CARE-GO
A Quality Control System for Perishables

for

KLM CARGO

KLM Royal Dutch Airlines
Business Unit Special Cargo (SPL/JK)
Amsterdam Airport Schiphol

Report 1

CONFIDENTIAL

J.J.M. Sillekens
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Dienst Landbouwkundig Onderzoek
Instituut voor Agrotechnologisch Onderzoek

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1. Aims of the project

1.1 Quality management of perishable products

Transport of perishable products is an important activity of KLM CARGO. Currently responsibility for product quality is primarily with the producer of the products. KLM CARGO takes care of transportation and deliverance to the buyer of the products. For two reasons it is of great importance to KLM CARGO to maximize the quality of the product after transportation. First, good quality is required by the buyer. Sub-optimal conditions before and during transport can result in quality deterioration and claims by the buyer. Second, also the producer requires good transport conditions because bad transportation renders the products unsaleable.

In order to be able to guarantee product quality preservation during transport, it is necessary to be able to assess the initial product quality at acceptance from the producer as well as predict product quality loss during transport. In the CARE-GO project KLM CARGO and ATO-DLO aim at realizing a quality control system which makes this possible. CARE-GO is subsidized under the SENTER Information Technology Program.

1.2 Quality management tools

The quality control system mentioned in the preceding paragraph will consist of three subsystems:

- A sensor system.
  The sensor system will consist of a set of sensors. One type of sensor measures objectively quantities related to the climate surrounding the perishable products offered for transport to KLM CARGO. Another type of sensor measures parameters related to the quality of the product at the moment of receipt and to the stress effects the product has accumulated from harvest till arrival at the airport.

- A monitor system.
  The monitor system consists of sensors for monitoring climatic conditions during flight which influence product quality. The monitor system can be employed on a random check basis in order to signal problems during flight *a posteriori*. A subsequent evaluation of flight conditions will facilitate problem solving.

- A simulation system.
  The simulation system will determine optimal perishable cargo loading schemes on the basis of the initial quality of produce and its packing and within constraints like LIFO (Last In First Out) procedures. The simulation system will consist of:

(I) A model which predicts product quality and characteristics on the basis of given climatic conditions of the immediate environment of the product.
(II) A model predicting package performance (e.g. water permeability).
(III) A model of cargo hold performance (e.g. ventilation and temperature during flight).
(IV) A user interface allowing the user to predict or simulate product quality in different cargo loading situations

In the following we will not consider the monitor system separately, because the sensors involved in the monitor system are also involved in the sensor system. The sensor (monitor) system will provide input and calibration data to the simulation system. The combination of the three systems is required to:

- Detect product quality parameters at receipt of perishable cargo.
- On the basis of detected quality parameters, advise an optimal cargo loading scheme and present a warning in the case of critical pieces of cargo.
- On the basis of a limited amount of sensor data, simulate the climatic environment of the perishable products. This allows revealing the reason for eventual product quality losses.

2. Results presented in this report

2.1 CARE-GO in phase 1 and 2

The CARE-GO project has been divided into six separate phases. For each phase several activities are described (CARE-GO, 1995). In the current report we present results obtained in phase 1 (A1, A2 and A3) and part of phase 2 (B1) of the project:

Phase 1. Problem analysis and system specifications
- A1. Literature study
- A2. Determination of specifications to be met by the sensor system
- A3. Determination of specifications to be met by the simulation system

Phase 2. Feasibility and constraint definition
- B1. Selection of the best qualified sensor technology

The literature was scanned for relevant information on sensor techniques. Results are presented in chapters 4 and 5 and section 6.1. In a number of meetings at KLM CARGO, information was gathered related to the specifications to be met by the sensor system and the simulation system (chapters 3 and 6). A literature-based feasibility study concerning the sensor technology is included in chapter 5. In a following report, practical aspects will complete the feasibility study.

2.2 Selecting important perishables and aircraft

The quality control system will incorporate product- and aircraft-specific information. Also, some sensors will only be applicable to one kind of perishables. Therefore, initially we will limit our attention to (the most) important kinds of perishables and aircraft. Many of the elements which will be developed for the quality control system for these perishables and aircraft will be immediately applicable to other kinds of perishables and aircraft. For instance, package and cargo hold models need only little adjustment in order to work for other perishables and aircraft. On the other hand, some sensors may be applicable for only one group of perishables.

