □ constant 0% O2;■ constant 21 % O_2; ○ 0-21-0-21% O2 ● 21-0-21-0% O_2. Conditions were changed directly after measurements on day 0,2,4,6 and 8.

Acetaldehyde concentrations increase sharply after a period of low oxygen, the produced ethanol, which doesn't diffuse out of the product, is directly re-metabolised to acetaldehyde. Another possibility is that other precursors of acetaldehyde accumulate and are directly converted. At 21 % oxygen there is no measurable quantity acetaldehyde or ethanol produced.

Conclusions

The physiological state/behaviour of a product at a certain environmental condition is dependent on the "history" of the product.

Adaptation of a product to an upsurge in oxygen or temperature or a decline of these parameters is substantially different. It should be noted that elevated levels of ethylene speed up the ripening process. Elevated levels of acetaldehyde may lead to degradation of plant tissue, since one deals here with a reactive volatile. Carbon dioxide production is linked to heat release; better-defined relations are focused on within the next period.

The temporal control of climate conditions in the container can be related to the period necessary for the product to adapt to the changing in climate.

To predict respiration rate, ripening etc. under varying conditions models are needed, that can describe product quality in a dynamic way.

On-line measurements of metabolites such as ethanol, ethylene can be helpful to assess the products physiological sate.

Deliverables

Task 1.1 (Heat release over the entire storage period) and task 1.2 (Fruit post-harvest physiology) delivered insight in changed adaptation for either increased or declined levels of temperature and oxygen. These results implicitly indicate the physiological state of the product and thus heat release.

Requirements from/interactions with other tasks

Task 2: Data about the characteristics (flow rates, temperature profiles, O_2 profiles, CO_2 profiles) of the CA unit. Based on these parameters experiments will be set-up and the required sensitivity for the sensors can be estimated.
Task 4: Green chemicals in combination with gas conditions will be tested on the model products on an experimental scale. Effects of these chemicals on the micro-organisms and model products will be monitored.
Task 5: With data from experiments based on the characteristics of the CA unit the sensitivity of the sensors can be discussed. If any operational sensors are available they can be tested.

Evaluation parameters

The dynamic experiments give a first guess about the possibility to be less strict in the range the climate is allowed to be changed. Thus, instead of focusing on keeping the temperature within 0.25°C constant, this range may be substantially larger. Consequently, the energy demand of the control unit may be less. So far, this can not yet be quantified.

Time schedule

In the next period experiments will be mainly focussed on adaptation of the model products to changes in CA conditions. Other experiments will also be carried out based on the containers CA characteristics (flow rates, temperature profiles, O_2 profiles, CO_2 profiles, variations in temperature, O_2 and CO_2). These experiments will be performed in close cooperation with task 2.
The time schedule of the previous report still holds.

1.2 Contribution of The Greenery International

Introduction

The Greenery International as internationally operating marketing and sales organisation for fresh fruits and vegetables is importing and exporting fruits and vegetables per a.o. reefer container and by air. There is an ongoing interest to cut on costs e.g. by replacing airfreight in reefer transport and to win on product quality e.g. by more optimal atmospheric conditions during boat transport.
Furthermore The Greenery is committed to sustainable production and distribution.
In the above-mentioned perspective CEET2005 is an important and strategic project for The Greenery International.

Aim

The aim for the Greenery is to implement new technology and new tools in order to save on transport costs, to save on energy-input and to improve on product quality. In this project The Greenery is supplying fruits and vegetables for quality assessments by ATO-DLO. Furthermore The Greenery is delivering information on experiences with container shipments, product quality information and quantitative information about export and import of fruits and vegetables.

Results

There is commercial interest in exporting by reefer container to the U.S for tomatoes on the vine and for bell pepper. At present large quantities of both products are airfreighted. For import there is commercial interest in replacing air transport of green beans into reefer transport. In case of measurable quality improvements due to better atmospheric conditions in the container there might become commercial interest for products like nectarines, strawberries, mango's etc. The idea is that because of improving shelf life in the container, products can be picked more mature for better flavour.

For bell pepper huge price fluctuations between successive weeks occur. Bell peppers per reefer container arrive on the US-market at the same time as one week later air-freighted bell peppers. This implies that in 1999 in 50 % of the weeks bell peppers by air-freight could be offered for lower prices (and with better quality) to the US customer than peppers transported in reefer containers. Supplies-forecasting and with that the possibility of estimating price increase or decrease is a useful instrument in order to prevent the above-mentioned situation.

Products like bell peppers and tomatoes on the vine can only be exported by reefer container if they are of absolute perfect quality. There is the experience that only selected growers with specials varieties and programs to ensure quality during growth, harvesting, grading and packing are delivering the required quality. Controlling and auditing is needed to assure this.

Deliverables
Information-sheets are forwarded to the experts of ATO-DLO for task and task 6. An excursion was organised to The Greenery-trading to judge container import of avocados for two ATO-experts and to judge the filling of a container with bell peppers for boat transport to the U.S. A presentation was given at the seminar of September 27 1999.

Resources
From 01/04/99 till 30/09/99 48 hours were invested in the project.
It is expected that in the next period equal amount of time will be invested. ATO-DLO will be supplied with the necessary products.

Requirements from other tasks
From other tasks the tools (models) are required with which can be decided - in a commercial setting - either to choose for air-freight, reefer container transport or reefer transport in the to be developed sustainable container. These tools must be able to give clear insight in the effect of this choice per (model supply chain and product) on costs, product quality and energy-use.

Evaluation parameters
- Information and documentation about optimal climatic and atmospheric conditions for reefer container-transport of several products from Holland to the U.S. and for import from Southern countries to Holland; the residual shelf-life of the products after boat transport.
- Information and documentation about prerequisites in the chain and for the chain partners for successful reefer container-transport (per product).
- Information and documentation about product characteristics as are determined in task 1.
- Information and documentation for an operating decision-model for choosing the means of transport.
- Implementation of the above-mentioned information in practice.

2 Task 2: Optimisation of climate control under energetic and quality constraints

2.1 Contribution of ATO

Introduction

This task models the physical transport phenomena in the container (airflow, heat, vapour and gas transport) and the working of the refrigeration/controlled-atmosphere unit. Models will be developed at the following levels:

1. product level
2. micro level (packaging)
3. macro level (container)
4. controller level (refrigeration/CA unit)

Low level models will be simplified and aggregated into the models at a higher level. This results finally in a simple, but reasonably accurate macro-model for use by the supervisory controller. The macromodel will predict the climatic conditions on average and at critical points in the load. Furthermore, the model predicts the amount of energy demanded by the refrigeration/CA unit.

Aim

The aim of this task is to deliver a simple model, describing the climatic conditions inside the container, for use by the supervisory control algorithm, to be developed in task 7. Here we take a dual approach: a top-down approach delivers a rough template for the final model, which is to be used by the supervisory control algorithm. By a bottom-up approach the final model is constructed from reliable models having a more detailed description of the physics in the container. The bottom-up approach will validate and refine the 'crude' model obtained by the top-down approach.

Results

In the last period we have worked on four activities:

- 2.A First prototype-model of the packed products inside the container.
- 2.B Experimental design for measuring thermophysical properties of produce.
- 2.C First model on cooling of individual products.
- 2.D Refrigeration unit model

The model developed in activity 2.A is build for the purpose that task 7 can start developing now its model-based supervisory control algorithm. We anticipate that the structure of the final model describing the macroclimate has similar structure as this first prototype, and can serve as a template for developing the supervisory control algorithm.

In activity 2.B experiments are designed for measuring thermophysical properties of agricultural produce; a prerequisite for having reliable models describing the behaviour of packed products in the container.

Activity 2.C is a first trial of applying a mathematical procedure of obtaining simplified model for detailed (finite element) models, which we intend to apply in this project in order to obtain the final model for models on the product level (bottom-up approach).

In activity 2.D the structure of the first prototype model is laid down. Furthermore, measurements have indicated the components using large amounts of energy.

The results obtained in these research activities will be described in detail in appendices 2.A-2.D.

Deliverables
In this period the crude macro-level model developed in activity 2.A is delivered to task 7. Furthermore an experimental design for the measurement of respiration and transpiration is delivered to task 1.

The model developed in activity 2.C is presented at the Fluent User Seminar in Sheffield, 16-17 September 1999. In the Appendix 2.C one finds a reprint of the paper presented.

Time schedule
No time has been spent on subtask I.1 (measurements of airflow in packagings). In the coming period this task will be performed.
In task 2 the following subtasks will be performed:

- P.2 Analysis of respiration and transpiration of products.
- I.1 Development of airflow model
- I.2 Development of thermal and humidity model (partly).
- M.2 Development of network airflow model
- C.1 Identification experiments
- C.2 Development of first prototype of refrigeration-unit model

Evaluation parameters
First experimental results indicate that improvements of the control algorithm, without any modification to the reefer's hardware, can make significant energy reductions. The possible success of this control algorithm can be decoupled from the rest of the project; it will be applicable to any refrigerated container and probably even to any refrigerated storage or transport facility.

Energy saving by more efficient operation of refrigerating units is only possible at the expense of introducing small temperature fluctuations. ATO product experts have no evidence that high-frequent 1°C product temperature oscillations harm the product. As a side effect of temperature oscillations the relative humidity may be reduced due to more condensation on the evaporator, this may constraint the permissible temperature range and hence the possible energy saving.

2.2 Contribution of Carrier Transicold

The contribution of Carrier Transicold will be communicated seperately.

2.3 Contribution of P&O Nedlloyd

Aim
The aim of this project is to develop a Container with a much better K-value then the present Reefer Containers. In this way we need less power to keep the cargo temperature controlled which is contributing to the total power saving.

Results

At the moment we have no concrete results regarding actual testing however some calculations proved that the K-value can be reduced by some 30% to 35% of the present value when we decide for a new foam technique.

We are discussing with a Chinese Container manufacturer and some European foam manufacturer's the possibilities for a new foam technique. As soon as we have some results we will inform the project team accordingly.

After we have decided what kind of foam panels we will use, some test panels will be built on which we will actually do strength tests and heatleakage tests.

3 Task 3: Development of a robust integrated sustainable energy system

3.1 Contribution of Ecofys

Introduction

Reducing the energy demand of the container puts weaker requirements on the energy supply system and increases the number of optional supply systems. Therefore Ecofys has been exploring ways to reduce the containers energy consumption assuming constant climate conditions. After that, we have focused our efforts on the selection of a suitable energy supply system.

Power consumption CA-unit

It can be considered daring to propose changes to a climate system without knowing the effects on reliability. Still Ecofys suggested changes to the containers atmosphere control system in order to reduce the power being consumed to maintain the required climate conditions.

Heat recovery after condenser

A compressor in combination with a condenser is used to dehumidify and clean the inlet air before it is supplied to the nitrogen filter. An electrically powered resistance heaterreheats the air to the temperature required by the filter. A modification to this configuration would be to insert a heat exchanger between the compressor and the condenser. This could reduce the power needed to cool the condenser and reduce the power consumed by the reheater.

Dehumidification with dessicant wheel

The installation dehumidifies the inlet air by compressing and cooling the air so vapor and dust can be removed. A modification would be to dehumidify the inlet air by means of a dessicant wheel. This could make the condenser redundant and thus reduce the demand for cooling. The temperature increase caused by the compressor would reduce the demand for heating the air before it is supplied to the filter. Possibly the heater would be redundant too. Warm air from the main condenser fan can be used to dry the dessicant wheel.

Air recycling during initial conditioning

During initial conditioning after stowage, container air is replaced with filtered inlet air. As conditioning proceeds, the replaced air gets nearer to the required conditions. A modification would be to reuse the inside air instead of treating outside air. This would reduce the time and energy required to condition the air inside the container.

Energy supply

Current CA-containers and container infrastructure are highly optimized to meet actual market demands. Developing an energy supply system that is more efficient, more reliable or based on renewable sources is therefore challenging. However, several conditions can be distinguished that enable the application of energy supply systems likephoto-voltaic cells or fuel cells.

Continental transport

During sea transport, containers will usually be supplied with electricity from the ship. Efforts to improve the efficiency or apply renewable sources can turn out favorable, but will not take effect on the containers installation. Transportation on trains or trucks usually involves a per-container energy supply. This offers possibilities to apply renewable, cleaner or more efficient sources, e.g. photo-voltaic cells or fuel cells.

Drastic reduction of power consumption
Container installations have been optimized to offer very high reliability. Little attention to power supply has led to relatively high power consumption. This makes it difficult to match the energy demand with an energy supply from renewable sources, which typically offer a low capacity with a high cost to power ratio. Reduction of the containers power consumption by 50% would seriously favor the cost effectiveness of energy supply systems from renewable sources.

Autonomous operation
A need for the container to run autonomously, e.g. during transfer or storage, would favor the use of an energy supply system that runs virtually without maintenance or fuel refilling. This would typically make the container suitable for the use of a photo-voltaic energy supply system.

Future developments
In the coming period, Ecofys intends to cooperate closely with P&O Nedlloyd to evaluate the market potentials of a container that combines the advantages of a renewable, cleaner or more efficient energy supply system with less compliance to the current standards for reefer containers (in co-operation with task 6). Close cooperation with ATO-DLO will enable us to draw conclusions on the energy demand of the container (co-operation with task 2). The outcomes will be used to value optional supply systems in ecological, economical and technological detail.

Time schedule
At the end of 1999 all restrictions of applying any energy supply system must be clear. In the first three months of 2000 the resulting options of the energy systems will be thoroughly studied with respect to technical and economical feasibility.

3.2 Contribution of Shell Solar Energy

During the last period, Shell Solar had contributed to several discussion-meetings with Ecofys, P&O Nedlloyd and ATO-DLO. Besides, an overview of and a tour trough the production facilities of Shell Solar has been given.

Especially the energy demand of the container and the performance and robustness of solar panel systems have been topics in the discussions. Although for intercontinental see-transport robustness may be a shortcoming of solar panels, application of solar panels for inland intermodal transport and transshipment areas seems to be feasible.

4 Task 4: Development of slow-release systems for green chemicals

4.1 Contribution of ATO

Introduction

From an agro-industrial point of view, plants are a very obvious source natural antimicrobial and are known to contain antimicrobial or medicinal metabolites. In many instances, these compounds play a role in the natural resistance or defence against microbial or other diseases. A wealth of literature exists describing their favourable properties and identifying the active components. In general, herbs and spices and several of their active ingredients have been Generally Recognised As Safe (GRAS), either because of their traditional use without any documented detrimental impact or because of dedicated toxicological studies. Their application in postharvest crop protection may be facilitated by this feature although appropriate toxicological evaluations cannot be passed-by in any legislation.

Aim

The aim of task 4 is to implement the use of green chemicals in the climate control system of the container. In principle this is an energy efficient means of preventing deterioration of the perishable product, since the requirements for temperature and humidity control can become less strict.

Results

In the second half year six months of the project the screening programme including 9 natural antimicrobials has been completed for *Botrytis cinerea, Rhizopus stolonifer* and *Penicillium expansum* (see appendix Task 4). We investigated the inhibition of germination of conidia and the delay in linear growth of the mycelial mat at different doses of the selected compounds. Decanal and E-2-pentenal were found to be the most potent antifungal agents towards *B. cinerea* and *P. expansum.* E-2-hexenal was also the most active inhibitor of *R. stolonifer.* However, the latter fungus was relatively insensitive towards decanal. Microscopic analysis revealed that *R. stolonifer* forms special survival structures in response to exposure to decanal. For the second phase, E-2-hexenal and decanal are selected for further research.

The effect of exposure of conidia of *Botrytis cinerea* to decanal administered via the gasphase was investigated in more detail. Decanal (approximately 35 µg/l) was found to reduce the viable count of *Botrytis* conidia by 1 log cycle in 20 minutes. This observation indicates that decanal act as a fungicidal agent on *Botrytis* conidia.

Long-term growth studies have shown that the inhibition of mycelial growth of *B. cinerea* is complete for at least 18 days at 8°C. AT 18°C however, full suppression is observed for only 8 days. This can be explained by the observation that decanal is sensitive for chemical oxidation (oxygen) and bioconversion by *Botrytis cinerea.* Both processes lead to a drop in the headspace concentration of decanal resulting in decreased antifungal activity.

Deliverables

E-2-hexenal and decanal are selected for research in phase 2.
Decanal acts as a fungicidal agent on *Botrytis* conidia
Decanal is sensitive for chemical oxidation (oxygen) and bioconversion by *Botrytis cinerea.*

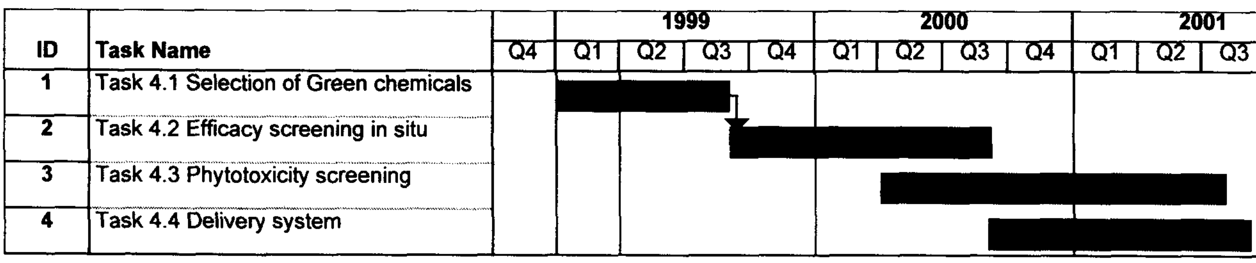
Requirements from other tasks and partners

Execution of task 4 will be performed in close collaboration with task 2 (climate control), task 5 (monitoring systems) and task 7 (system control). Other partners directly involved are Carrier Transicold and P&O Nedlloyd.

Progress in relation to planning

Work on task 4 of the project is progressing according to general project planning. In the second year, the Screening of natural antimicrobials will be continued on *Pseudomonas marginalis*, *Monilinia fructigena* and *Alternaria alternata.* In addition, we will start the ***in situ*** activity testing of selected plant derived antifungal compounds.

Time schedule



5 Task 5: Monitoring the surrounding environment and the product response

5.1 Contribution of ATO

Aim

The objective of task 5 within CEET2005 is to develop sensors that can monitor product traits and the product environment such that these measurements provide the required information to be able to control product quality. The sensors to be developed should detect warning signals of product deterioration, due to excessive respiratory activity, ripening, or attacks by pests and pathogens. Such signals can subsequently be used to control the product environment and thus prevent further quality loss.

For monitoring product traits in the container, two types of sensors will be developed. Firstly, a *volatile detection system* will be developed to measure signs of product deterioration, such as anaerobiosis, ripening or damage due to pathogens. Secondly, a *particulates detector* will be developed to detect the presence of fungal spores. In addition, the product environment needs to be monitored to ensure the proper conditions for maintenance of product quality. Therefore, we have chosen to develop a combined *CO_2/O_2 sensor*, since manipulations of the CO_2 and O_2 concentration in the air are an important means of controlling product respiration and ripening. All sensor systems require sophisticated *signal processing and calibration*. Finally, we will assist in developing a system for the *measurement of heat production* in conjunction with respiration. This type of measurement system is required to provide data for the climate control model.