2.2.1 Cut flowers: an important claim generator

Perishable products are classified into four product groups:

- Flowers/plants
- Fruits/vegetables
- Fish/seafood

- Rest perishables

Of these product groups, flowers/plants generate by far the largest amount of claims to KLM CARGO, followed by fish/seafood (CCA 1994/95). In the flowers/plants group, cut flowers are dominant. For this reason, in the CARE-GO project we will initially focus our attention on cut flowers. In a later phase, fish/seafood transport may be included as well.

2.2.2 The Boeing 747-400: a model aeroplane

A wide range of aircraft is being used for perishable cargo transport. A list of several aeroplanes in use by KLM is given below. Cargo capacity and temperature control data, which are relevant to the simulation system, are included.

MD11		
		hold 1-2: temperature between about 4 and 10 °C hold 3: temperature between about 10 and 20 °C hold 4: temperature selectable between 4 and 35 °C
Airbus A310		
		holds 1-2 and 4: temperature selectable between 5 and 25 °C hold 3: no temperature selectable, temperature between 9 and 18 °C
Boeing 737		16 ton cargo no temperature control: hold 1-2: 4 to 9 °C, hold 3-4: 0 to 6 °C
Boeing 747		102 ton cargo
	300	hold 1-2: temperature between about 2 and 13 °C holds 3 and 4 can be kept below 3 °C main deck: temperature selectable between 4 and 29 °C
	400	hold 1-2: temperature between about 5 and 10 °C (Flow off) temperature selectable between 5 and 26 °C (Flow low/med.) hold 3: low temperature between 4 and 9 °C (depending on hold 4) hold 4: low temperature of 4 °C is selectable, actual temp. between 4 and 9 °C main deck: temperature selectable between 4 and 25 °C

For intercontinental transport of cargo, the Boeing 747-400 is being used most frequently. Also, much technical data on the aircraft are readily obtained. The aeroplane contains several different holds, which may serve as an example for similar holds in other aircraft. For these reasons, we will use the specifications of the Boeing 747-400 in our simulation system.

3. Conditions during air transport of perishables

3.1 Material aspects of perishable transport by KLM

In our simulation system, we will use the Boeing 747-400 as a model aircraft. In this section, a description is given of aspects of this aircraft that will be used in the simulation system.

3.1.1 Temperature control in the Boeing 747-400

The temperature control and ventilation of the Boeing 747-400 as used by the Dutch KLM will be considered in more detail. As pointed out in the previous table, the loading space is divided into a front compartment (hold 1-2), a back compartment (hold 3-4) and section E on the main deck (Combi configuration), as sketched in Figure 1.

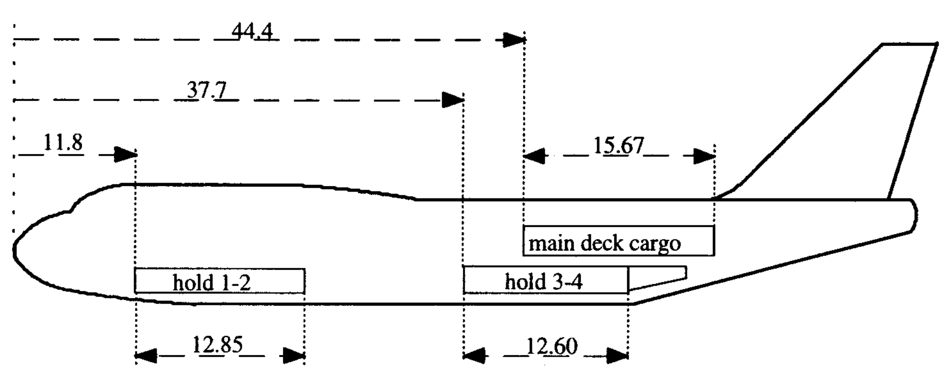

Figure 1. Location of cargo holds in a Boeing 747-400. Dimensions are given in *m*.

The Boeing 747-400 has three units (called air-conditioning packs, although humidity is not controlled) by which the temperature of the ventilation air coming from outside the plane (bleed air) can be modified. The air outside the plane is compressed to about 0.3 *bar* and enters the pack at approximately 110 °*C*. In the pack, bleed air is cooled down using outside air and further compressed to cabin pressure of about 0.8 *bar*. The conditioned air coming from the packs is distributed over the different temperature zones in the plane: the flight deck, the upper deck and zones A to E. The temperature of the conditioned air from the packs is set to the lowest temperature required in one of the zones. The temperature of ventilation air in the other zones then is regulated by adding hot bleed air (trim air). In total the three packs can supply maximal 5 m^3/s conditioned air. The main deck cargo compartment (temperature zone E) is supplied with about 0.3 m^3 conditioned air (temperature selectable between 4 and 25 °*C*) per second.

The aeroplane walls are insulated by a 2.5 *cm* (one inch) thick fiberglass cloth, covered by a reinforced metalled Polyvinyl Fluoride film. The total heat resistance of this cloth approximately equals 0.8 m^2 °*C/W*, which may result in a considerable heat loss from hold 1-2 (of the order of 1 *kW*) during flight.

With air-conditioning on, the temperature in hold 1-2 directly depends on one air-conditioning pack (pack 3). The outlet temperature of pack 3 is determined by the zone requiring the lowest temperature, where also the temperature required in hold 1-2 is taken into account. When necessary also hot bleed air is added to hold 1-2. Under normal conditions the forward cargo compartment is ventilated by 0.43 m^3/s air, coming from 6 ventilation grates (□ 0.25 *m*) in the ceiling of the hold. When cut flowers are transported in this compartment, the temperature can best be set at 4 °*C*, in which case no hot bleed air will be introduced. In the case without air-conditioning, the temperature in hold 1-2 is kept above 5 °*C* by ventilation from the equipment room and by additional electrical heating when necessary. In this case the only cooling results from the cold aeroplane walls, especially near the door (due to bad insulation). Since considerable temperature differences in the hold then may be expected, temperature control is dependent on the location of the temperature sensor. Especially when cooling down of produce is required, air-conditioning of hold 1-2 seems the better option. Due to stronger ventilation the heat transfer from the produce then is enhanced and the temperature in the hold is expected to be more uniform. On the other hand ventilation by dry air may cause dry-out of cut flowers. During transport in hold 1-2 cut flowers may loose of the order of 1% water per hour, and even more at the outer layers of a pallet. As mentioned previously, 6 to 10% water loss is unrecoverable.

The temperature control in hold 3-4 is fundamentally different. In hold 4 the minimum temperature can be set to 4 or 20 °*C*. The temperature then is modified by spraying hot bleed air from a spray tube at the bottom of the hold into the compartment. Further there is some leakage from the passenger compartment. Hold 4 is not suited for transport of pallets due to its inappropriate shape. In hold 3 pallets of cut flowers can be shipped. Hold 3 is in direct contact with hold 4, and thus the temperature control of hold 4 also applies for hold 3. Essentially hold 3 is not well suited for transport of cut flowers, either. The temperature can only be kept low by heat leakage to the outside air. Since ventilation with bleed air will not be frequent, the circulation rate in hold 3-4 is expected to be low, and therefore large temperature differences may occur (temperature differences of the order of 10 °*C*, in space and in time for instance between the cold areas near the cargo doors and the warmer areas near the ceiling may be expected).

3.1.2 Loading of the Boeing 747-400: Pallets and Containers

Pallets are stacks of boxes containing products, packed on a 2.44x3.18 *m* aluminium plate, with a maximal loading volume of 2.33x3.07x1.60 *m* (lxbxh) on the lower deck and 2.33x3.07x2.44 *m* on the main deck. A Boeing 747-400 can load 6 or 12 pallets on main deck (depending on number of passengers) and up to 7 pallets (plus 10 LDCs) on the lower deck. Usually, cut flowers are packed in AA-boxes, which have dimensions very suitable for loading onto pallets. Pallets of cut flowers build at Aalsmeer auction are often protected against rain by a plastic cover. Pallets build at Schiphol airport, or at foreign airports, often have no protection against rain. If it rains at Amsterdam, the cardboard boxes on the pallet can become wet and lose strength.