In order to measure product quality and product environment under container circumstances, the utilised sensors must be tested for sensitivity, durability, reliability, robustness, low energy consumption and must be low-cost. Further boundaries for the sensors to be developed are set by the fact that direct measurements on products in a container are hard to realise, as products in a container are packed in boxes and a container should be able to function stand-alone. Thus, the implementation of sensors that need to be in contact with or close to the product is physically limited. In contrast, measurements of thevolatiles in the air surrounding the product in a container seem much more attractive and feasible.

The sensor limitations will be established in the course of phase 2. The requirements of the sensors depend on the concentrations of volatiles in the container, which are unknown at present, as they depend on the final climate control regime such as e.g. the rate of refreshment of air determining the concentration of volatiles released from the products.

Results

CO_2/O_2 Sensor

For this sensor, two detection systems will be combined in one housing:

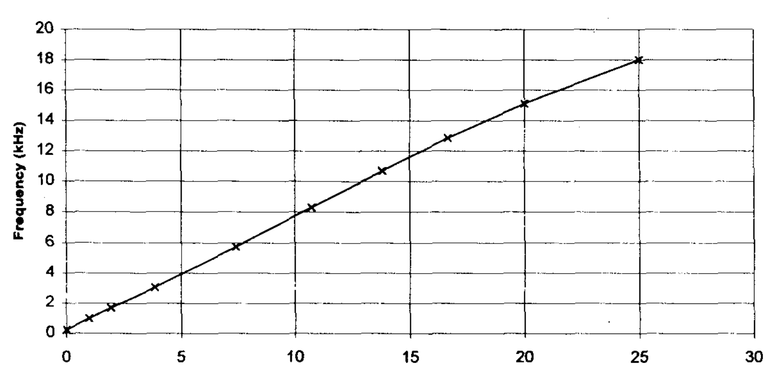
A 4.23µm infrared absorption measurement system for CO_2 was described in the previous report. We have found this device already packaged with a read-out system etc and available in the Netherlands from CaTec. At this point it seems better to use the packaged form of the sensor rather proceed with building our own readout/control unit.

O_2 sensor

For fruit and vegetable storage conditions under controlled atmosphere, a reliable and sensitive oxygen sensor is needed to accurately measure oxygen at concentrations of around one percent (v/v). Most existing sensor designs are expensive or require regular maintenance, calibration or replacement. The principle of fluorescence and luminescence quenching of some dyes by molecular oxygen has been known for many years, but low-cost, stable and accurate commercial sensors are not available. We have developed a sensor, based on luminescence lifetime measurements, that uses low-cost, off-the-shelf components. The dye, a palladium porphyrin with a very long luminescence half-life, was custom synthesised and thus expensive, but with one gram of the dye is sufficient for thousands of sensors. The total cost for materials per sensor is estimated to be around $100. The innovative aspects of this development are the construction of the sensing layer and the method of measuring the half-life, so that the sensor output without the addition of linearization circuitry is nearly a perfectly linear function of O_2 concentration. The luminescence lifetime measurement is based on a so-called 'Phase Locked Loop' (PLL), which is a common circuit in high frequency electronics. This circuit comprises a voltage controlled oscillator (VCO), a phase comparator and an integrator. A blue light source, used to generate the luminescent state in the dye, is driven from the output of the VCO and, and the red luminescent signal from the dye is amplified and input to the phase comparator. The circuit forms a loop that maintains a constant phase shift between these signals, by varying the frequency. Changes in the O_2 concentration produce changes in the lifetime of the luminescent state and thus the frequency output of the phase-locked –loop.

The prototype sensor is capable of measuring at normal air conditions with 21% oxygen, while maintaining excellent sensitivity and accuracy at low oxygen levels. Because the intensity of the luminescence signal decreases with increasing oxygen concentration because of quenching, the measurement is most accurate and stable at low O_2 concentrations.

The effect of changing the humidity of the air being measured is very small, about one percent of the signal output from dry to saturated air. There is a bigger effect of changing temperature on the response of the sensor; a one percent signal change is produced per degree Celsius, but this can be compensated for by simultaneous temperature measurement. As the sensor measures oxygen partial pressure, an atmospheric pressure dependent correction must be applied to get a volume percent O_2 value (if this is required). For this, a small monolithic absolute pressure sensor is included in the design. All compensation and linearization will be done by a simple microprocessor system included in the sensor housing.



Further work will be done on improving the linearity, temperature compensation and producing a production prototype. This will require further improvements on the optical system, the composition of the sensing layer and writing the software for the microprocessor. The sensor will be built into a compact, waterproof metal housing, with a compensated 0 to 5 V analogue and RS485 digital output. Using the analogue output, it can be used as a replacement for the currently used oxygen sensor in the CA unit.

Volatiles Detection

The volatile detection system can be used to provide warnings of deterioration of the product, anaerobic metabolism and also to control the level of green chemicals. Volatiles of interest are ethanol, ethylene, NOx, methyl jasmonate, hexenal etc and substances used as green chemicals such as aliphatic aldehydes, terpenes and phenolics.

For the development of this system we will follow two tracks: one based on solid state sensors form the University of Ferrara, and the other based on an electronic nose.

In another project carried out in co-operation with the University ofFerrara in Italy and other participants, ethanol and ethylene sensors are being developed. These sensors are based on the dependency of the electrical resistance of heated metal oxide semiconductors to a range of gaseous phase components. The sensors are being developed in Italy and being tested and evaluated in ATO-DLO as sensors for ethanol in controlled storage conditions. Tests on these sensors indicate that they need major improvement of both sensitivity and selectivity if they are to be used to prevent ethanol toxicity problems by avoiding anaerobiosis during low O_2 concentration storage. Selectivity may be improved by using multiple sensors in an array to correct for interfering gasses, for example with a neural network circuit. Another type of ethanol sensor with a sensitivity sufficient to detect ethanol in the gaseous at concentrations low enough to be able to prevent ethanol toxicity damage in stored produce is being developed by Lion. We are still waiting to receive the technical specifications of this sensor.

An electronic nose is a gas sensor system that can analyze complex mixtures of volatiles from a vast range of products on a fast, cost-effective and reliable basis. Individually or as mixtures, these volatiles produce the aromas and off-smells that we detect from foods, flowers and other smelly materials An electronic nose is considered as an analytical instrument complementary to other olfactory measurements, such as (human) sensory panels, GC/MS or GC/sniffing.

The most important part of an electronic nose is the sensor head which mostly consists of an array of 8 to 32 individual sensors. Each of these individual sensors has a differing, not necessarily very specific, response towards organic volatiles. Since all of the electrodes are slightly different in nature, the complete set of electrical responses can be regarded as a characteristic digital spectrum of the volatiles, the so-called fingerprint.

So, the electronic nose comprises of a small array of non-specific sensors that leads to different patterns when exposed to different odours or gaseous emissions. When this pattern is unique for the given odour that is analyzed, the set of sensors can be used to selectively determine the odour or gaseous emission. In practice, the odour or gas of interest is mostly mixed with many other odours and gases. This makes it difficult to determine the selectivity of the set of sensors. However, with the help of sophisticated data acquisition and signal processing, the different patterns can be marked out. This signal processing varies from signal reduction, sensor subset selection, signal scaling, signal filtering, signal normalization and signal correction (e.g. drift removal). Though we plan to develop microbalance sensors for volatile detection, we will begin the electronic nose programme using a existing electronic nose based on semiconductor detectors in order to test the feasibility of this approach to monitoring various physiological processes within the container.

The present research has been focussed on two phases. Phase one entails the preparation of the laboratory equipment (electronic nose) for measuring product quality. A commercial electronic nose has been obtained and is now fully operational for test measurements. The system is used to investigate the added value of electronic nose measurements for product quality determination. Phase two entails the development of software techniques to evaluate electronic nose measurements. A MLF neural network has been developed and tested for the classification performance with existing measurements. Because the MLF network has been implemented in a widely known general purpose programming language, it will be possible to incorporate the network in the container control module when this appears to be useful.

The next phase will start off by developing a measurement strategy. Depending on the chemical composition and the concentration of the odours, a sampling procedure will be developed, which is sufficiently sensitive and accurate to discriminate between various samples of emitted perishable odour. This part of the research also includes optimizing statistical processing of the aroma fingerprints.

Particulates Detector
Detectors for airborne particles are commercially available, so no specific development of this kind of sensor will take place until their usefulness has been demonstrated in a model container containing decomposing, sporulating products. If commercial sensors prove effective at detecting fungal infections of products by means of their released spores, we will proceed with tests and development of this sensor system

Deliverables
The O_2 sensor is at an advanced prototype stage; it is a usable device, but still needs some refinement. The development of the CO_2 sensor is on hold until we have completed tests with the commercially available made-up version of the sensor. The volatiles detection system is still being developed – this is the most difficult project within the sensors component of the overall programme, but within the coming year we will have demonstrated the ability to detect key volatiles or else demonstrated that the technology will not work.

Resources

Costs for electronics/chemicals O_2 sensor:	NLG 3000
e-nose: costs of use of e-nose	in negotiation
ethanol/ethylene: setup of testing facility :	NLG 12 500

Requirements from / interaction with other tasks:
Information needed on acceptable limits for gaseous phase ethanol levels, and further interaction required with regard to calorimeter development (currently on hold). Longer-term development of O_2 sensor will be done in co-operation with Carrier Transicold to ensure mechanical and electrical compatibility (likewise, all other sensor systems). More info is needed from Task 4 (in relation to e-nose).

Evaluation parameters
The oxygen sensor will be applicable to markets other than the container. Industrial and scientific applications for such a simple, low-cost device are numerous, and are currently filled by expensive electrochemical or paramagnetic sensors. Once we are satisfies with the sensors performance we proceed with finding a partner with whom we can co-operate in manufacturing the device.

6 Task 6: Chain optimisation and marketing opportunities

Introduction
Task 6 of the CEET2005 project will result in the description of market opportunities and marketing and logistical concepts for the CEET container. Participants in task 6 are P&O Nedlloyd and ATO. P&O Nedlloyd has outsourced a considerable amount of work to the Erasmus University through Eteca bv.

Aim
Task 6 of CEET2005 is meant to smoothen the market introduction of the CEET container and describe her market opportunities. In order to reach this goal, Task 6 will result in the description of a cost model that will give a better insight in the present logistical chain of climate controlled goods and the existing bottlenecks. Together with this knowledge the marketing and logistical concepts that will be formulated in task 6 will provide a proper feed-back on container design and a market introduction plan that aims on optimizing the use of the CEET container and avoid existing logistical bottlenecks.

Results
Task 6 has commenced in July 1999 and is expected to complete in September 2001. The first part report, the market analysis, is expected in January 2000, after which the cost model as well as the client profiles will follow in October 2000. No reports have been finalized as of yet.

Deliverables
A market analysis, which is an in-debt description of the present reefer market, the present logistical chain and the actors. Secondly Task 6 shall result in a cost model and a customer/market database. Thirdly task 6 shall describe the marketing and implementation strategy for the CEET container.

Resources
Existing market studies, but mostly interviews with the main actors in the reefer industry. Most of these interviews will be held at the end of 1999.

Requirements from / interactions with other tasks
In general we would like to be closely updated by the over-all project leader on eventual boundaries/assumptions that might have been formulated in order to proceed in a more focused way.

Task 1 (Product quality)
We expect feedback on which conditions per commodity provide least damage and loss of the value of agricultural produce. The next step is the support of the Greenery and ATO-DLO members involved in this task to translate a higher product quality into possible benefits such as a longer possible transportation time (modal shift), higher price, less waste, less claims, larger market area, longer shelf life of the products (how much longer).

Task 2 (Climate control)
Based on the discussions we have had at the meeting of the 27th of September at ATO, we would like to be kept closely updated on the consequence of energy reduction on reliability. In case an interesting source of energy reduction will be found, we would be interested in knowing the boundaries of this source and receiving a quantification of the possible energy reduction.

Task 3 (Energy supply)
We expect a quantification of the cost (both investment cost and operating and maintenance cost) of energy supply devices (all alternatives that are being investigated). Also we would be interested in the weight and volume of the alternative energy supply devices (most of all since it was mentioned that we could talk about more than one supply source). In case sun panels will be used, we would like to receive feedback on weight, position on the box and possibility to approach sun panels as a clip-on.

Task 4 (Green chemicals)
We expect a quantification of the cost of green chemicals and appending devices. We also would like feedback on effect of green chemicals on other commodities (the whole range: fruit/frozen/deciduous/etc) and consequences of the use of green chemicals on dry cargoes stowed in the new CEET container.

Task 5 (Sensors)
We expect a quantification of the cost of the sensors. We would also like to receive output reports/temp logs and information that is provided.

Task 7 (Control system)
We expect a quantification of the cost of the control unit.

Evaluation parameters EET
Task 6 will give more insight in the following parameters as established by EET:
Economy
- Looking at all reefer commodities bananas is the largest seabourne reefer commodity, meat the second largest and fish the third. The transport of reefer commodities used to be a controlled by the conventional carriers, however since 1997 the reefer container has taken over the position as 'market leader' as nowadays 55% of the reefer cargo is moved in containers;
- Due to EC regulations trucking will become a less attractive mode of transport compared with rail or inland waterways, however looking at the reefer market, this transition will go slow, as presently a lot of perishables are trucked within Europe break-bulk rather than in a reefer container, which makes a modal shift less likely in the short run;
- Looking at the competition (other than the container carriers) there might be a change in focus of the conventional reefer operators. This industry at the moment is looking into multi-modal new buildings with a large container capacity on deck;
- Once we are at the stage where the market introduction of the CEET container is described, we will give insight in the time-planning as well;
- The marketing study will express the market demands/expectations as far as new developments in the reefer industry are concerned;
- Task 6 will evaluate costs of the CEET container in comparison with existing reefer containers and argue whether the market is ready to make the additional investments in case there are any (which right now seems to be the case);
- Savings on energy costs;
- Economical and technical life-span;
- Modal shift from air transport to sea transport. The market analysis phase will contain the information on air cargo flows as well.

Ecology
- Savings on waste
- Increase in product shelf life and quality

Time-span
The attached MS Project Gantt Chart will give some more insight in the planning of the described key objectives and deliverables.

7 Task 7: Development of integrated dynamic control strategies

7.1 Contribution of ATO

Introduction
In the current situation climate control objectives in CA/refrigerated transport containers are limited to *fixed* setpoints for temperature, O_2, sometimes CO_2 and humidity (usually only *de*humidification is possible). The setpoint values are based on rules of thumb. The measured values of the controlled variables in *either* supply *or* return airflow are controlled to their setpoints.
Improvements to the control algorithms may yield better preservation of product quality at reduced energetic costs, without any modification to the container hardware.

Aim
The aim of this part of the project is to develop a supervisory optimising control (SOC) algorithm, based on the principles of non-linear model predictive control. This controller will optimize the setpoints, that may vary in time. The algorithm manipulates the setpoint trajectories such that the value of its objective functional is optimized. Inputs to the algorithm are actual measurements, forecasted system behaviour (models) and information about the product, logistics and energy.

Results
The global structure of the future SOC has been defined.
The boundary conditions have been inventoried.
The timescales involved, and how to handle these, have been evaluated.
The possibilities for on-line measurement or estimation of the product state have been inventoried.
See (Appendix task 7) for more details.

Deliverables
The aim is to deliver a Supervisory Optimal Control algorithm that will optimize the CA/refrigerator setpoint trajectories. This optimization will take into account both product quality preservation and energy consumption. On the basis of first results in tasks 1 and 2 the impressions are that:
- significant energy savings are possible without harming the product quality by allowing minor temperature variations
- product quality improvement is possible by gradually decreasing the O_2-setpoint at start of the trip and also gradually increasing the O_2-setpoint to ambient conditions at the end of the trip.

Resources
In the near-future experiments are needed to test the algorithm. In these experiments the available 40 ft container from P&O will be used. To enable manipulation of the external climate around the container it is positioned inside an ATO store with climate-control. The container will be loaded with apples/tomatoes put available by the Greenery. Software for communication with the CA/refrigerating units is put available by Carrier.

Required inputs from other tasks
The SOC will be the part that at the end of the day performs the overall optimization. Therefore it combines inputs from all other tasks (see table 1).

Table 1, required inputs from other tasks.

task no.	required input
1 (product)	product quality models
2 (models/controller hardware)	models of CA-unit, refrigerating unit and cargo-hold
3 (energy system)	model of energy supply system
4 (green chemicals)	economics of e.g. exchanging less tight temperature control for green chemical usage
5 (sensors)	cheap, reliable, free-of-maintenance sensors (O_2, CO_2, ethylene, calorimeter)
6 (marketing/logistics)	knowledge of trip path/duration

Evaluation parameters

The SOC-algorithm will allow for better product quality preservation, by improved control of the climatic conditions *around the product*. Control of climatic conditions *around the product* comes natural in the SOC-algorithm by computation of setpoints for supply air on the basis of measurements in both supply and return air, and possibly in the cargo-hold's headspace.

As a consequence of improved product quality preservation during transport longer transport chains become possible. As a consequence further transport becomes possible, and part of the energy-spoiling air transport can be replaced by energy efficient sea/land transport. Another effect is that more mature harvesting becomes possible, which will allow higher yields for farmers and improved flavor for consumers.

First impression is that more efficient operation of the CA/refrigerating-units will result in significant energy savings, by just exploiting favorable ambient conditions.

Putting the algorithm to the market can be quick, as it just concerns a piece of software. Parts of the SOC-algorithm will be applicable to any refrigerated storage facility.

Besides the technical challenge, there is the challenge to convince transporters about the superiority of the control algorithm. Therefore a demonstration at the end of the project is needed.

The intended SOC-algorithm will use weather-forecasts, an estimate of the remaining duration of the trip, market-prices of the transported product. To feed this information to the container requires communication of the container's microprocessor with the outside world. This communication is technically feasible, but not available in current reefer transport.

Time schedule

In the oncoming half-year part of the SOC-algorithm, the secondary controller (Appendix task 7), will be built. The objective is to test the algorithm both in simulation and in experiments. Developments of the oncoming half-year will be limited to refrigerated conditions. Optimization of CA-conditions will be incorporated in the remaining part of the project.

APPENDICES

Appendices

Appendix 2.A Macroscopic model of CEET-container

1. Introduction

In this chapter we present a 'crude' macroscopic model of the CEET-container. This model will be the basis for several tasks in the CEET-project. For task 7 it will serve as a working model for the development of the supervisory control algorithms. For task 3 it will be basis for calculations of energy demands and reductions. For task 2 it will be a template for the development of a physical model describing the climate in the stowage space.

In figure 1.1 the CEET-container is drawn schematically. The container is divided in three domains:

1. Control Unit
2. Cool Unit
3. Stowage Space

Models for all three domains will be developed and used in the model-based control algorithm. In this activity we have focussed only on the last domain: the stowage space. The stowage space contains the pallets with packed product. Air is entering the stowage space from the cool unit through the T-bar floor. The air flows through the packed products and leaves the stowage space through the bulkhead, which is the connection between the cool unit and the headspace above the pallets.