Although the amount of cut flowers shipped from Schiphol by plane depends on the day of the week (Tuesdays more, Fridays less) and on the season, a typical freight of cut flowers consists of 6 pallets. In the Boeing 747-400, cut flowers are best loaded in hold 1-2 or at the main deck. The load pattern is shown in Figure 2, which also shows the cross-section of hold 1-2. For reasons of stability, hold 1-2 is loaded first. Hold 3 is generally used for transport of passengers luggage. Transport of cut flowers in hold 3 frequently gave rise to complaints, which may well be due to inadequate temperature control. In hold 4 a mixture of load is transported. Transport of cut flowers in hold 4 is not recommended.

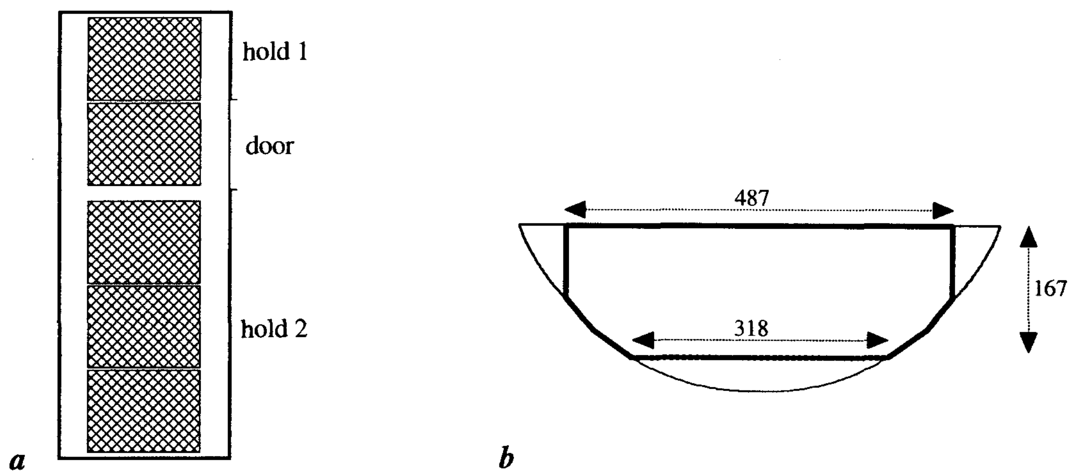

Figure 2. *a*: Common load pattern of hold 1-2 (top view). Pallets are indicated by the hatched rectangles (l×b = 2.44×3.18 *m*); *b*: Cross-section of holds 1-2 and 3 (dimensions in *cm*). Pallets are positioned on a roller floor. The maximal height of the pallets is 1.62 *m*. The roller floor is indicated by the lower horizontal line.

LDC (Lower Deck Container) or LD3 (Lower Deck 3) containers are large boxes made of aluminum and plastics. They are shaped to fit on the lower deck and their dimensions are 2.01×1.53×1.63*m* (l×w×h). They can contain 4.5 m^3 of load. In terms of weight this is, for different commodities:

- flowers : 600 *kg*
- soft fruit (berries) : 700 *kg*
- hard fruit (apples) : 1200 *kg*
- boned meat : 3500 *kg*

Added to this comes a tare weight of 190 *kg*. A Boeing 747-400 can load up to 22 LDCs (plus 3 pallets) on the lower deck.

Many types of insulated and refrigerated containers have been developed. In general they weigh more, the available load space is less and they are harder to handle. For these reasons this type of containers is hardly in use.

3.1.3 Ventilation and circulation in the Boeing 747-400

Cut flowers and also other perishables like fruits require a certain amount of ventilation in order to remove gases produced by the perishables from the surrounding atmosphere. Ethylene and CO_2, both of which can have adverse effects on product quality, are such gases. Air with a higher contents of these gases is replaced by fresh air from the surroundings. Circulation is required to keep the atmosphere in the loading room homogeneous in temperature and composition by mixing the air in the room. The air velocity around the produce thus should be sufficient to maintain a uniform temperature and composition of the surrounding atmosphere, but not so vigorous as to cause dehydration or physical damage.

In order to avoid ethylene damage, generally replacing the air surrounding the perishables 1 to 5 times per hour is sufficient. In the Boeing 747-400, during transportation of agricultural products air in hold 1-2 is replaced about 20 times per hour. This would be sufficient for preventing high ethylene concentrations.

In the above, we have assumed that refreshing air can reach the perishable product. Often this is not the case, *e.g.* when pallets are covered with plastic. Then both CO_2 and ethylene concentrations can in principle become dangerously high.

3.1.4 Cooling

Living produce breaths and releases energy. Flowers may produce an amount of heat of typically 0.1-1 *W/kg*, decreasing with decreasing temperature (a decrease of 10 *°C* leads to 2-3 times less heat production). In order to remove the released energy, and to cool down the products during transport, cooling is required.

- Mechanical cooling.
  A small amount of mechanically (cold cycle) cooled containers for transport in aeroplanes has been developed during the last decades. The cooling unit then is electrically powered by a battery. This type of containers showed to be no success, due to their high expense, logistic problems and high weight (a mechanically cooled LC3 container weights about 400 *kg* more).

- Cooling by dry ice.
  Dry ice is frozen CO_2. In air it sublimes, thereby absorbing 574 *kJ* of heat per kilogram and producing CO_2 gas having a temperature between -110 °C and -78 °C (Frank, 1982). Containers cooled by dry ice are used in air transport of perishable goods. For instance, meals can be kept cool for 5 hours in catering tray carts (trolleys), containing a few *kg* of dry ice. Cargo can be kept cool for 24 hours in IATA Contour 'Igloos' containing several tens of *kg* of dry ice. In order to avoid freezing of the product (except for frozen meat of

course), the dry ice is always separated from the product by a temperature insulating barrier. Before loading into the trolley or 'Igloo', the perishable product has to be pre-cooled: 20 kg of dry ice can cool a 600 *kg* load of cut flowers with about 6 *°C* at most, so this amount of dry ice thus is hardly effective for cooling down of cargo.

Further it should be realized that using dry ice, the atmosphere in a container will change while dry ice sublimes. At sea level, the atmospheric CO_2 contents is 0.03%. After sublimation of 20 *kg* of dry ice in a LC3 container, the CO_2 contents may become as high as 35% (and locally even higher) when the container is not sufficiently ventilated. For the transported commodity this may have positive or negative effects. But for safety reasons, the maximum allowable CO_2 content of the air is 0.5%. This limits the maximum allowable quantity of dry ice to be transported in the lower compartments of a Boeing 747-400 to 1500 *kg*, in which case the compartment must be ventilated. No live animals may be transported in a lower compartment together with dry ice.

- Cooling by wet ice.
  Fish is one of the products that are frequently packed with wet ice (frozen water). Wet ice melts at 0 *°C* with a heat consumption of 332.4 *kJ/kg*. Evaporation of one kilogram of water costs another 2257 *kJ*. Especially since the atmosphere in an aeroplane likely is very dry, cooling with wet ice might be a better option than cooling with dry ice, especially since then also the relative humidity in the storage increases. For comparison: after evaporation of 20 *kg* of wet ice, 600 *kg* of cut flowers can be cooled with about 30 *°C* (since also the surrounding air will be cooled, this again is an over-estimation). A problem with the use of wet ice compared to dry ice is that wet ice does not sublime and one therefore has to deal with the production of water. Cut flowers in general are packed in cardboard boxes (cartons). Cardboard looses its stiffness after absorption of a certain amount of water, and one therefore has to be careful using ice to cool cut flowers. When the relative humidity at the cartons is higher than 90%, the cardboard rapidly weakens. At 90% relative humidity the strength of cardboard is only 30% of its strength at 30% relative humidity.

  Ideally, when ice is used to keep the relative humidity in the plane at about 90%, one needs of the order of 1 kg ice per cubic meter storage room for a typical flight of 10 hours.