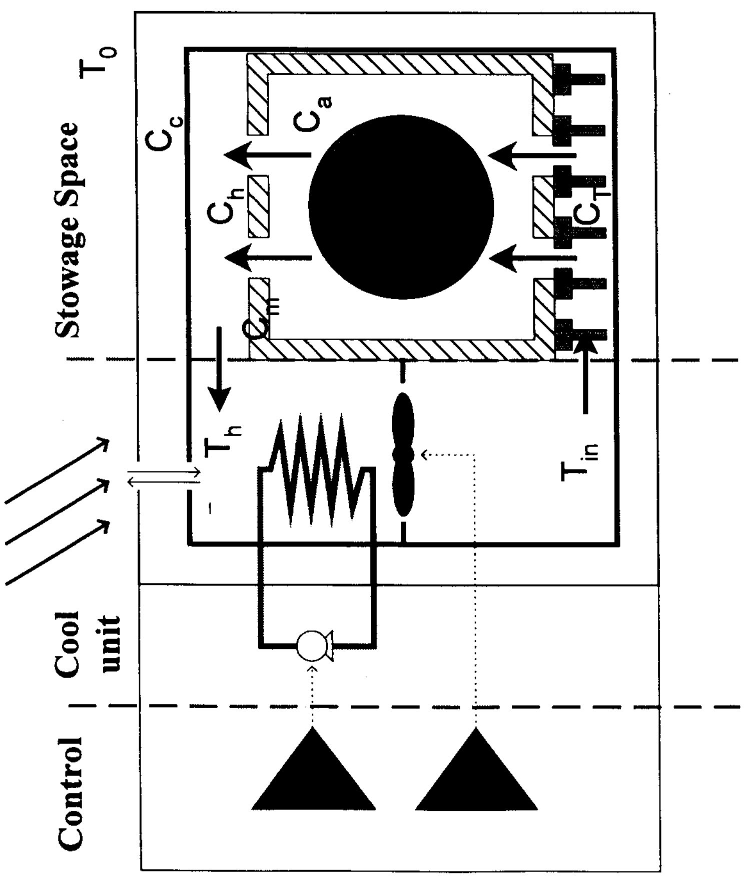


Figure 1. Diagram of CEET-container, divided in the sections Control, Energy System and Stowage space.

2. Thermal model of stowage space

In the stowage space we will describe the temperature of several objects, which can store significantly amounts of energy, contain water vapour and (metabolic) gasses. These objects will be modelled as (heat) capacities. (Heat) exchange between the (heat) capacities is either by conduction/diffusion or convection. Exchange with the ambient and the cool unit will also be given.

In a first approximation, the following objects are distinguished in the stowage space (see figure 1.1):

- C_p: The load of products.
- C_a: The air inside packages, surrounding the products.
- C_m: The packaging material.
- C_T: The T-bar floor.
- C_h: The air in the headspace above the load of products.
- C_c: The steel and aluminium cladding of the inside of the stowage space.
- C_e: The steel (cladding) at the exterior of the container.

Here we have neglected the heat capacity of the insulation material. Also, we assumed that the air between the T-bars has the same temperature as the T-bar floor. The load of packed product is assumed to be stacked tightly together, such that all air flows around the products.

Exchange with the ambient of the stowage space-subsystem is by heat conduction through the insulation material. The outside temperature is denoted as T_0. The energy input by radiation is transferred from the external metal cladding to the stowage space by conduction through the insulation material.

The stowage space also has exchange with the cool unit. Air will flow at a certain rate, Φ, in the container. This air is conditioned by the energy-system (including the CA-unit) at a certain temperature (T_{in}), humidity (c_{in}), and gas concentrations ($CO2_{in}$, $O2_{in}$, $N2_{in}$).

Below we will describe the various energy balances for the heat capacities in the model. We will be using the following symbols. The amount of heat contained by object x is denoted as $Q_x = C_x T_x$, with C_x the heat capacity and T_x the temperature. The heat flow by conduction is equal to a temperature difference $(T_x - T_y)$ divided by the heat resistance R_{xy}. The volumetric airflow rate is denoted by Φ.

In the heat balances below, several assumptions have been made. All in all, these assumptions state that several heat flows are insignificant. Below we summarise these heat flows:

- heat transfer from product to packaging material.
- heat exchange between the packaging material and the walls
- heat exchange between the packaging material and the T-bar floor.
- heat transfer from packaging material to headspace.

2.1 Energy balances

Load of product

The change in the amount of heat contained in the load of products is given by:

$$dQ_p/dt = -(T_p - T_a) / R_{pa} + P_{resp} - P_{evap} \quad (2.1)$$

with P_{resp} the rate of heat production by respiration of the product and P_{evap} the power needed for the evaporation of moisture from the product. The production terms will be described in detail later in this document. For Eq. (2.1) we have assumed that the direct heat transfer from product to packaging material in negligible.

Air inside packaging
The load of packed product is assumed to be stacked tightly together, such that all air flows around the products. Hence, the change in the amount of heat contained by the air in the packaging is given by:

$$dQ_a/dt = (T_p\text{-}T_a) / R_{pa} + (T_m\text{-}T_a) / R_{ma} + \Phi \rho_a c_{p,a} (T_T - T_a) \quad (2.2)$$

Packaging material
The change in the amount of heat contained by the packaging material is given by:

$$dQ_m/dt = - (T_m\text{-}T_a) / R_{ma} - P_{abs} \quad (2.3)$$

Here, we assumed that heat exchange with the headspace and the T-bar floor is negligible, as the packaging material is in more contact with the air in the packaging. Another contribution in the energy-balance is, P_{abs}, the power needed to absorb/ desorb water from the packaging material (cardboard).

T-bar floor
The change in the amount of heat contained by the T-bar floor is given by:

$$dQ_T/dt = - (T_T - T_e) / R_{Te} + \Phi \rho_a c_{p,a} (T_{in} - T_T) \quad (2.4)$$

Here, we assumed that the air between the T-bars has the same temperature as the T-bar floor. Heat exchange with the environment is through the bottom plate of the insulation, having a heat resistance of R_{Te}.

Head space
The change in the amount of heat contained by the air in the headspace is given by:

$$dQ_h/dt = - (T_h\text{-}T_c) / R_{hc} + \Phi \rho_a c_{p,a} (T_a - T_h) \quad (2.5)$$

In Eq.(2.5) the heat transfer through the packaging material is assumed to be negligible.

Steel and aluminium cladding
The change in the amount of heat contained by the metal cladding is given by:

$$dQ_c/dt = + (T_h\text{-}T_c) / R_{hc} - (T_c - T_e) / R_{ce} \quad (2.6)$$

The metal cladding has exchange with the environment by heat conduction through the insulation of the walls and the roof of the container. In Eq.(2.6) we have assumed that the heat transfer through the packaging to the cladding is negligible.

Exterior steel
The change in the amount of heat contained by the steel in the exterior of the container is given by:

$$dQ_e/dt = - (T_e\text{-}T_0) / R_{e0} + (T_c - T_e) / R_{ce} + P_{rad} \quad (2.7)$$

P_{rad} represents the heat flux by radiation. The convective heat resistance of the boundary layer between the container and ambient air is given by R_{e0}.

3. Thermophysical properties of objects in thermal model

3.1 Properties of the product

The heat capacity C_p of the product is calculated as their mass multiplied with their specific heat: $C_p = m_p\ c_{p,p}$. The mass is calculated as the volume of the stowage space, V_c, times the packing density $\rho_{m,p}$ (#kg of product / packaging volume). The properties of several products are listed in Table 3.I.

Also in table I the specific heat of respiration, $q_{resp} = P_{resp} / m_p$, is listed for several temperatures at atmospheric conditions. Under controlled atmosphere conditions we assume the heat of respiration to be negligible in comparison to other terms in the energy balance.

Table 3.I. (Thermo)physical properties of products

Product	$\rho_{m,p}$ (kg/m^3)	$c_{p,p}$ (kJ/kg.K)	γ_v (kg/kg.Pa.s)	q_{resp} (4°C) (W/ton)	q_{resp} (12°C) (W/ton)	q_{resp} (20°C) (W/ton)
Apple	475	3.83	$0.7\ 10^{-10}$	20	45	83
Chicory	450	4.01	$4.5\ 10^{-10}$	100	225	412
Tomato	560	4.04	$0.3\ 10^{-10}$	20	45	83

3.2 Properties of the packaging material

The packaging for agricultural products in refrigerated container are generally made of cardboard. Their dimensions are: 0.30 x 0.40 x 0.15 = V_m = 18 10^{-3} m^3. The weight of a single packaging is $m_{s,m}$ = 0.5 kg. The total mass of packaging material m_m is given by

$$m_m = m_{s,m}\ V_c / V_m \qquad (3.1)$$

The specific heat of card board is given by $c_{p,m}$ = 1.7 kJ/kg/K.

Total volume of air in packaging is about $V_a = \varepsilon\ V_c$, with ε the volume fraction of air in the packaging, which is about 0.5.

3.3 Properties of container

The volume of the stowage space is V_c = 11.6 x 2.28 x 2.50 = 66 m^3. The height of the headspace above the product load = 0.08 m. Hence, the volume of the headspace is 2.11 m^3. The maximum payload is 25.7 ton. Hence, the products listed in Table I will reach this maximum limit.

The thermal insulation is made of foamed polyurethane, with a thermal conductivity of 0.021 W/m.K. The thickness of the floor-insulation is 95 mm, of the front andsidewalls 67 mm, the door 80 mm, and of the roof 95 mm. Its density is 38 kg/m^3, and its weight is 375 kg.

The T-bar floor is made of aluminium, it has a thickness of 4 mm, its height is 63.8 mm, its width=30 mm and the number of T-bars=35. Hence, the mass of the T-bar floor = 700 kg.

The roof is lined with 0.8 mm thick aluminium, and the walls are lined with stainless steel plates with 0.7 mm thickness. Hence, the mass of the roof lining is 57 kg, and the mass of the wall lining is 383 kg. The heat capacity of aluminium and stainless steel are respectively 0.88 kJ/kg.K and 0.46 kJ/kg.K.

The weight of the exterior steel is set equal to the tare weight (4740 kg) minus the weight of inner linings, the T-bar floor and insulation. Hence, its weight is equal to 3250 kg and its heat capacity is equal to 2860 kJ/K.

The volumetric flow rate, Φ, is typically 20 to 80 times the empty volume of the stowage space (V_c) per hour. Hence $\Phi = 0.4$ to $1.6\ m^3/s$. The airflow through the product load is from bottom to top. The superficial airflow velocity in the load is then typically: u = 1.5 to 6 cm/s.

3.4 Table of heat capacities

In Table 3.II below, the heat capacities (C_x) will be given for the various heat capacities in the stowage space. Assumed is that the weight of product is equal to the maximum payload of 25.7 ton.

Table 3.II Heat capacities in stowage space CEET-container

Symbol	Heat capacity (kJ/K)
C_p	102800
C_a	40
C_m	3160
C_T	616
C_h	2
C_c	226
C_e	2860

3.5 Heat resistances

Product-air interface

The heat resistance of product to air, R_{pa}, is equal to:

$$R_{pa} = 1 / h_{eff} A_p, \qquad (3.2)$$

with h_{eff} the effective heat transfer coefficient, and A_p the total surface area of all products in the load. The effective heat transfer coefficient is composed of two contributions:

$$1/h_{eff} = 1/h_{int} + 1/h_{ext}, \qquad (3.3)$$

with h_{int} the internal heat transfer coefficient of the individual product, and h_{ext} the heat transfer coefficient of the boundary layer around the product. The external heat transfer coefficient (for spherical products) is determined by the correlation between the Nusselt number and the Reynolds number (Ref.) Re<60000:

$$Nu = 2.0 + 1.1\ Re^{0.6}\ Pr^{0.33} \qquad (3.4)$$

Here the Nusselt number is $Nu = h_{ext}\ d_h / \lambda_a$, the Reynolds number is $Re = u\ d_h / v_a$ and the Prandtl number is $Pr = v_a / a$, with d_h the products diameter, $a = \lambda_a / \rho_a\ c_{p,a}$ the thermal diffusivity of air, and v_a is the kinematic viscosity of air. For the range of velocities u=1.5 to 6 cm/s, and product diameters d_p=6 cm, the range of the external heat transfer coefficient is: h_{ext} = 6 to 12 $W/m^2.K$.

The internal heat transfer coefficient is determined by:

$$h_{int} = \lambda_p / d_c \qquad (3.5)$$

with λ_p the thermal conductivity of the product and d_c a characteric length of the product, which depends on its geometry. For spherical products this length is:

$$d_c=d_p/8. \qquad (3.6)$$

For spherical products with d_p=6 cm and λ_p=0.6 W/m.K, the internal heat transfer coefficient is h_{int} = 80 W/m^2.K. Only is the high flow velocity range the internal resistance is of importance. The effective heat transfer coefficient ranges from h_{eff}= 5 to 10 W/m^2.K

The specific surface area of products, a_p, is calculated by using the formula for the area and volume of a sphere:

$$a_p = A_p / m_p = 6 / \rho_p d_p \qquad (3.7)$$

For d_p=6 cm and ρ_p=1000 kg/m^3 the specific area is a_p = 0.1 m^2/kg. For a product load of 25 ton, the total surface area is A_p = 2.5 10^3 m^3. Hence, the heat resistance between product and air ranges from R_{pa} =40 to 75 µK/W.

Packaging-air interface

The heat resistance of product to air, R_{pa}, is equal to:

$$R_{ma} = 1 / h_{m,eff} A_m, \qquad (3.8)$$

Here A_m is the surface area for packaging, which is equal to 1650 m^2. The effective heat transfer coefficient is equal to:

$$1/h_{m,eff} = 1/h_{m,int} + 1/h_{m,ext}, \qquad (3.9)$$

The internal heat transfer coefficient is given by:

$$h_{m,int} = \lambda_m / d_m \qquad (3.10)$$

Here λ_m=0.065 W/m.K is the thermal conductivity of corrugated board, and $d_m \approx$ 4 mm is the thickness of the packaging. Hence, $h_{m,int}$=2 λ_m/ d_m= 32 W/m^2.K.

The external heat transfer coefficient is estimated to be $h_{m,ext}$=6 W/m.K, which is a general estimate for moderate airflow along a wall with contributions due to natural convection. Hence, $h_{m,eff}$= 5 W/m.K.

The heat resistance is then R_{ma}=165 µK/W.

T-bar floor-exterior steel interface

This resistance is mainly due to the insulation of the bottom, and is given by:

$$R_{Te} = 1 / (\lambda_{PU}/d_{PU}).A_{Te} \qquad (3.11)$$

Here λ_{PU}=0.021 W/m.K the thermal conductivity of polyurethane foam, d_{PU}=90mm the thickness of the bottom insulation, and A_{Te}=26 m^2 the surface area of the floor. Hence, R_{Te} = 0.17 K/W.

Cladding-head space interface
This resistance is mainly due to the boundary layer in the air flow, which is characterised with h_b=6 W/m.K. Hence, the resistance is given by:

$$R_{Te} = 1 / h_b A_{hc} \quad (3.12)$$

Here A_{hc}=26 m^2 the surface area of the roof. Hence, R_{Te} = 6.4 mK/W.

Cladding-exterior steel interface
This resistance is mainly due to the insulation of the roof and walls, and is given by:

$$R_{ce} = 1 / \Sigma_i (\lambda_{PU,i}/d_{PU,i}) A_{ce,i} \quad (3.13)$$

Here λ_{PU}=0.021 W/m.K the thermal conductivity of polyurethane foam, $d_{PU,i}$ the thickness of the insulation components, and $A_{ce,i}$ surface area of the roof or walls. Hence, R_{Te} = 0.036 K/W.

Exterior steel-ambient interface
This resistance is mainly due to the boundary layer in the air flow, which ischaracterized with h_b=6+4 v_e (ASHRAE,1993). Assuming the exterior air flow velocity is $v_e \approx 4$ m/s, then $h \approx 20$ W/m.K. Hence, the resistance is given by:

$$R_{e0} = 1 / h_b A_{e0} \quad (3.14)$$

Here A_{e0}=90 m^2 the surface area of the container. Hence, R_{e0} = 0.5 mK/W.

3.6 Table of heat resistances

Heat Resistance	Value (mW/K)
R_{pa}	0.040 .. 0.075
R_{ma}	0.17
R_{Te}	170
R_{hc}	6.4
R_{ce}	36
R_{rad}	6.0
R_{e0}	1.0

Solar Radiation model

There is a contribution due to black body radiation (between exterior and sky) P_{sky} and (direct and diffuse) solar radiation P_{sun}.

$$P_{rad} = - P_{sky} + P_{sun} \quad (3.15)$$

$$P_{sky} = A_{top}\, \sigma\, (\varepsilon_e\, \theta_e^4 - \alpha_e\, \theta_0^4) \quad (3.16)$$

Here σ=5.7 10^{-8} $W/m^2.K^4$ is the Stefan-Boltzmann constant, θ_e is the absolute temperature of the exterior, θ_0 is the absolute temperature of the sky (ambient), ε_e=0.95 is the emissivity of the exterior, α_e=0.95 is the absorbency of the exterior (grey body assumption for infrared radiation: $\varepsilon_e=\alpha_e$). A_{top}=26 m^2 is the surface area of the roof. It is assumed that only the roof absorbs the radiation.

Eq.(3.16) can be linearised for small temperature differences. Equating $\theta_e = \theta_0(1+\delta T/\theta_0)$, and $\theta_e^4 \approx \theta_0^4(1 + 4\ \delta T / \theta_0)$, then Eq.(3.16) becomes:

$$P_{sky} = 4\ A_{top}\, \sigma\, \varepsilon_e\, \theta_0^3\ (T_e - T_0) \qquad (3.17)$$

This can be modelled as a heat resistance:

$$R_{rad} = 1 / 4\ A_{top}\, \sigma\, \varepsilon_e\, \theta_0^3 \qquad (3.18)$$

The intensity of direct (beam) sunlight is I_b and the intensity of diffuse sunlight is I_d. The absorbency of solar radiation is different than for infrared radiation. For sky-blue paint its value is $\alpha_{sol} \approx 0.5$. Hence the absorbed solar radiation is given by:

$$P_{sun} = \alpha_{sol}\, A_{top}\, (I_d + I_b) \qquad (3.19)$$

The solar radiation changes with time in intensity and direction.

There are data on the (monthly) ratio of diffuse and global radiation (Duffie and Beckman,1980).
Variation of the direction of beam radiation (θ), indicated by angles:
ϕ = latitude (angular location north or south of the equator ($-90^\circ < \phi < +90^\circ$)
δ = declination is angle of the sum with respect to the equator plane ($-23^\circ < \delta < +23^\circ$)
ω = hour angle, angular displace placement of the sun relative to the local meridian (15° per hour).

$$\cos(\theta) = \sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(\omega) \qquad (3.20)$$

with

$$\delta = 23.45 \sin(2\pi(n-81)/365) \qquad (3.216)$$

Sunrise and sunset can be calculated from Eq.(3.26) by setting $\theta = 90^\circ$.

Note, that absorption of radiation can be dependent of the angle of incidence (θ).

<u>Water vapour balances</u>

The following components inside the container have water (vapour) holding capacity:
The load of products
The air inside the packaging, surrounding the product
A film of condensed moisture on the product
The packaging material
The air in the T-bar floor
The air in the head space above the product load
The amount of water vapour of the air in the T-bar floor will be equal to the amount of moisture in the incoming air. Also, the amount of moisture in the air in the headspace is assumed to be equal to that of the air inside the packaging (no condensation on the roof is considered).

Consequently we will state the mass balances for only the following quantities:
M_p the moisture content of the product.
M_a the mass of water vapour in the air.
M_f the mass of condensed moisture.
M_m the moisture content of the packaging material

The mass balances are:

$$d_t M_p = - J_{pa} \quad (4.1)$$

$$d_t M_a = + J_{pa} + J_{fa} + J_{ma} + \Phi (c_{in} - c_a) \quad (4.2)$$

$$d_t M_f = - J_{fa} \quad (4.3)$$

$$d_t M_m = - J_{ma} \quad (4.4)$$

Here c_{in} and c_a are the water vapour concentration in the incoming air and the air inside the packaging respectively. Here $c_a = M_a / V_a$ with V_a the volume of air inside the packaging. The water vapour concentration is controlled by the relative humidity (R.H.=$a_{w,in}$) setting of the cool unit. Hence, using the ideal gas law, one has:

$$c_{in} = a_{w,in}\, p_{sat}(\theta_{in})\, m_w / R\, \theta_{in} \quad (4.5)$$

Here θ_{in} is the absolute temperature of the incoming air.

Model assumptions

We assume that if there is a moisture film present on the product, first evaporation of the moisture takes place, and after the film is removed evaporation of the moisture of the packed product occurs. Also, if condensation occurs latent heat is released and is absorbed by the product. This extracted/absorbed heat will be incorporated in the source term P_{evap} of the energy balance of the product, Eq.(2.1).

Furthermore, we assume no condensation on the metal parts of the container (walls, roofs etc.).

4.1 Evaporation

The evaporation from fruits and vegetables is linear with vapour pressure gradient(Sastry and Buffington,1983). They state that:

$$J_{pa} = k_{skin} A_p (p_p - p_a) \quad \text{if } p_a > p_{sat}(T_s) \text{ or } M_f = 0$$

$$J_{pa} = 0 \quad \text{otherwise} \quad (4.6)$$

Here J_{pa} is the transpiration rate in kg/s, A_p is the surface area of the product, p_p is the (nearly) saturated vapour pressure in the boundary layer around the fruit, p_a is the vapour pressure in the air in the packaging, and k_{skin} is the skin transpiration coefficient in (kg/s.m^2.Pa). The transpiration coefficient k_{skin} is shown to be independent of temperature for tomatoes in the range of 10°C to 16°C (Sastry and Buffington,1983). We assume that this holds for every commodity and the range of storage temperatures which occur in refrigerated containers (0°C .. 20°C). Values for the transpiration coefficients are listed in Table A.1. For some product with high transpiration coefficient the external mass transfer coefficient (k_{film}) is not negligible (40..90 g/s.m^2.MPa).

The vapour pressure in the boundary layer p_p is proportional to the water activity of the product $a_{w,p}$ and the saturated vapour pressure p_{sat}, which is function of the surface temperature T_s (Sastry and Buffington,1983):

$$p_p = a_{w,p}\, p_{sat}(T_s) \quad (4.7)$$

For most products the water activity is $a_{w,p}$=0.98 .. 0.99 (Becker, Misra et al.,1996). Some values are listed in table A.1.

The saturated vapour pressure follows the Clausius-Clapeyron relation:

$$p_{sat}(\theta_s) = p^0 \exp(-\Delta H_w / R\, \theta_s) \qquad (4.8)$$

with p^o a constant, ΔH_w the latent heat of vaporization per mole, which is equal to $\Delta H_w = m_w L_w$. For water L_w = 2473 kJ/kg (at 13°C), the molar mass is m_w = 18 g/mol, and $p^0 = 2.05\ 10^{11}$ Pa. Mind, that the surface temperature θ_s is given in Kelvin.

The surface temperature is located between the internal and external heat transfer resistance. Hence,

$$T_s = T_a + (T_p - T_a)/(1 + Bi) \qquad (4.9)$$

With $Bi=h_{ext}/h_{int}$ the Biot number, which will be derived for spherical product in appendix 2.C.

The partial vapour pressure in air is calculated using the ideal gas law:

$$p_a = M_a R\, \theta_a / m_w V_a \qquad (4.10)$$

Here V_a is the volume of air inside the packaging material, which is about 0.5 V_c.

Condensation

Water vapour can condense on the product or packaging if their temperature is below the dew point of air, or expressed in partial vapour pressures:

$$p_a > p_{sat}(T_s) \quad \text{or} \quad p_a > p_{sat}(T_m) \qquad (4.11)$$

The condensed water will be absorbed by the packaging material. But, on the product it will form a moisture film, which can eventually evaporate (if $p_a < p_{sat}(T_s)$).

The evaporation rate from the film is given by:

$$(4.12) \quad \begin{cases} J_{fa} = k_{film} A_p (p_{sat}(T_s) - p_a) & \text{if } p_a > p_{sat}(T_s) \text{ or } M_f > 0 \\ J_{fa} = 0 & \text{otherwise} \end{cases}$$

The coefficient k_{film} is related to the mass transfer coefficient β_{film}:

$$k_{film} = \beta_{film}\, m_w / R\, \theta_s \qquad (4.13)$$

The mass transfer coefficient β_{film} is given by the correlation between the Sherwood and the Reynolds number, analogous to Eq.(3.4):

$$Sh = 2.0 + 1.1\, Re^{0.6}\, Pr^{0.33} \qquad (4.14)$$

The Sherwood number is $Sh = \beta_{film}\, d_p / D_w$, with d_p the product diameter and the diffusion coefficient of water vapour in air is $D_w = 25.6\ 10^{-6}\ m^2/s$. For velocities u=1.5 to 6 cm/s and d_p=6 cm, the range of the film mass transfer coefficient is β_{film}=0.005 .. 0.01 s^{-1}. For typical value of θ_s=278 K the range of k_{film} is 40 .. 90 g/m^2.MPa.

Sorption of moisture by the packaging material

The mass flux from packaging to air is given by:

$$J_{ma} = k_{eff,ma} A_m (p_{eq} - p_a) \quad (4.15)$$

Here A_m is the surface area of the packaging material, p_{eq} the partial vapour pressure in equilibrium with the packaging material, and $k_{eff,ma}$ is an effective 'transpiration coefficient', related to an effective mass transfer coefficient:

$$k_{ma,eff} = \beta_{eff,ma}\ m_w / R\ \theta_a \quad (4.16)$$

The effective mass transfer coefficient is composed of an internal and an external part:

$$\beta_{eff,ma} = \beta_{ext,ma} + \beta_{int,ma} \quad (4.17)$$

The external mass transfer coefficient is obtained from the heat-mass transfer (Nu/Sh) analogy. Given the fact that $h_{ma,ext}$=6 $W/m^2.K$ one has $\beta_{ext,ma}$= 6 10^{-3} m/s. The internal mass transfer coefficient is related to the water vapour diffusion coefficient in the packaging material D_m:

$$\beta_{int,ma} = 2\ D_m / d_m \quad (4.18)$$

Here $d_m \approx 4$ mm is the thickness of the packaging material. The values of D_m are given by (Tanner,1998):

D_m=26 10^{-7} m^2/s for corrugated board, and

D_m=5 10^{-7} m^2/s for solid fibreboard.

Hence, $\beta_{int,ma}$= 13 10^{-4} m/s .. 7 10^{-4} m/s and the effective mass transfer coefficient is $\beta_{eff,ma}$= 11 10^{-4} m/s .. 5 10^{-4} m/s. The 'transpiration' coefficient k_{ma}= 5 .. 9 g/m^2.MPa.

The equilibrium vapour pressure is determined by the water activity of the packaging material:

$$p_{eq} = a_{w,m}\ p_{sat}(\theta_m) \quad (4.19)$$

If the moisture content is below fibre saturation point ($X_{fsp}\approx 24\%$), the water activity of the packaging material is given by the sorption isotherm, which relates the water activity to the moisture content X (related to dry matter content). Above the fibre saturation point the water activity a_w=1, as only liquid water is absorbed by capillary forces (it is not bounded) (Pang,1997).

For paper-based materials the GAB-theory describes the sorption isotherm (Eagleton and Marcondes,1994):

$$X = C_{Gug}\ k_{mul}\ X_0\ a_{w,m} / (1 - k_{mul}\ a_{w,m}) (1 - k_{mul}\ a_{w,m} + C_{Gug}\ k_{mul}\ a_{w,m}) \quad (4.20)$$

Here $a_{w,m}$ is the water activity of the packaging material. Other variables in Eq.(4.20) are parameters from the theory of the GAB-isotherm, which are temperature dependent. At T_{ref} =10°C for corrugated board X_0=5.4, C_{Gug}=106000, k_{mul}=0.771 (these values are given for sorption, due to hysteresis the values for desorption are different). At constant moisture content the water activity changes according to the Clausius-Clapeyron relation (Eagleton and Marcondes,1994). Hence,

$$a_{w,m}(T_m) = a_{w,m}(T_{ref}) \exp(-\Delta H_b / R\,\theta_m) / \exp(-\Delta H_b / R\,\theta_{ref}) \qquad (4.21)$$

Here ΔH_b is the binding energy of water to the paper.

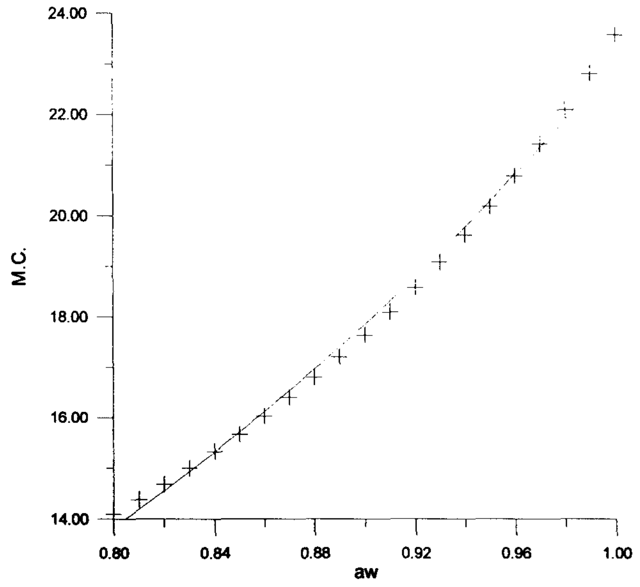


Figure 4.1 Water activity versus moisture content of currogated board.

When plotting the water activity versus the moisture content (mc) for high a_w values (0.8 .. 1.0) one can see that the relation is approximately exponential (see figure 4.1). (Data obtained from (Eagleton and Marcondes,1994)). For 10°C (θ_{ref}=283 K), the inverse relation is:

$$a_w(T_{ref}) = [\ln(mc) - \ln(1.78)] / 2.55 \qquad (4.22)$$

Here the moisture content (mc) is given in percentage (0..100%).

When fitting the Clausius-Clapeyron relationship to the approximate exponential relationship from the data of (Eagleton and Marcondes,1994) for T=10°C and 40°C, one obtains an estimate for the binding energy ΔH_b=1.8 kJ/mol. This value is comparable to values of dry foods at comparable moisture contents (mc≈20%) (e.g. pastas) (Xiong, Narsimhan et al.,1991). For moisture contents below 10% the binding energy rises (exponential) (Xiong, Narsimhan et al.,1991), but this regime is not of interest to our application.

4.5 Heat of evaporization and desorption

The heat consumed by evaporation is given by:

$$P_{evap} = L_w (J_{fa} + J_{pa}) \qquad (4.23)$$

If bound water evaporates (desorbs) from the packaging material energy is required for the heat of vaporisation (L_w) and the binding energy ($L_b=\Delta H_b/m_w$=1 MJ/kg). Hence, the heat of desorption $L_d=L_w+L_b$=3.5 MJ/kg. Above fibre saturation point there is unbounded liquid water in the packaging material, for which only the heat of evaporation is needed.

Hence the heat consumed by desorption of water by the packaging material is given by:

$$P_{abs} = L_d J_{ma} \quad \text{if } X<X_{fsp}$$
$$(4.24)$$
$$P_{abs} = L_w J_{ma} \quad \text{otherwise}$$

Network models.

Using the analogy between thermal and electrical physics we depict the heat and mass transfer models by means of an electrical network below in figure 5.1 and 5.2.

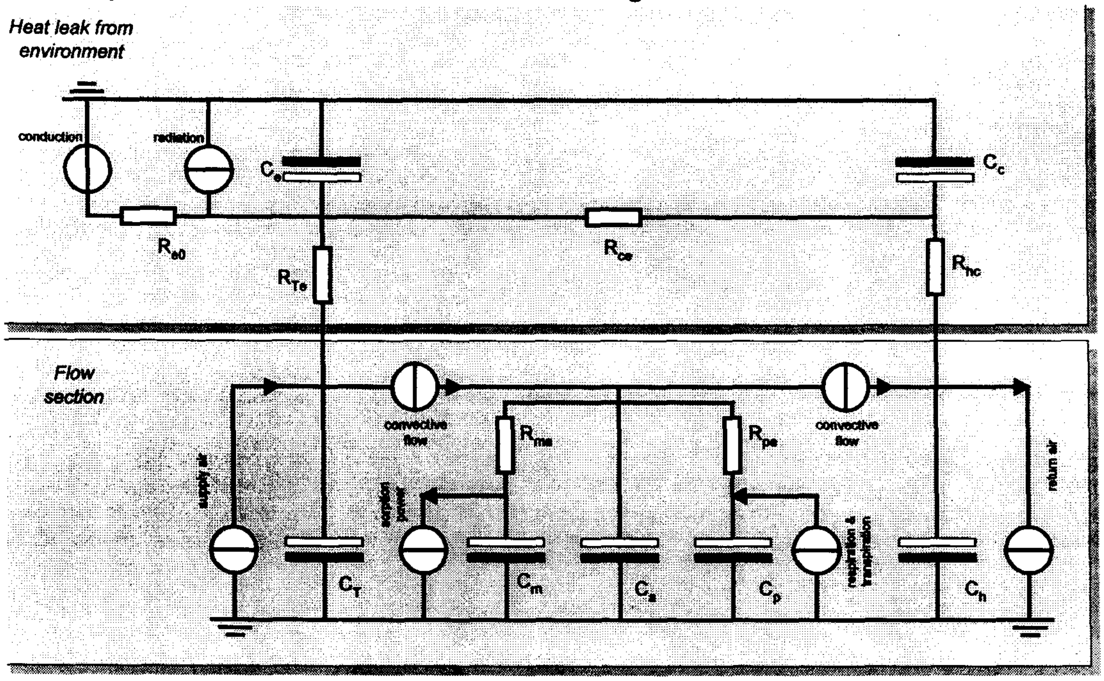


Figure 5.1 Network model representing the heat transfer model of the stowage space.

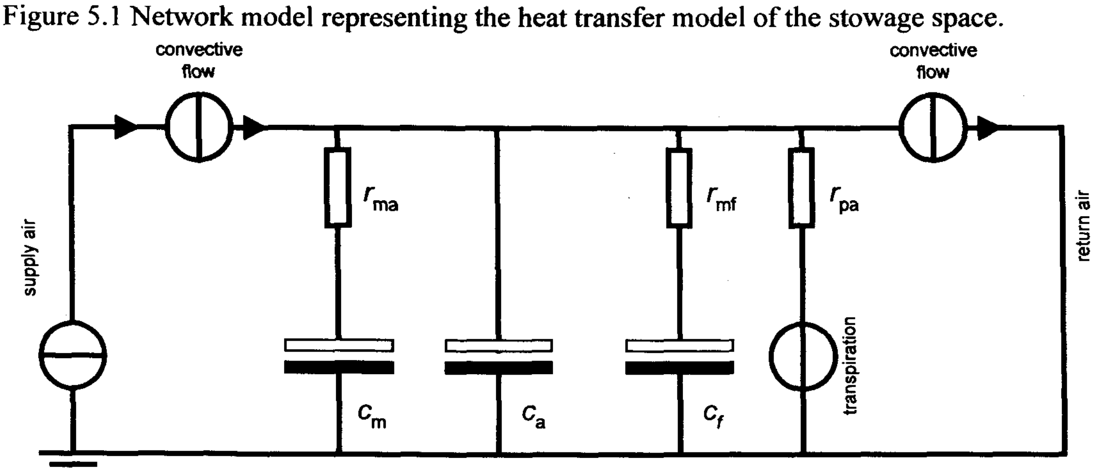


Figure 5.2 Network model representing the water vapour transfer model of the stowage space.

6. Energy consumptions

Heat production of various fruits and vegetables

Table 6.I Heat of respiration of certain fruits and vegetables

Product	Storage temperature[2] (°C)	Heat of respiration[2] (W/ton)	Transpiration coefficient[1] (g/m^2.s.MPa)	Water activity (-)
Apples	1	20	0.167	0.98
Asparagus	1	180		
Avocados	13	300		
Brussels sprouts	0	90	13.3	0.99
Chicory	0	100		
Cucumbers	7	60		
Grapes			0.40	
Lemons			2.08	
Mangoes	12	120		
Oranges			1.72	
Tomatoes, green	13	80	1.10	0.99
Tomatoes, red	10	60		0.99

[1] (Becker, Misra et al.,1996)
[2] (Hardenberg et.al,1978)

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Appendix 2.B: Experimental design of respiration and weight loss measurements

Introduction

When determining the weight loss of agricultural products, it is common to assume that it due only to evaporation. One reasons that the transpiration rate is only depend on the properties of the product surface and water vapour pressure difference between that of the surrounding air and the evaporation surface, which is assumed to be saturated (Gaffney,1985).

However, various studies (Sastry,1978; Chau, 1985; Gaffney,1985; Becket,1996a; Tanner,1998; Kang,1998) have shown that in storage conditions (with high relative humidity and low air velocities) various other factors affect the weight loss. These factors are:
Heat production by respiration, giving a rise in the product temperature.
Evaporative cooling, lowering the product temperature.
Water activity of the product surface, lowering the vapour pressure in the evaporating surface below the saturated level.
Airflow velocity, changing the heat and mass transfer characteristics of the boundary layer around the product.
Carbon mass loss due to respiration.
For high transpiring products some factors are already significant at low humidity levels.

If the above mentioned factors are disregarded it appears that the weight loss has a non-linear relationship with the water vapour pressure deficit, apparent at high and low humidity, as concluded by (Fockens, 1972) and (Villa,1973).

By using a simple model we investigate whether above mentioned couplings between respiration and evaporation etc. are significant for the conditions during container transport. Based on these calculations an experimental design will be made for measuring respiration and weight loss.

For the model calculations we assume that measurements will be done in a flow-through system, with optionally thermally insulated walls, through which a controlled amount of air flow (indicated by the volumetric airflow Φ). (see figure 1.1).

In the experiment the following physical quantities are measured:
- Temperature
- Water vapour concentration
- Oxygen concentration
- Carbon dioxide concentration
- at inlet and outlet, and measuring the product temperature and weight loss, one can estimate the various parameters such as the heat of respiration and transpiration rate.

These parameters can be estimated using the physical laws describing the stationary behaviour of the system (i.e. heat and mass balance), which will be given below.