- Cooling by liquid nitrogen.
  In order to prevent a high CO_2 content of air, cooling with liquid nitrogen might be an option. However, cooling with liquid nitrogen is expensive, not practical and hardly effective. In order to cool 600 *kg* of cut flowers with 6 *°C*, one needs about 30 *kg* of liquid nitrogen, stored in insulated tanks. Cooling with liquid nitrogen therefore only is an option in airfreight if it is also used to change the air composition in containers.

3.2 Logistic aspects of perishable transport by KLM

3.2.1 Export

Cargo movement during export from Schiphol is given schematically in Figure 3. We will briefly discuss the different stages of handling. Normal cargo has to be delivered at least 3

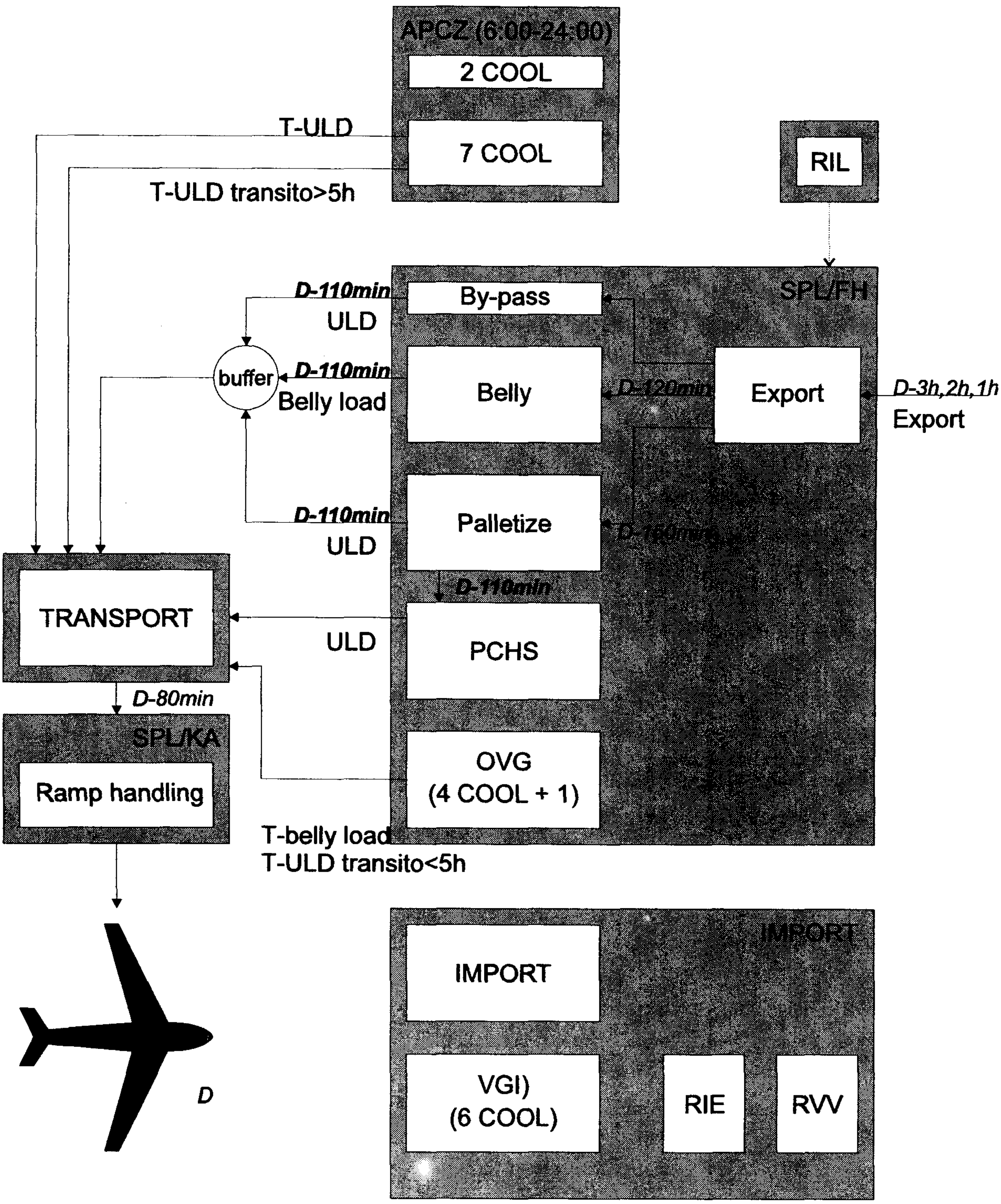

Figure 3. Cargo handling during export at Schiphol. Continuous arrowed lines represent cargo displacement for export and transit. In normal italics, the end time is indicated at which all cargo should be at the location indicated by the arrow (*D* denotes departure time). Fat times are aircraft-dependent. The time given is for the Boeing 747. Dotted lines denote information and control.

hours before departure. Flower cargo already palletized at the auction in Aalsmeer has to be delivered 1-2 hours in advance. Since it does not need to be stacked on belly carts at the 'Belly' location, nor has to be palletized at 'Palletize', it can directly be transported to the platform via the 'By-pass'. At the platform, cargo carts are arranged in buffer queues. From there, 'Transport' takes them to the aircraft. Here cargo is loaded onto the plane by SPL/KA. Other ULDs (pallets and containers) are taken to SPL/KA from the PCHS (Pallet and Container Handling System). From the cooling cells at OVG, cargo with the predicate 'COOL' is taken (T-ULDs and T-belly load). This cargo often originates from an earlier flight and was placed there for bridging a transit time of less than 5 hours. At transit times larger than 5 hours, T-cargo is not stored at OVG but in one of the 7 cooling cells that KLM CARGO uses at APCZ.