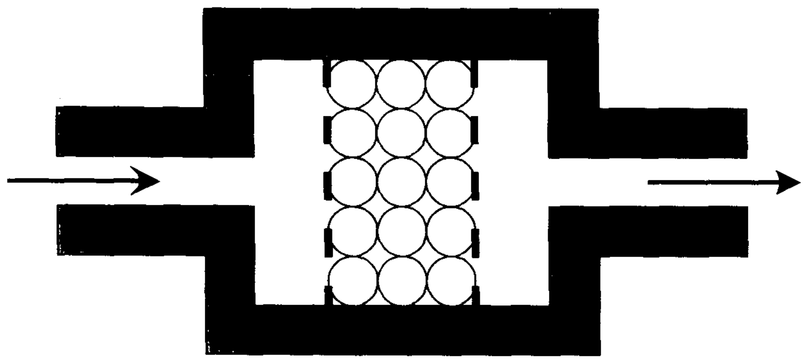

Figure 1.1 Flow-through system for respiration/evaporation measurements.

Heat and mass balances.

In the heat and mass balances will be described using the following physical quantities:
Conditions of inlet air:

T_0	temperature (°C)
$\rho_{V,0}$	water vapour concentration (kg/m^3)
$\rho_{C,0}$	carbon dioxide concentration (kg/m^3)
$\rho_{O,0}$	oxygen concentration (kg/m^3)

Conditions of outlet air

T_a	temperature (°C)
$\rho_{V,a}$	water vapour concentration (kg/m^3)
$\rho_{C,a}$	carbon dioxide concentration (kg/m^3)
$\rho_{O,a}$	oxygen concentration (kg/m^3)

By measuring the in- and outlet conditions of the air flow, one can calculate the various mass and energy flows from product to air flow (assuming stationary conditions). There is also a heat flux through the walls of the calorimeter, having a certain *K*-value.

The convective heat flux out of the system is:

$$J_Q = (\Phi\, \rho_a c_{p,a} - K)\,(T_0 - T_a) \qquad (2.1)$$

The convective water vapour flux is:

$$J_V = \Phi\,(\rho_{V,0} - \rho_{V,a}) \qquad (2.2)$$

The convective flux of carbon dioxide is:

$$J_C = \Phi\,(\rho_{C,0} - \rho_{C,a}) \qquad (2.3)$$

The convective flux of oxygen is:

$$J_O = \Phi\,(\rho_{O,0} - \rho_{O,a}) \qquad (2.4)$$

In steady state the convective heat flux is equal to the heat flux from product to air, which is due to respiration (linear with CO2-fluxes due to oxidation and fermentation, i.e. $J_{C,ox}$ and $J_{C,f}$) and evaporative cooling (linear with transpiration, i.e. J_V):

$$J_Q = -L_V J_V + q_{c,ox} J_{C,ox} + q_{c,f} J_{C,f} \qquad (2.5)$$

Here L_V=2473 kJ/kg is the heat of evaporation, $q_{c,ox}$ = 10600 kJ/kg is the heat of oxidation per kg of CO2, and $q_{c,f}$ = 932 kJ/kg is the heat of oxidation per kg of CO2.

Other fluxes can be calculated using constitutive relations. The evaporation is linear with the water vapour deficit:

$$J_V = \gamma\ (p_{sat}(T_p) - p_{V,a}) \qquad (2.6)$$

Here $p_{sat}(T_p)$ is the saturated water vapour pressure above the product, which is dependent of the products temperature. $p_{V,a}$ is the partial vapour pressure in the air surrounding the product, which is linear with the water vapour concentration $\rho_{V,a.}$

The fluxes of CO_2 and O_2 are functions of the (volumetric) concentrations $[O_2]$ and [CO2], and product temperature, which are obtained from (Hertog et.al.,1998). For model products values of these fluxes (in µmol/kg/s) are listed in Table 2.I.

Table 2.I Respiration fluxes for three model products at different temperatures and gasconditions.

Produkt	Temperature (°C)	[O2] (%)	[CO2] (%)	J_O (µmol/kg.s)	J_{CO2} (µmol/kg.s)
Apple	1	21%	0%	0.04	0.04
	11	21%	0%	0.10	0.10
	21	21%	0%	0.20	0.20
	1	5%	5%	0.02	0.04
	11	5%	5%	0.05	0.07
	21	5%	5%	0.10	0.15
Chicory	1	21%	0%	0.05	0.05
	11	21%	0%	0.12	0.12
	21	21%	0%	0.30	0.30
	1	5%	5%	0.02	0.02
	11	5%	5%	0.05	0.06
	21	5%	5%	0.17	0.20
Tomato	8	21%	0%	0.05	0.05
	13	21%	0%	0.08	0.08
	18	21%	0%	0.12	0.12
	8	5%	5%	0.01	0.02
	13	5%	5%	0.02	0.04
	18	5%	5%	0.03	0.07

Experimental design calculations

Calculations are performed for 9 kg of apples. The product is put in a flow-through system measuring 0.3 x 0.4 x 0.20 m^3, with the surface area is A=0.63 m^2. For the K-value of the flow-through system calorimeter, we chose two values: 1) for a polystyrene box of d=4 cm thickness, and 2) for a stainless steel box. For polystyrene foam with λ=0.033 W/m/K the K-value is K=(λ/d) A=0.5 W/K. In a stainless steel container the K-value is determined by the boundary layer of air on the inside of the container, which has a heat transfer coefficient of h=6 W/m^2.K, the K-value is K=hA=4 W/K. The various properties of products are taken from Table 3.I.

The first calculation is performed for heating in a closed polystyrene box, which is impermeable to gas, and through which no air flows. Inside the box the temperature will rise due to the heat production by respiration. But, the respiration will change the gas conditions inside the box, which will retard the respiration and consequently the heat production. Hence, the product temperature will eventually fall to the surroundings temperature.

Such an experiment is calculated by means of the model described in the previous section. The dynamics are calculated by assuming a quasi-steady state. In figure 3.1 the product temperature versus time is shown. A reasonably well measurable temperature difference of 5°C can be obtained at an ambient temperature of 20°C.

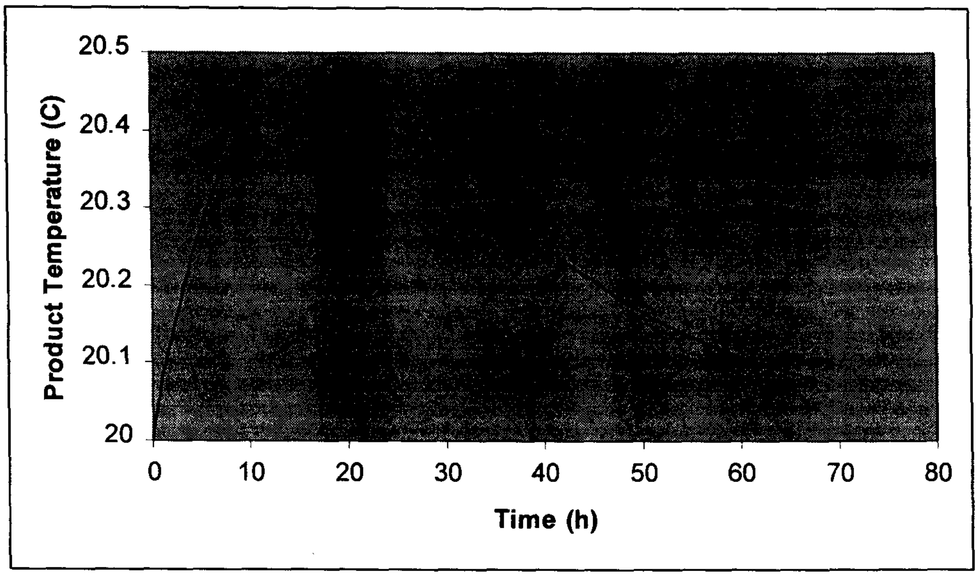

Figure 3.1 Product temperature versus time of apples inside a closed polystyrene box with an ambient temperature of 20°C.

The model shows that the R.H. stays saturated for the duration of the experiment. Hence, there is no significant coupling between evaporation and respiration. If the box is flushed with air of certain R.H. (R.H. = 80 to 95%, Φ=10 to 1000 ml/s), the form of the curve is similar that of figure 3.1, but will give a significant lower signal, which will be difficult to measure. Hence, measurement of heat production by respiration is only sensible in a closed box with significant thermal insulation, with no air through-flow.

A next calculation is performed for apples in a flow-through system of stainless steel, which is flushed with air at 200 ml/s, ambient temperature = 5°C and R.H. ranging from 30-100%. In figure 3.2 we show the weight loss versus the R.H. inside the steel container. If the coupling of respiration, evaporative cooling and evaporation are significant, we expect a non-linear relation between the R.H. inside the container and the weight loss.

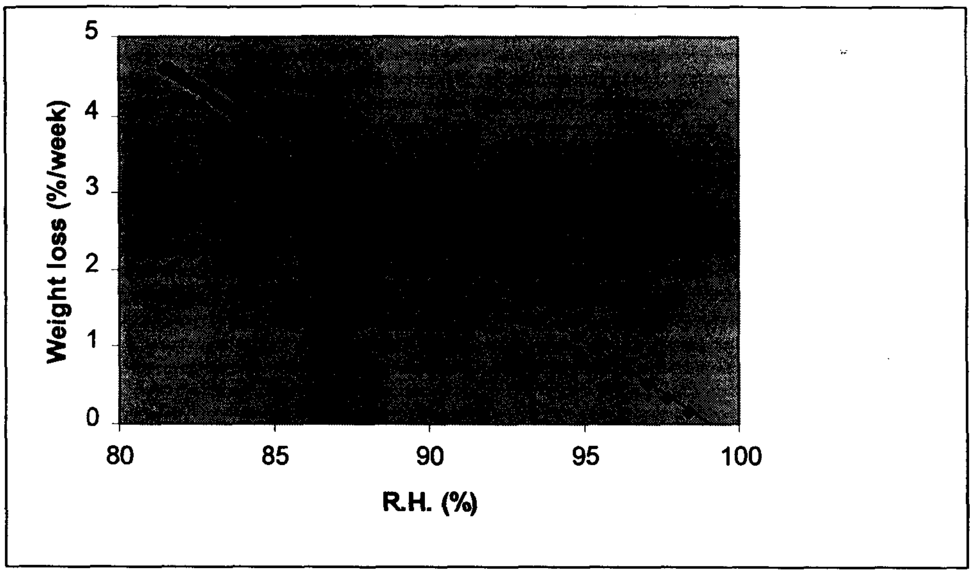

Figure 3.2 Weight loss of apples in a stainless-steel flow-through system, flushed with air at rate 200 ml/s, temperature = 5°C and various R.H. levels.

Figure 3.2 shows that weight loss is linear with the R.H. level in the range of 80 to 100%, which is the range which applies to container transport. Hence, the weight loss can be measured without any significant disturbance by non-linear effect due to coupling with respiration and evaporative cooling.

Table 3.I Physical properties of exemplary products (Source: Sprenger Institute)

Property	Apple	Chicory	Tomato
Density of tissue sap (kg/m^3)	1050	1005	1005
Product Density (kg/m^3)	800	845	1005
Air content of product (m^3/m^3)	0.24	0.16	0.01
Packing Density (kg/m^3)	360	380	400
Porosity of packed bed		0.47	0.44
Water content (%)	87	94	95
Freezing point (°C)	-1.0	-1.1	-1.0
Specific heat (kJ/kg/K)	3.83	4.01	4.04
Thermal conductivity (W/m/K)	0.42	0.46	0.59
Heat Production (W/ton) (4°C, 21% O_2)	20	100	20
Transpiration rate (kg H_2O/ kg/Pa/s)	0.7 10^{-10}	2 – 7 10^{-10}	0.3 10^{-10}
Specific surface area (m^2/kg)	0.1		
Diameter (cm)	6.5	3	5.7
Height (cm)		14	

Conclusions

The heat production by respiration and the weight loss can be measured separately in two different experimental designs, in which the coupling between the two effects is weak.

Heat production by respiration can best be measured in an impermeable box with thermal insulation (polystyrene) at room temperatures. Temperature differences are approximately

0.5°C, which can be measured accurately. By measuring simultaneously the gas concentrations the model described above can be validated.

Weight loss can best be measured in a flow-through system with a moderate airflow of about 200 ml/s and a certain temperature and R.H. Gas conditions will remain atmospheric, so the heat of respiration and the product temperature will be constant. Hence, there is weak coupling between respiration and weight loss. Temperature and gas conditions have only to be measured for checking the above assumptions.

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Appendix 2.C: Averaged cooling behaviour of spherical fresh food products

1. *Introduction*

Due to the simultaneously occurring heat transfer, water vapour transfer by evaporation, and the heat generation by respiration, the cooling and weight loss behaviour of fresh food products during cooling is quite complicated [1],[2]. Knowledge of this behaviour is of importance for the design of storage systems, packaging systems and refrigerated containers. At ATO-DLO, a refrigerated container is being developed which will have an advanced climate control algorithm based on Model Predictive Control.

This control algorithm needs a simplified model of the cooling behaviour of the transported fresh food products. Viewing the available literature on cooling of fresh food products, one finds hardly any simple models for the case of a significant internal temperature gradient (which does occur in practice of cooling). Many authors resort to detailed Finite Element of Finite Difference models [1-3].

However, we hypothesise that cooling processes with internal temperature gradients can be modelled with a first order system, following the work of Smith[4],[5] and Dincer[6]. In their work, Smith and Dincer obtain their simplified equations by truncating the eigenvalue expansion of the analytical solution for simple shapes. This approach is restricted to simple shapes and does not give any physical insight.

In this paper, we present a novel method of deducing a simplified model for cooling of fresh products, by applying the volume-averaging procedure to a detailed Finite Element model. This method we will apply to products having a spherical shape, but the method is applicable to product of any geometry. After applying the volume-averaging technique one obtains a first order ordinary differential equation. This equation can be represented by a network model, consisting of a thermal heat capacity connected to the environment with an external and an internal heat resistance in series. The magnitude of the internal resistance will be computed numerically with the FEM-model, which is developed by means of FIDAP.

2. *Physical description*

The heat and mass transfer of stored or packed fresh products is in general controlled by airflow around the product removing excess heat and moisture. For a physical description of the heat and mass transfer, the packed products are frequently treated as a porous medium [7, 8]. A representative volume element (REV) for the spherical product is presented in figure 1.

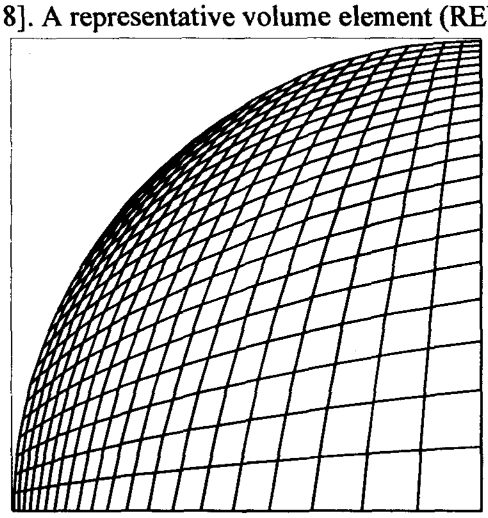

Figure 1. Representative volume element of spherical packed fresh products. The vertical axis is the rotation axis.

For this volume element, we will describe the heat and mass transfer from the product to the airflow surrounding it. For the sake of simplicity, we assume that the average airflow temperature and humidity is constant. The temperature and moisture gradients in the boundary layer are accounted for by the convective heat and mass transfer boundary condition on the product-air interface (Γ). In addition, we assume that evaporation occurs only at the surface of the product and that the internal moisture gradients are negligible.

Under these assumptions, the heat and mass transport inside the product are given by the following equation [9]:

$$\rho_p\, c_{p,p}\, \partial_t\, T_p = \nabla \cdot (\lambda_p \nabla T_p) + q_{resp} \qquad (1)$$

completed with the following boundary condition on the product-air interface (Γ):

$$-\lambda_p\, \partial_n T_p = h\,(T_p - T_a) - p_{evap} \qquad (2)$$

Here ∂_t and ∂_n denote temporal and normal derivatives. The last term in boundary condition Eq.(2) represent the heat extracted from the surface by the evaporation of moisture. The evaporation is driven by the water vapour deficit, i.e. the difference between the average water vapour density in air (c_a) and the water vapour density in the intercellular voids under the products skin ($c_p = a_w\, c_{sat}(T_\Gamma)$) [9]. Here, c_{sat} is the water vapour density of saturated air at temperature T_Γ, the temperature of the product at the product-air interface. Hence, the heat of evaporation is given by

$$p_{evap} = L\, k\,(c_p - c_a) \qquad (3)$$

However, for the sake of simplicity in this paper we assume a constant evaporation rate. Therefore, we assume a constant p_{evap} term in the boundary condition Eq.(2), instead of the more realistic formulation of Eq.(3), which will be dealt with in a subsequent paper.

3. *Volume-averaging method*

The method is pioneered and propagated by Stephen Whitaker [10]. By applying this method one obtains a more macroscopic equation describing the volume-averaged behaviour, which has shown quite useful for complex phenomena like (multi-phase) flow in porous media and moisture transfer in grains [11]. The volume average of a quantity like temperature T is given by:

$$\langle T \rangle = \frac{1}{V} \int T\, dV \qquad (4)$$

Taking the volume average of Eq.(1) and using Gauss theorem one obtains:

$$\rho_p\, c_{p,p}\, d_t \langle T_p \rangle = \frac{1}{V_p} \oint \lambda_p \nabla T_p \cdot d\vec{\Gamma} + \langle q \rangle \qquad (5)$$

The temperature gradient ∇T_p at the surface can be evaluated by Eq.(2). Still there is one unknown: the temperature at the surface T_Γ. A closed form is obtained by assuming the relation between the deviation of the surface temperature from the average temperature. Following Ref.[12] we take a first order approximation:

$$T_\Gamma = \langle T \rangle + \Delta r_\Gamma\, \nabla T \qquad (6)$$

Here Δr_Γ is the distance between the surface Γ and the location of the average temperature, which is known to have a constant location during cooling[4]. Substituting the closure relation Eq.(6) into the boundary condition Eq.(2) one obtains:

$$-\lambda_p \partial_n T_p = h/(1+Bi^*)\,(<T_p> - T_a) + p_{evap}/(1+Bi^*) \qquad (7)$$

with $Bi^* = h\,\Delta r_\Gamma/\lambda_p$ the (modified) Biot number, which states the ratio between the external and internal heat resistance. Using the definition of porosity, $(1-\varepsilon)=V_p/V$ and substitutingEq.(7) in the macroscopic equation, Eq.(5), one obtains the final equation:

$$(1-\varepsilon)\rho_p c_{p,p} V d_t <T_p> = hA_\Gamma/(1+Bi^*)\,(<T_p> - T_a) + p_{evap}A_\Gamma/(1+Bi^*) + (1-\varepsilon)V<q> \qquad (8)$$

Here A_Γ is the surface area of the product. Eq.(8) is fully determined if the parameter Δr_Γ of the closure relation is known. We will calculate this numerically and investigate the validity of the closure relation for a wide range of Biot numbers.

Eq.(8) can also be represented by a network with heat capacity $C=\rho_p c_{p,p}(1-\varepsilon)V$, two heat resistances in series, i.e. $R_{ext}=1/hA_\Gamma$ and $R_{int}=\Delta r_\Gamma/\lambda_p A_\Gamma$, and heat sources $Q=<q>(1-\varepsilon)V$ and $P=p_{evap}A_\Gamma$. The network is depicted in figure 2. By applying Kirchhoff's laws to this network one obtains Eq.(8).

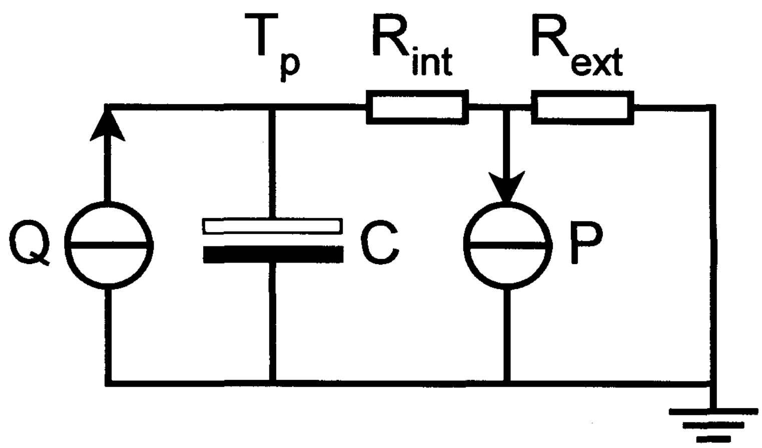

Figure 2. Electric network analogue of macroscopic equation Eq.(8).

This network gives a clear physical interpretation of the simplified model of the cooling behaviour of fresh products Eq.(8). The internal temperature gradient can be accounted for by an internal heat resistance R_{int} and the evaporative cooling effect can be modelled by a heat source in between the internal and external heat resistance.

4. *FEM-calculations*

For the numerical analysis of the temperature and moisture content distributions during cooling, we have developed a Finite-Element model using FIDAP. The meshes applied are depicted in figure 1. Eq.(1) is solved using the Galerkin Finite Element method, the standard solver of FIDAP for heat conduction problems. For the time-integration, a backward scheme is using with variable time stepping. For the simulation of the evaporation we have defined a thin shell (thickness = 0.01 r) under the surface of the product in which evaporation occurs, i.e. an entity having an extra source representing the heat of evaporation. This technique is chosen as FIDAP standard boundary conditions do not support formulations like Eq.(2).

From the simulation results the time evolution of the average product temperature is computed and is compared with the solution of the macroscopic equation Eq.(8).

The solution of Eq.(8) with initial condition $<T(0)>=T_i$ is given in dimensionless numbers by:

$$\theta(t) = \theta_e + \exp(-Fo/\phi)\,(1 - \theta_e) \qquad (9)$$

Here $\theta(t) = (<T>(t) - T_a) / (T_i - T_a)$, $\theta_e=\phi\, Po_q + \theta_p/Bi$, $Fo = \lambda t/\rho.c_p.r^2$, $Po_t=Po_q+Po_p$, $Po_q=<q>.r^2/\lambda.(T_i-T_a)$, $\theta_p=p_{evap}.r/\lambda$, $\phi=(1+\delta\, Bi)/3.Bi$, $Bi=h.r/\lambda$, $Bi^*=\delta.Bi$, $\delta=\Delta r_a/r$.

The solution of the macroscopic equation, Eq.(9), is fitted to the data describing the change of the average temperature in time using the non-linear regression toolbox ofMatlab. By varying the Biot number, its relation with the relaxation parameter ϕ and the final temperature θ_e are investigated.

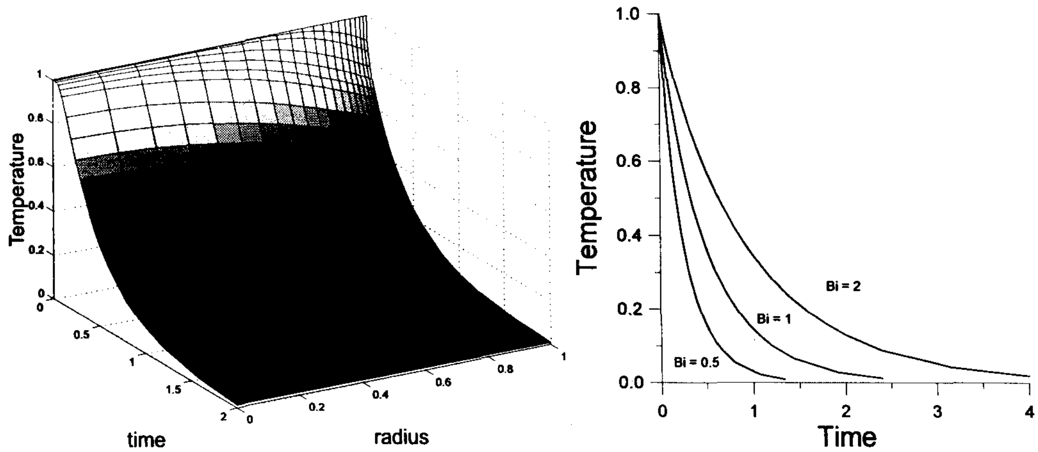

Figure 3. a) Surface plot of temperature distribution in a cooling sphere with Biot number Bi=1. b) Mass average temperature as a function of time for Biot numbers Bi=0.5, 1.0, 2.0. In both graphs, all parameters are in dimensionless units.

Results

First we investigated the function $\phi=\phi(Bi)$ for products without respiration and transpiration ($Po_t=0$). The computing procedure we have exemplified with some figures. First using the FEM model, the change of the temperature distribution in time is computed, as shown in figure 3a. Subsequently, using FIDAP post-processing procedures, the average temperature is computed as a function of time, as is shown in figure 3b. From this function, the parameters ϕ and θ_e are estimated using Matlab.

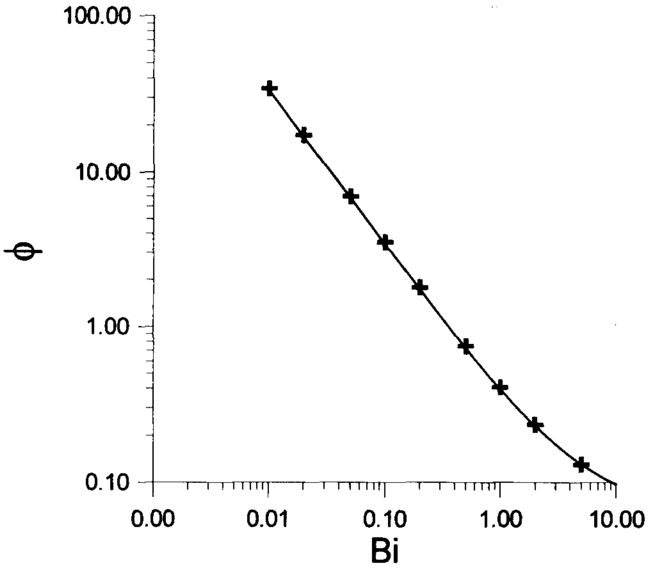

Figure 4. The dimensionless relaxation time f versus the Biot number for a cooling sphere without respiration or transpiration. The symbols are the numerical results and the solid line is obtained by non-linear regression with δ=0.193.

By varying the Biot number of a wide range ($0.01 \leq Bi \leq 20$) the relation between ϕ and Bi is obtained. In figure 4 ϕ is plotted against the Biot number Bi. Using non-linear regression we have estimated that δ= 0.193. This is approximately equal to the estimate given by Smith[4], who states that the location of the mass average temperature is the surface, which splits the volume into two equal parts.
For a sphere with radius r, the location of the mass average temperature is at $r^*=0.79$ r. Hence, as a first estimate $\delta=(r-r^*)/r_h=0.21$, which is indeed approximately equal to value found by us.

The next series of simulations are performed for spherical products with internal heat generation but without transpiration ($Po_q=0.1$, $Po_p=0$). Now the relations between ϕ and θ_e and the Biot number are computed. The results are shown in figure 5. Observe that for equal Biot number the parameter value of ϕ is independent of the value of Po, as is hypothesised in Eq.(9). The final temperature θ_e behaves as predicted by Eq.(9), although it is uncertain for high Biot number, due the relative large estimation errors.

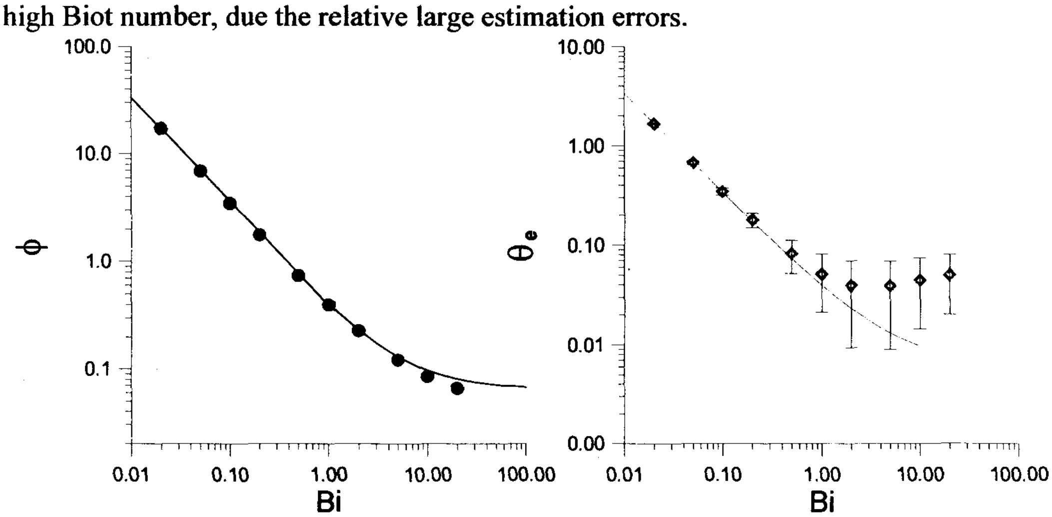

Figure 5. The dimensionless relaxation time ϕ and final dimensionless temperature q_e versus the Biot number for a sphere with internal heating. Symbols are simulation results and the solid lines are fits by non-linear regression.

The simulations are also performed for spherical products without internal heat generation, but with evaporative cooling (Po_q=0, θ_p=0.1). Again, the relations between ϕ and θ_e and the Biot number are computed, as shown in figure 6. Also in this case ϕ is independent of Po, and the final temperature θ_e is inversely proportional with Bi, as predicted by Eq.(9). Again, there are relative large estimation errors for high values of Bi.

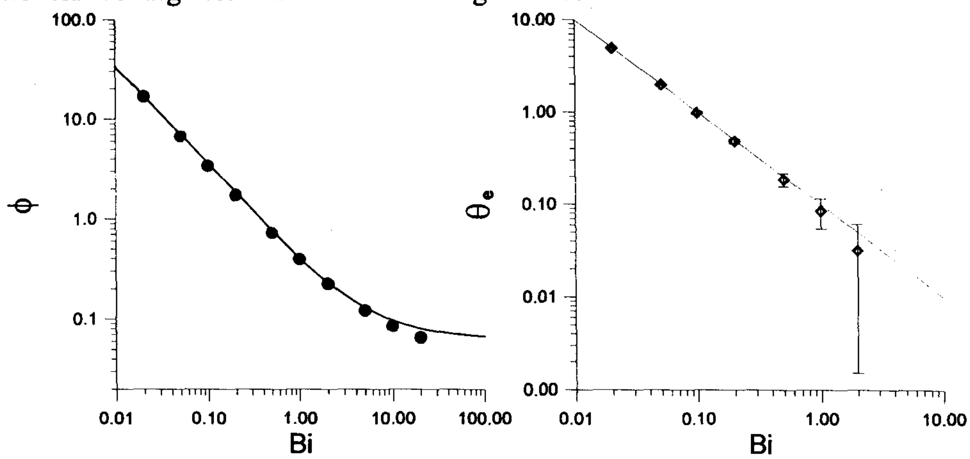

Figure 6. The dimensionless relaxation time ϕ and final dimensionless temperature θ_e versus the Biot number for a spherical product with surface cooling. Symbols are simulation results and the solid lines are fits by non-linear regression.

5. Conclusions

The averaged cooling behaviour of fresh products with internal heat generation and evaporation can be approximated with a first order system, even if there is a significant temperature gradient. An internal heat resistance can account for the temperature gradient. The value of the internal heat resistance is determined by the geometry of the product, and its thermal conductivity, but is independent of the heat produced by respiration and transpiration. The geometry factors in the expression of the internal heat resistance can be calculated by applying the volume averaging procedure, pioneered by Whitaker [10], to Finite Element simulations of cooling of individual products. The factors obtained are in good agreement with the values found by Smith [4, 5], who studied products without respiration and/or transpiration. In this paper, we have neglected the temperature dependency of respiration and transpiration. This dependency might introduce some more heat resistances in our network model, and hence they will be investigated in a subsequent paper.

List of symbols

a_w	water activity	(-)
c_p	specific heat	(J/kg.K)
h	heat transfer coefficient	($W/m^2.K$)
k	mass transfer coefficient	(m/s)
p	heat flux due to evaporation	(W/m^2)
q	volumetric heat generation by respiration	(W/m^3)
r_h	hydraulic radius	(m)
Bi	Biot number = $h\ r_h / \lambda$	(-)
C	heat capacity	(J/K)
Fo	Fourier number = $\lambda.t/\rho.c_p.r_h^2$	(-)
L	latent heat of evaporation	(J/kg)
P	heat extraction by evaporation	(W)
Po	Pomerantsev number = $q\ r_h^2 / \lambda\ \Delta T$	(-)
Q	heat production by respiration	(W)
R	heat resistance	(K/W)
T	temperature	(K)
δ	geometric factor	(-)
ε	porosity	(-)
λ	heat conductivity	(W/m.K)
θ	dimensionless temperature	(-)

indices

a	air
e	end
ext	external
i	initial
int	internal
p	product
sat	saturated

air – product interface

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Appendix 2.D: Modelling of refrigeration- and ca unit

Introduction

Reduction of energy consumption is one of the main purposes in the project. The energy consuming components of a CA-reefer are the CA-unit and refrigerating unit. It is possible to reduce the energy consumption of refrigerated transport without any change to the reefer/unit design by just controlling the units in an energy-efficient way.

Before one can select the most energy-efficient operation strategy the energy consumption as a function of operating conditions needs to be known. Formalizing this knowledge in a mathematical model enables the active on-line optimization of process operation by means of Model Predictive Control (task 7).

The aim of this part of the project is to develop a simple, computationally fast, model of the refrigerating – and CA-unit. The models will be used in the Model Predictive Control Algorithm, to be developed in task 7.

Refrigerating unit model

The refrigerating unit should take the form as depicted in the figure 2.1. Because the container climate and product quality loss exhibit much slower dynamics than the refrigerating unit, it is justified to use just a static model (algebraic and logical expressions) to describe the refrigerating unit's performance.

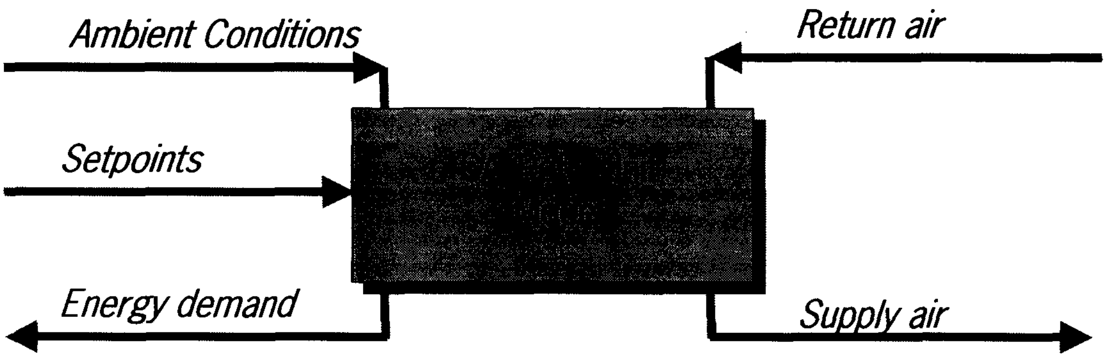

Figure. 2.1 Desired input-output mapping of refrigerating unit model.

3. Power Measurements

First identification experiments have been conducted. Because of the incompleteness of the currently available data, they have not yet been used to fit the model to the real data. Table D.I lists the drawn electrical current per component, observed in the first identification experiments.

Table D.I Measured electrical current per component, when switched on.

Component	Current (A)
Compressor	20 – 35[1]
Heater	10
condenser fan	1
evaporator fan (high)	1.5

[1] depends on temperature of ambient and return air.

Based on these figures the model predictive control algorithm (task 7) may be able to reduce the energy consumption by concentrating the operating periods of the units in periods with most favorable ambient conditions. Rough expectation is that only this may reduce the energy consumption for refrigeration with about 5-10%.

After some first identification experiments on the refrigerating unit the impression exists that another important energy saving is possible by periodically switching off the refrigerating unit's compressor. This is only possible at the expense of permitting high-frequent temperature oscillations. Hence more research is needed towards the effects of these temperature changes on product quality.

Appendix task 6

The effects of using the new container within a certain distribution chain will be quantified as much as possible. This can help to implement the container in daily practice.

Decision problems

The cost/benefit model will be developed with respect to the following two problem areas. Suppose the shipping company (or another party) intends to incorporate the new agro-container within its business. This company may have decision problems such as which price to ask for the new container. These kinds of questions concerning the market implementation of the container will be answered by Eteca in the marketing part of task 6. To support this a cost model for a detailed insight in costs is required.

On the other hand from the shipper's point of view the agro-container is one of the optional containers for transporting a product. For each shipping a decision problem exists about which transportation mode (e.g. air, sea, inland water, road or rail) and which type of container (e.g. reefer, CA,...) to use. A cost/benefit model can be considered as the basis of a decision support system for supporting this decision.

Deliverable: a cost/benefit model
ATO will develop a cost/benefit model having the following capabilities:
- To give insight how much it will cost to use the agro-container for transporting a certain product along a certain distribution chain.
- To give insight what will be the loss of product quality during transport
- To give insight what will be the energy use during transport
- To give insight what will be the door-to-door lead time of transporting the product
- To be able to compare these results with the results of making use of other (more conventional) containers.

With help of the model several distribution chains and container types will be compared.

Performance indicators of the model
In concreto this means that we want to measure the performance on the following indicators.
- Cost
- Quality loss
- Lead time
- Energy use
- Model input

The input of the model will be a certain distribution chain. A chain is characterized by the following attributes:
- its sequential activities (processes)
- its cost drivers for each activity
- its 'quality loss drivers' for each activity
- its 'lead time drivers' for each activity
- its 'energy use drivers' for each activity
- the 'tariffs' for each driver
- the type of container
- the volume and product distributed

Internal model structure

The model will be a static one. Calculation will take place according to the 'Activity Based Costing' technique.

Table *2* gives an overview of activities that may occur within a supply chain.

Table 2: Optional primary activities within a containerized supply chain.