Although there is one cooling cell available at 'Export', in general outgoing flower cargo is not cooled during the export intake and handling procedure. This need not inflict much damage onto the flowers, because of the short minimum time between intake and departure. Indeed, flowers harvested 1 day ago, auctioned in Aalsmeer at 8:00, and leaving the auction palletized at 8:30 arrive at Schiphol at 9:00, in time (*D-110 min*) for catching a Boeing 747-400 flight leaving at 11:00. But the auction generally closes at 10:00 or 12:00. A flower pallet leaving the auction at 10:30 will not be able to catch the 11:00 flight but will catch the 15:30 flight. The result is that sometimes flower pallets are on the platform for several hours. On average, at Schiphol flowers for export spend 2.5 hours at the platform. In summer this is undesirable, since in the buffer queues at the platform no shielding against sunlight is present.

3.2.2 Import

In Figure 4 cargo handling at Schiphol during import is depicted. Basically, cargo flows are just opposite to those during export. Transportation times are different. Unloading of a Boeing 747-400 has to be complete at 40 minutes after arrival. Temperature sensitive belly load and T-ULDs for transito are transported to cooling cells at OVG or APCZ. Between 24 pm and 6 am no access to APCZ is possible, which can be a problem for some long-duration transitos. If necessary, RIL (Regulation of Incoming Load) can direct also non-transito T-ULDs to APCZ. Additional cooling capacity (trucks) can be hired via RIL (the '+1' at OVG in Figure 4). Redirection of load can be done via the CARGOAL and CHAIN computer systems, to which all units of KLM CARGO have access. Mixed ULDs contain both temperature sensitive (denoted 'COOL' in CHAIN by RIL) and non-senitive cargo. Mixed ULDs have to be offered for deconstrucion at 'Palletized' 90 minutes after departure or sooner.

Part of the incoming cargo at 'Belly'and at 'Palletized' may have transito destinations. This is handled according to Figure 3 later on. The remaining cargo is transported to 'import', where