1.	Loading the harvested product on the truck
2.	Transporting the product from the plantation to a packing house
3.	Unloading the truck and storing the product
4.	Packing and pre-cooling at the packing house
5.	Picking the product
6.	Loading the product on a truck
7.	Transporting the product from the warehouse to the exporter's cold storage at the port
8.	Unloading the truck and storing the product
9.	Stock keeping
10.	Picking the product and stuffing the container
11.	Stacking the container until it can be loaded on board
12.	Loading the container on board
13.	Transporting the container to the port of destination
14.	Unloading the container from the ship
15.	Stacking the container until it can be loaded on a truck
16.	Transporting the container to the importer's distribution center
17.	Unloading the container and storing the product
18.	Picking the product
19.	Loading the product on a truck
20.	Transporting the product from the importer's warehouse to the retailer's distribution center

Besides these primary 'physical movement' activities secondary activities exist such as quality inspections, maintenance, planning activities, and the handling of claims. If relevant, they will be taken into account within the model.

Validation of the model

The model will be validated by describing 'case supply chains'. For these supply chains, a comparison will be made with the actual transport mode. Possible supply chains are the import of exotic fruit from Zimbabwe to the Netherlands (now air transport) and the import of green beans from Egypt to the Netherlands (now partly sea and partly road transport).

Requirement from other tasks

In all following cases, the item 'cost' represents both investment cost and operating and maintenance cost.

Task 1 (Product quality)

We expect support in translating a higher product quality into possible benefits such as a longer possible transportation time (modal shift), higher price, less waste, less claims, larger market area.

Task 2 (Climate control)

We expect a quantification of possible energy reductions

Task 3 (Energy supply)

We expect a quantification of the cost of energy supply devices

Task 4 (Green chemicals)

We expect a quantification of the cost of green chemicals and appending devices

Task 5 (Sensors)
We expect a quantification of the cost of the sensors

Task 7 (Control system)
We expect a quantification of the cost of the control unit

Evaluation parameters EET
The cost/benefit model will give insight into the following parameters:

Economy
- Modal shift from air transport to sea transport
- Acceptation of the new container by the market
- Development of the cost price of the product related to other containers
- Savings on energy cost

Ecology
- Savings on waste
- Increase in product shelf life and quality

Appendix task 7

Introduction

The development of the control algorithms that is part of both Task 2 and Task 7, will be discussed in this document. The structure of the system and a more specified time-schedule are presented. Furthermore, the necessary input from other tasks and partners will be indicated.
In the CEET 2005 project Supervisory Optimising Control algorithms (SOC-system) will be developed for transport of agro materials (apples, chicory and tomatoes) in a container.
The current control system of the container receives setpoints not from a SOC-system but directly from the user. In current operation the setpoints are determined only once in the beginning of the transport. The additional layer that will be developed in this project will improve the transport of agro-material by conditions to guarantee optimal quality against lowest possible cost. The system is illustrated in Figure 1.

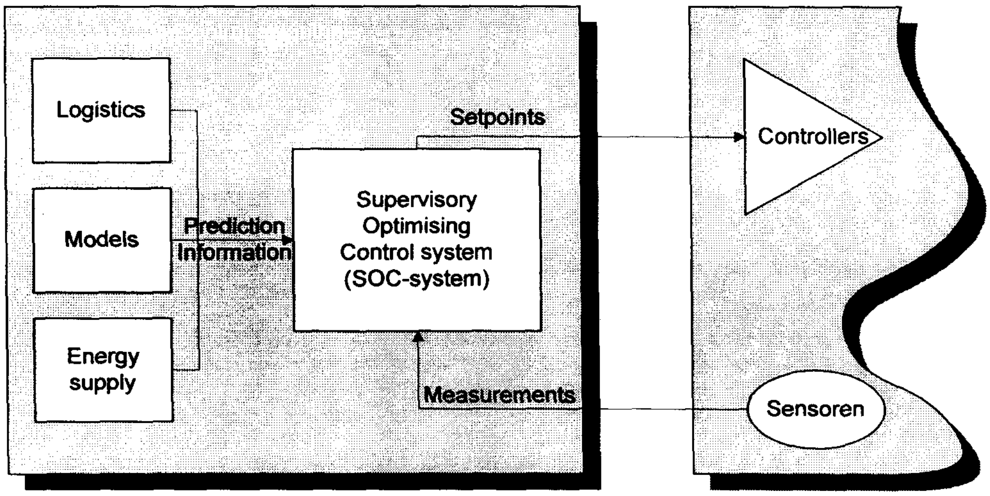

Figure 1: Global control structure

The SOC-system uses:

- monitoring information about product quality and product behaviour (Task 1, 4 and 5),
- information on energy supplies (Task 3),
- information about the trajectory of the container (Task 6).

This information is used to determine the optimal container settings. The main difference between the existing and the new structure is the direct use of product, logistic and energy information in determining the optimal setpoints for the hardware controllers. The existing hardware controllers try to reach and maintain these setpoints in the container.

Objectives
The main objective of this task is to develop supervisory optimising control algorithms (SOC-system) for agro-containers that optimises the transport of agro-products. This implies that the SOC-system:

- Optimises product quality and cost in the agro-container;
- Determines optimal setpoints and settings for the hardware controllers;
- Monitors product quality and cost.

Control design of processing agro-material
The design of a control system is an important step as it determines the process performance that can be achieved. The SOC-system consists of three modules:

- the Main module,
- the Estimator module and
- the Check module.

The configuration of the SOC-system is illustrated in Figure 2.

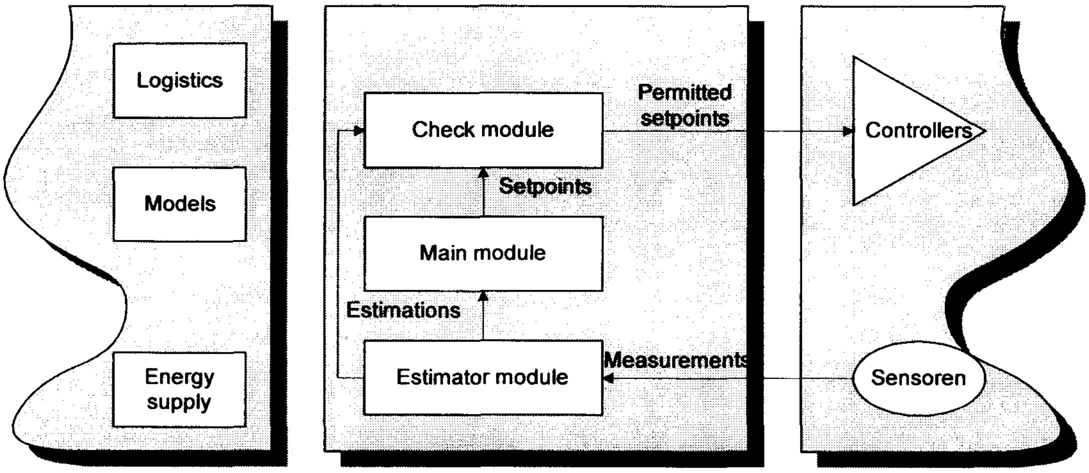

Figure 2: Configuration of the modules in the SOC-system.

The objectives of the main module are to determine those setpoints for the local control level that guarantee optimal efficiency of the transport process in economical and ecological terms. The estimator module calculates the unknown parameters and states in the model and the check module decides whether or not the calculated setpoints from the main module are sent to the local controllers.
In this stadium of the project the research is mainly concentrated on the main module.

Design of the Main module
A badly designed control system leads to a non-optimal operation of the controller and the process. There are several aspects of importance in the design procedure, but the most important in processing agro-materials are:

- Boundary conditions in the design procedure;
- The time scales of the (sub)-processes in the operation;
- The information about the process and product and the quality of this information;
- The effect of the controlled input on the process.

Figurally speaking the control design *CD* is a function of the boundary conditions *BC*, the time scale decomposition *TD*, the information density *ID* and the control effect *CE*

$$CD = g_0(BC) + g_1(TD) + g_2(ID) + g_3(CE).$$

These different aspects will be discussed separately, before the control system is presented for the transport of agro-materials.

Boundary conditions
At the moment the transport of agro-materials is controlled on local-level. This local-level consists of the hardware control system. Setpoints for this level as temperature and humidity are determined off-line. These setpoints are fixed and are not changed due to changes in product type or behaviour. In this project a Supervisory Optimising Control system will be developed that improves the total (control) performance. The boundary condition in this development is that the existing controllers must be implemented in the new control structure. The major drawback of this is the fact that not one control level can be implemented that optimises the whole plant in one algorithm. However, the advantage of this approach is the assurance that if the control system fails the operator can return to the existing low level system.

Time scales

A characteristic phenomena in transport of agro-materials is the different time scale on which different sub-processes operate. The product and direct product environment (e.g. air in packaging) respond relatively slowly on the controlled and uncontrolled inputs. This is typically in terms of days. The direct product environment is determined by packaging. Packaging acts as a filter for the product environment that directly interacts with the product. This results in slow dynamic behaviour of this product environment. The indirect product environment (e.g. air between packaging or in head space) responds much faster to new control actions, typically in the order of seconds or minutes. In Table 1 these time scales are illustrated.

Sub-processes	Time scales
Product	Days
Direct product environment	Days
Indirect product environment	Seconds/minutes
Local controller	Seconds

Table 1: Different time scales in transport of agro-materials

The differential equations for the dynamics of the container transport are written in the following equations where c represents the slow dynamics and x the fast dynamics

$$\dot{\bar{c}} = f_1(\bar{c},\bar{x},\bar{u},v,t),$$
$$\dot{\bar{x}} = f_2(\bar{c},\bar{x},\bar{u},v,t),$$

where u is the control input, v represents the inputs that are not controlled and t is the process time. In these equations the fast dynamics are ignored by assuming a pseudo-steady state, while studying slow dynamic behaviour

$$\dot{\bar{x}} = 0.$$

This is a valid approximation in presence of slow fluctuating inputs u and v. In this approximation the time for the fast dynamics to settle in the pseudo-steady state is ignored. In presence of fast fluctuating inputs this will give rise to non-optimal control performance. In these cases, the singular perturbation method may be used. This technique is used in controlling processes with different time scales, see e.g. van Henten (1994) in greenhouse climate control. In the singular perturbation technique the differential equations are written slightly different

$$\dot{c} = f_1(c,x,u,v,t),$$
$$\varepsilon\dot{x} = f_2(c,x,u,v,t).$$

In these equations the pseudo steady state assumption is modified into the multi time scale property. In this technique the differences between the slow and fast dynamics are expressed by the time scaling parameter epsilon. Although this singular perturbation technique seems to be a rather logical choice for operations involving agro-materials, there are two major problems. First, the boundary condition that the local control level can operate as backup system. This is the boundary condition as is discussed earlier. Secondly, the difficulty to persuade industry to change from proven technology towards relatively new techniques. In general, the control systems consists of a local control level with the objective to reach and maintain processing setpoints as temperature and humidity, and a supervisory level with the objective to economically optimise the operation. In Figure 3 both control structures are shown.

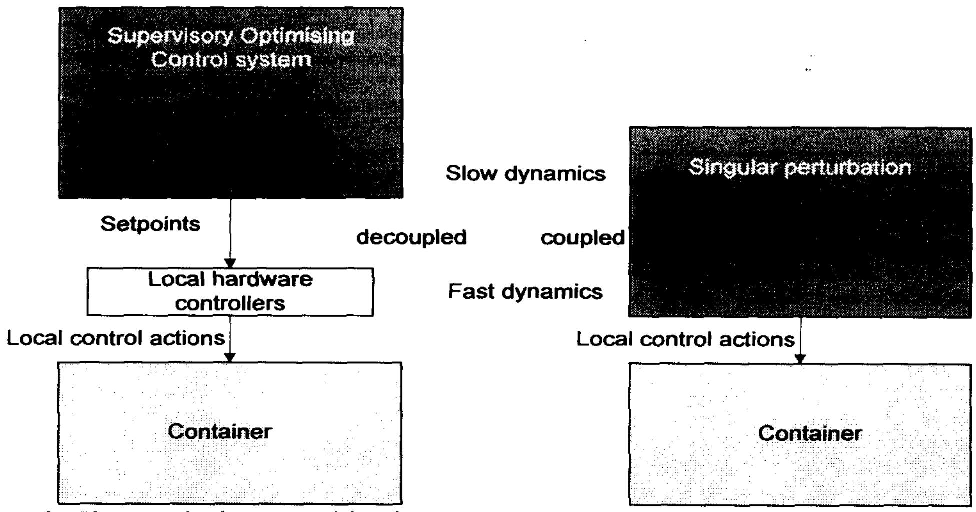

Figure 3: Time-scale decomposition in the control system

In the choice between both control structures in Figure 3, the most important aspect is the dynamics of the system inputs, both the controlled inputs as the expected disturbances. The controlled inputs are constrained to slowly changing values to prevent product stress. The expected disturbances consist mainly of outside weather conditions that may change rather fast. However, the container acts as a filter and fast outside disturbances only effect the inside conditions with slow dynamics. This is illustrated in the Figures 4a-d.

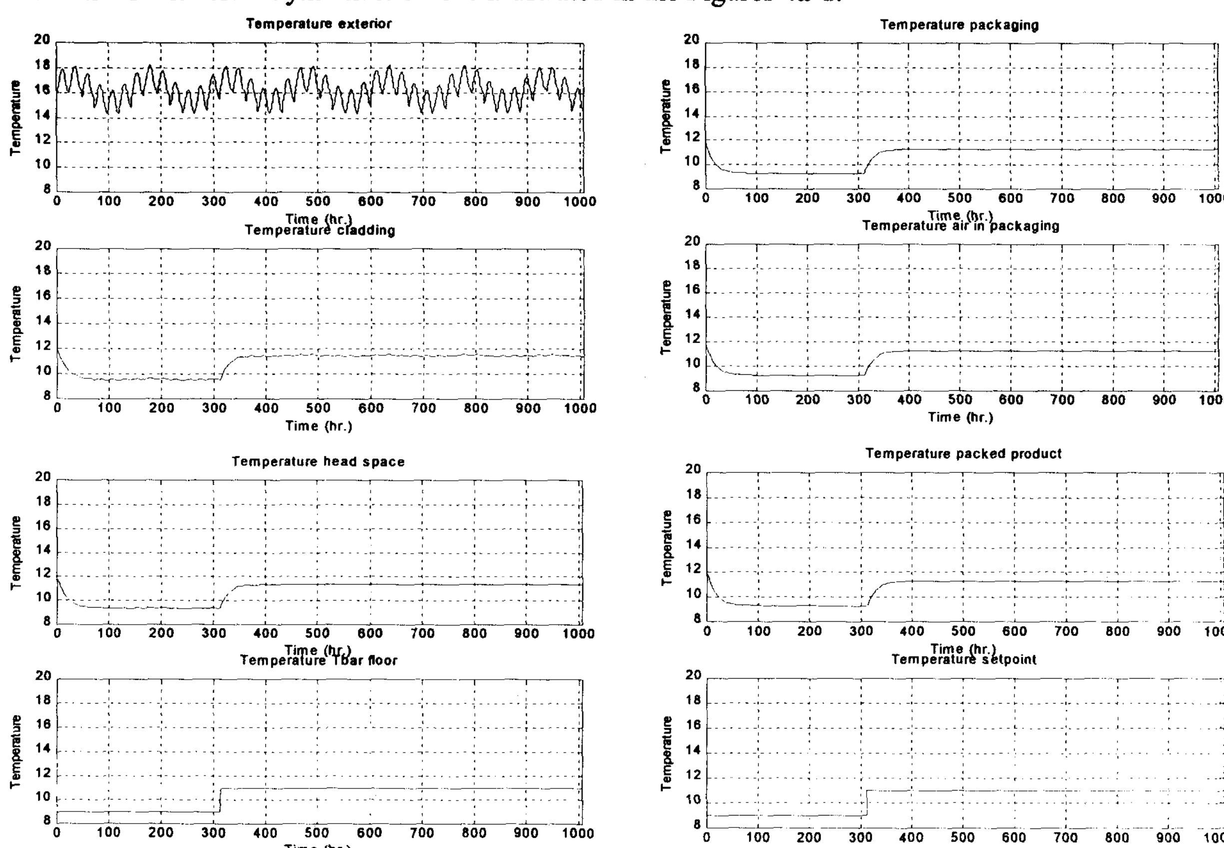

Figure 4: a) Temperatures exterior and cladding, b) Temperature head space and Tbar floor, c) Temperature packaging and air in packaging, d) Temperature packed product and setpoint

In these figures results of a simulation study for temperature behaviour are shown that is performed for the container transport of agro-materials. Outside temperature is 15 degrees with a sinusoid with an amplitude of one and frequency of 1/(24*3600) Hz, and a sinusoid with an amplitude of one and frequency of 1/(2*pi*24*3600).

The model is analysed in the frequency domain using the transfer functions with respect to temperature. The disturbances are not exactly known, but the frequency range is known. This complicated model is analysed and results in a significant model reduction. The first step is to analyse the dynamics of the different transfer functions and remove the dynamics that will not be excitated in the process. This results in the replacement of dynamic transfer functions by steady gains. In the following step the significance of the transfer functions is considered and non-significant transfer functions are removed. In the third step states in the model that are not relevant as a separate state are combined and this step results in combined transfer functions. From the analysis it can be concluded that the most important inputs in the transport process are the ingoing air temperature from the unit, outside temperature and the respiration and evaporation of the product. The most important states are the air in the packaging, product temperature and the head space air temperature (that is a necessary input in the model of the unit as this is the return air).

From both the time domain analysis in the simulation study as in the frequency domain analysis the conclusion is that fast disturbances, such as occur in the outside weather conditions, cause only slow dynamic behaviour inside the container. This motivates the choice to use the decoupled control design.

Information density

An important problem that often occurs in processes is that not all information is known or known with enough accuracy. This certainly is the case in the transport of agro-materials. This problem occurs at the level of outside weather conditions and on the level of changing process conditions for optimal product behaviour. On the outside weather level only nominal weather conditions are known beforehand. This nominal weather can be used to determine optimal control actions to achieve maximum efficiency of the transport. The problem is that actual weather may differ from the nominal weather. On the level of the process conditions the influence of certain system inputs, e.g. relative humidity, is not known with the same accuracy as e.g. for temperature and oxygen. This causes problems in determining optimal transport conditions. To deal with this information problem on both levels the control structure is further modified and in the SOC-system the main module is divided in two sub-controllers. The primary controller that determines the long-term economical objective of the transport and uses nominal weather conditions and the secondary controller that determines a short term objective. In potato storage an example of such an approach can be found in Verdijck 1999. The outputs of the primary controller are either used by the secondary controller, mainly consisting of prize information, or are directly used by the local controllers, e.g. the level of the relative humidity inside the container. This is shown in Figure 5.

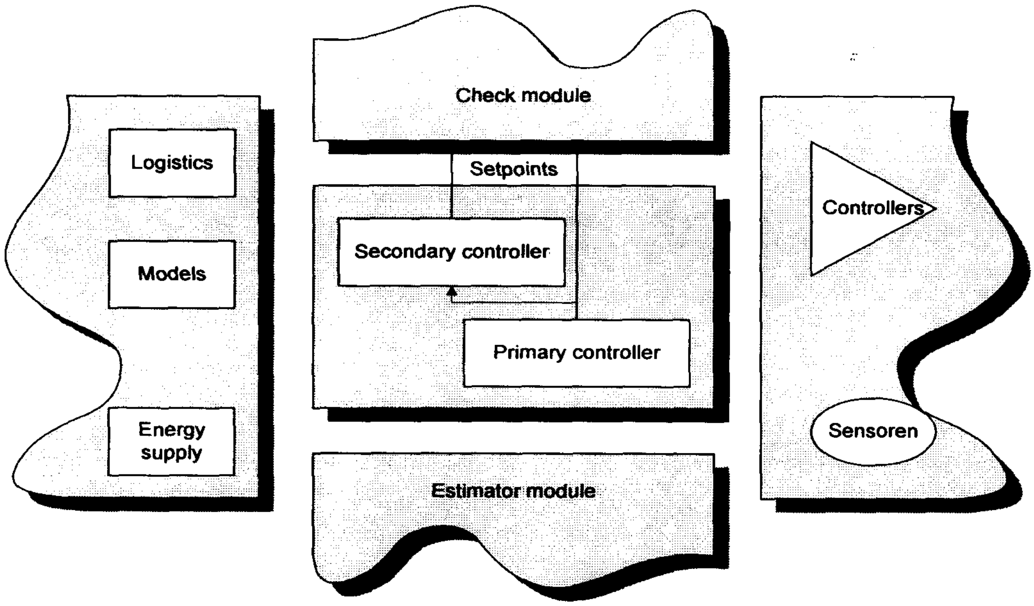

Figure 5: Information density included in the control system

Control effect

Choosing the controllable inputs must not only include the information density, but also the effect the control input has on the product states. Those inputs must be selected that can be changed within their control domain such that the outputs (product states) can be manipulated in their domain. With respect to product quality it can be concluded that temperature and oxygen are the most important inputs that can be controlled. As information on both temperature and oxygen is available they are selected as main controlled inputs. In addition, the relative humidity can be important in minimising the energy usage.These main inputs will be determined by the secondary controller in the main SOC-module. The other controllable inputs will result from the primary controller. In fact, this separation of controllable inputs can be evaluated in terms of partial control, see Kothare (1998). The main controlled inputs are used to control the most important aspects of the product. This is referred to as exact control. The other inputs are used to control the other aspects of the product, but as these aspects outnumber the inputs these other aspects can only be kept in certain domains. This is referred to as partial control.

Control system

In Figure 6 the total control system is shown. In this figure the different results from earlier sections are included.

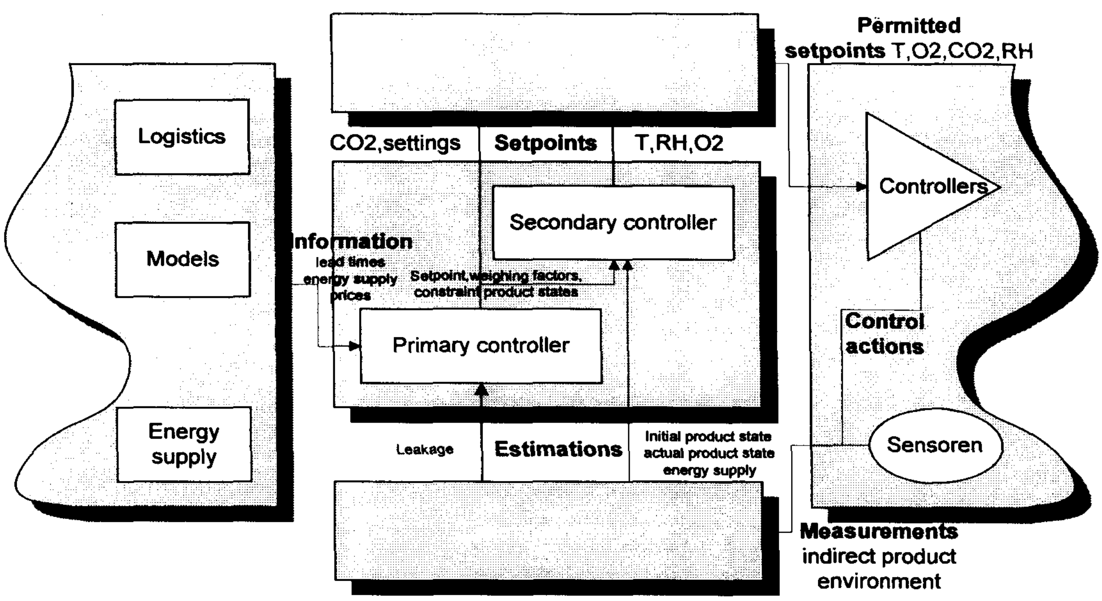

Figure 6: The structure of the total control system

System equations

Product

Product quality states

The main assumption in modelling the product quality aspect in container transport of agro-materials is that quality is directly linked with respiration. A higher rate of respiration leads to more changes in the product and therefor also quality changes. Controlling respiration during the transport process enables the control of quality. A second aspect that is important for quality during transport is the occurrence of fermentation in the product. Fermentation must be restricted in the process. For information about modelling of respiration and fermentation, see Peppelenbos (1996). The two differential equations for respiration and fermentation can be written as

$$Q = f(R)$$

$$\dot{c}(product\ state\ 1) = \dot{R} = q_1(c)$$

$$\dot{c}(product\ state\ 2) = \dot{F} = q_2(c)$$

The parameters in these equations strongly depend on type of product and this information must be supplied to the SOC-system by the user. The initial values for the respiration state R follows from an estimation. This estimation results either from measurements of from the user through the estimator module.

Two on-line measurement results are possible for the evolution of the respiration reaction. The first is that the time derivative of R is measured and the second is that R(0)-R(t) is measured. In fact, the second possibility is the integral from the first one. Because the actual value can not be measured very accurately the second possibility is, at least at this moment, chosen to be used in the control system. In practice this results in the measurement of the supplied oxygen during the whole transport up to time t, from which R(0)-R(t) can be estimated. E.g. the estimation can result from information from the local hardware controllers on how much oxygen, that is used in respiration, must be transported to the container. This will be performed in the estimator module.

The target for the controllers with respect to the fermentation reaction is to minimise this reaction and this is forced in the controller by constraining the time derivative of F. This derivative can be measured with a sensor that measures ethanol, that can be seen as an representative this derivative.

Product states

Besides the product quality states there are other product states that do not contribute directly but indirectly to the quality of the product. These states are the temperature of product and the mass of product. Product temperature influences reaction rates in the product and product mass is important in considering undesired weight-loss of the product. Weight-loss not only can decrease product quality, but is also, of course, important for the financial yield of the product after transport.

$$\dot{c}(product\ states) = f_0(c,x,u,v,t)$$

Direct product environment

5 differential equations for the direct product environment (temperature, oxygen, carbondioxide, moisture content, ethanol) within each packaging with product that must be considered in the controllers.

$$\dot{c}(direct\ product\ environment) = f_1(c,x,u,v,t)$$

The parameters in this model are determined both by off-line calculation and experiments that stay fixed in time and by on-line estimation (e.g. leakage) by an, possibly, extended pre-trip inspection that may vary between different transports.

From on-line measurements on the indirect product environment return air in the CA-unit the estimator module calculates the actual values for the direct product environment states.

The inhomogenity of the conditions inside the container is accounted for by selecting the most sensitive spots in the container with respect to disturbances. Together with the nominal conditions it can be expected that these spots describe reasonably well the inhomogenity in the container.

Indirect product environment

The indirect product environment (head space, T-bar) is the intermedium between the output of the unit and the direct product environment.

$$\dot{x} = f_2(c,x,u,v,t)$$

The state values can be measured on-line on the return air in the CA-unit.

Hardware controllers

At this moment of the research project it is assumed that the dynamics of the hardware controllers can be neglected as these dynamics are relatively fast. Of course, this assumption must be validated as soon as the required information is available. If this assumption is indeed validated the hardware controllers can be described with algebraic equations. These algebraic relations must relate desired process states to energy usage (perhaps as function of outside or inside conditions).

Objectives for the different controllers

Primary controller

Optimal control to calculate process conditions with an economic objective based upon nominal weather conditions. The objective function can be written as

$$J = P(Q)\,M - \int_{t0}^{te} L(c,x,u,v,t)dt$$

where P is the price of the product that depends on the end-quality Q, M is the end-mass of the product and the integral represents the cost that are made to achieve the desired product states at the end of the transport process. This objective function tries to achieve maximum product quality, minimum weight-loss and minimum cost.

Inputs:
- Logistic information including lead times, energy supply and prices
- Initial product state values from estimator module (and perhaps indirect from the user)

Outputs:
- Setpoints for partial control to the local hardware controllers
- Setpoint for respiration to the secondary controller
- Constraint for fermentation to the secondary controller
- Weighing factors for product states and energy usage to the secondary controller

Secondary controller
Control to calculate process conditions with short-term economical/ecological objective. The main objective is to achieve the desired setpoint as calculated by the primary controller and to reject the undesired disturbances. These are outside weather conditions that are mainly responsible for inhomogeneous conditions inside the container. The controller must optimise between achieving the setpoint, inhomogenity inside the container and cost (energy usage). As outside weather conditions may change the controller may benefit from weather predictions. Together, this leads to a short-term economical objective function that can be written as

$$J = \int_{t}^{t+\Delta t} (W_r(actual\ value - quality\ setpoint) - L(c,x,u,v,t) - W_i \Delta c)dt$$

$$\dot{F} \le \dot{F}_{\max}$$

$$\dot{R}_{\min} \le \dot{R} \le \dot{R}_{\max}$$

where W are the weighing factors that relate differences between actual and desired behaviour, and inhomogeous conditions to economical terms that can be optimised. The inhomogenity is expressed in terms of the product states in c. Note, there are constraints for the time derivatives of the fermentation and respiration reaction. This secondary controller will be a MPC type controller with horizon in terms of maximum one week.

Inputs:
- Setpoint and respiration from primary controller
- Constraint for fermentation from primary controller
- Weighing factors for product states and energy usage from primary controller
- Actual state values from estimator module

Outputs:
- Setpoints for product environment states to check module and from there to local hardware controllers

Local hardware controllers
The objective of the local hardware controllers is to minimise the error between the desired and actual product environment states.

Inputs:
- Setpoints and settings (e.g. bandwiths) from check module

Outputs:
- Control actions to container
- Number of control actions to estimator module

Problems

When optimising the transport with respect to product quality and energy usage it is important to have information available on the actual states. Some kind of measurement for product quality must be available by the estimator module. Probably, the amount of local control actions on the oxygen supply can be related in quantitative terms to respiration and therefor to product quality. Furthermore, the initial condition or the initial state of the product must be known, either from the user or from measurements. This must be a topic of future research in this project.

In the development of the control algorithms an important item is the stability of the algorithm. This gets complicated as one or more parameters in the controller will be adapted during the transport process. This leads to the question of stability for an adaptive model predictive control algorithm. Probably this will result in certain restrictions for the type of algorithm that will be used in this project.

An important problem that is encountered in this project is the amount of uncertainty in the information that is available to the control algorithms on the different control levels. In the control algorithms the confidence one has in the information on e.g. the initial product state must be incorporated. It would be possible to even consider to include the amount of risk the user finds acceptable. No risk means enormous operating cost.

Future work and desired information

In this period of the research project the main focus will be on the secondary control algorithms. This includes the problems as mentioned in section 4.5. These are measurability, stability, uncertainty and risk evaluation.

Furthermore, the necessary information must be completed. This includes information on the local controllers in the unit, product behaviour and energy supply. Another topic is the use of green chemicals and how this can be included in the SOC-system.

Time schedule

Duration

Phase 1-3 of the CEET 2005 projects is from October 1998 until 30 September 2001.

Schedule

The time-period for the development of the SOC-system consists of three parts that largely correspond with the phases as defined in the CEET 2005 proposal. The deviations are due to the fact that information from other tasks is essential for the development of the system. In Figure 7 the original time schedule is presented.

Part 1: Preparation and global SOC-system structure development

The duration of this phase is from 1 October 1998 until 31 May 1999. The deliverables are:

- Report phase 1;
- Structure of the SOC-system developed;
- SOC-system structure tested and tuned in a simulation study using simple models for temperature, humidity and product quality.

Part 2: Conditioning of climate and testing the SOC-system

The duration of this phase is from 1 June 1999 until 31 May 2000. The deliverables are:

- Report phase 2;
- Final structure of the SOC-system developed;
- Primary subsystem tested and tuned in a simulation study using models for temperature, humidity and product quality with variance;
- Primary subsystem tested and tuned in the climate room.

Part 3: CA-control and implementation in a test container
The duration of this phase is from 1 June 2000 until 30 September 2001. The deliverables are:

- Final report;
- Final algorithms of the SOC-system and documentation;
- SOC-system tested and tuned in a simulation study using models for temperature, humidity, product quality and gas conditions;
- SOC-system tested and tuned in a container.

ID	Task Name	Duration	Start	Finish
1	SOC-system development CEET	782d	Thu 1-10-9	Sun 30-9-0
2	Part 1: Prep. and global SOC-system structure develop	173d	Thu 1-10-9	Mon 31-5-9
3	Preparation	131d	Thu 1-10-9	Thu 1-4-9
4	Development of structure of the SOC-system	21d	Fri 2-4-99	Fri 30-4-9
5	Development of simulation	10d	Mon 3-5-9	Fri 14-5-9
6	Simulation with the SOC-system structure	55d	Mon 17-5-9	Sat 31-7-9
7	Part 2: Conditioning of climate and testing the sec. cont	262d	Tue 1-6-99	Wed 31-5-0
8	Preparation of the available models	44d	Tue 1-6-99	Sat 31-7-9
9	Development of final structure of the SOC-system	22d	Thu 1-7-99	Sat 31-7-9
10	Development of the secondary control algorithms	110d	Mon 2-8-9	Fri 31-12-9
11	Testing the secondary control algorithms	174d	Fri 1-10-99	Wed 31-5-0
12	Part 3: CA-control and implementation in a container	347d	Thu 1-6-00	Sun 30-9-0
13	Preparation of available models	152d	Thu 1-6-00	Sun 31-12-0
14	Development of SOC-system	153d	Tue 1-8-00	Thu 1-3-0
15	Implementation and testing of the SOC-system	195d	Mon 1-1-0	Sun 30-9-0

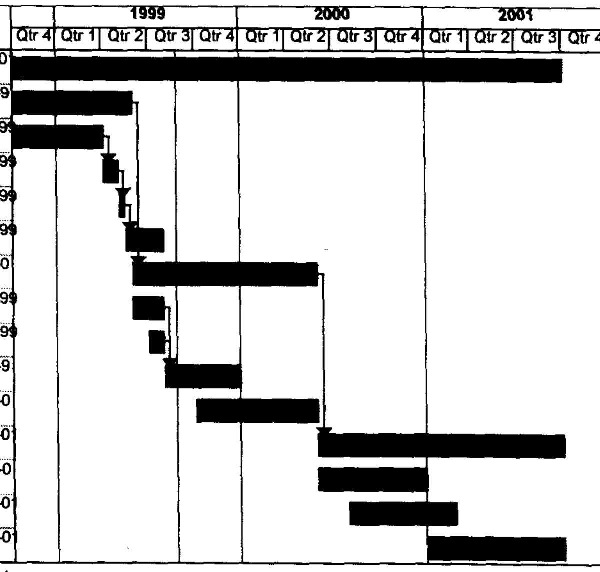

Figure 7: Time schedule of the SOC-system development

Evaluation of the time schedule
In the first part of the research project the global and total SOC-system structure is developed as planned. Furthermore, a simple simulation study of the transport process is performed. Results of the study are included in this report. This simulation study will be continued to enable the testing of the different control algorithms (secondary and primary) before they will be implemented in the test-container. The preparation of the available models is not completed yet. For the product model this is caused by the fact that it is necessary to perform enough experiments to have sufficient confidence in the predictive capability. Descriptive models are already available to a certain amount, but the predictive capability must be improved. With respect to the hardware controllers more detailed information is needed from Carrier Transicold. This is communicated between both parties and this will be solved in the next period. From Ecofys an idea of the possibilities for the energy supply must be received to be able to improve the energy optimisation in the secondary control algorithms

Deliverables

At the end of part 3 as scheduled in this report, the programmed SOC-system with corresponding documentation is implemented and tested in a testing-environment. The SOC-system is a tested prototype that is fitted on the container present at ATO. The deliverables are:

- The tested SOC-system algorithms of the prototype consisting of the primary and secondary subsystems, and additional managing software;
- A report presenting the results and possibilities of the tested SOC-system;
- A technical report presenting technical details on the structure, algorithms and tuning of the SOC-system.

Boundary conditions

The boundary conditions for the development and practical use of the SOC-system are:

- The availability of sufficient computing conditions for the system (either central in the agro-container or decentral);
- The benefits of the additional layer are higher for longer transport chains;
- The benefits of the additional layer depend on the type, quality of the product and the information about it.

Requirements

The requirements for the development of the SOC-system are listed for the three parts in the SOC-system development.

Part 1: Preparation and global SOC-system structure development

The requirements in this part are fulfilled with two exceptions. These are:

- information about the local controllers, that will be solved in the next period,
- a simple product model for apples needs to be improved further, experiments for this are being performed.

Part 2: Conditioning of climate and testing the SOC-system

No.	Input	Date	Correspondent	Check
10.	Preliminary model lead time and outside conditions	31 July 1999	Task 6-ATO	
11.	Selection product quality for all products	31 July 1999	Task 1-ATO	
12.	Preliminary model of product quality of apples in relation with process conditions (T and RH)	31 July 1999	Task 1-ATO	
13.	Simple model of product quality of all products in relation with process conditions (T and RH)	31 July 1999	Task 1-ATO	
14.	Parameter heat production apples and estimates other products	31 July 1999	Task 1-ATO	
15.	Parameter transpiration rate apples and estimates other products	31 July 1999	Task 1-ATO	
16.	Preliminary model of process conditions (T and RH)	31 July 1999	Task 2-ATO	
17.	Preliminary energy model	31 July 1999	Ecofys	
18.	Identification measurements and procedure	30 June 1999	Task 2,5-ATO	
19.	Settings of the hardware controllers can be manipulated in the container available for ATO	30 June 1999	Carrier Transicold	
20.	Selection of measurable process conditions (T,RH)	30 June 1999	Task 5-ATO	

The information that must be collected in this part is partly available. Most information needs more detail and this is researched at this moment. E.g. the heat production at atmospheric conditions is known, but at CA-conditions experiments are necessary. From these experiments a simple model will be constructed that relates the quality aspect to process conditions. An extra question in this part of the research is how the green chemicals can be included in the SOC-system.

Part 3: CA-control and implementation in a test container

No.	Input	Date	Correspondent	Check
21.	Final model lead time and outside conditions	31 December 2000	Task 6-ATO	
22.	Selection of measurable CA conditions	1 October 2000		
23.	Final model of product quality in relation with process conditions (T and RH)	31 December 2000	Task 1-ATO	
24.	Parameter heat production all products	31 December 2000	Task 1-ATO	
25.	Parameter transpiration rate all products	31 December 2000	Task 1-ATO	
26.	Final model of process conditions (T and RH)	31 December 2000	Task 2-ATO	
27.	Final energy model	31 December 2000	Ecofys	
28.	Interaction microbiology with product quality and process conditions	1 October 2000	Task 3-ATO	
29.	Characteristics of measurement dynamics (T,RH)	1 June 2000	Task 5-ATO	
30.	Characteristics of measurement dynamics (CA)	31 December 2000	Task 5-ATO	

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