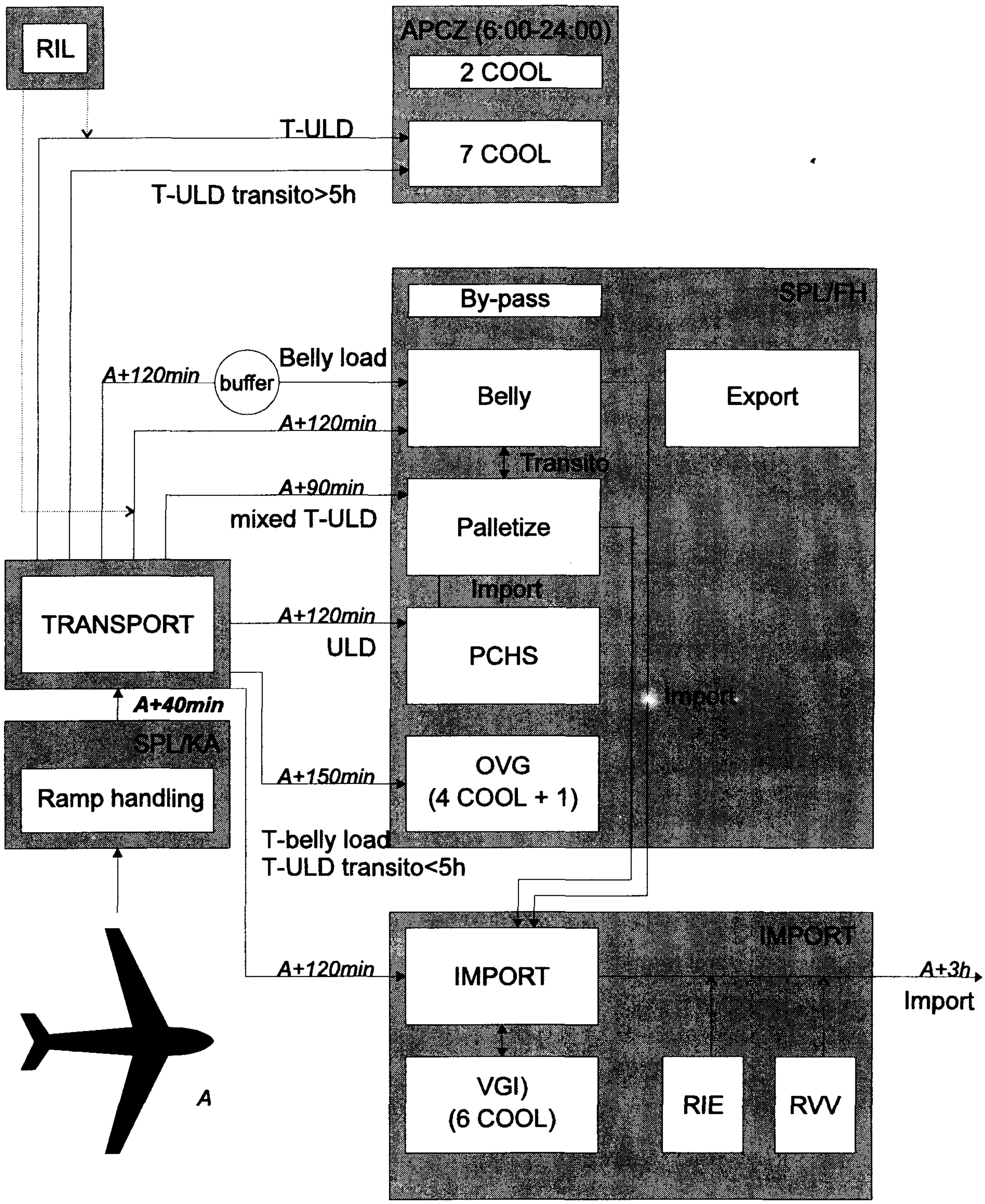

Figure 4. Cargo handling during import at Schiphol. Continuous arrowed lines represent cargo displacement for import and transit. In normal italics, the end time is indicated at which all cargo should be at the location indicated by the arrow (*A* denotes arrival time). Fat times are aircraft-dependent. The time given is for the Boeing 747. Dotted lines denote information and control.

further deconstruction of the load is often performed by agents of the buyer. Cargo is checked by the RIE (KLM) and the RVV (Netherlands Customs). Within 3 hours after arrival, imported goods leave Schiphol.

The above shows that transito at Schiphol may sometimes cause problems. A quality control system may assist in the optimization of transito handling. If a set of measurements at a foreign airport has shown that the accepted load is extra sensitive to unrecoverable temperature damage during the following flights and a transito at Schiphol, then via telex this information can reach RIL. Subsequently, via an indication in CHAIN, RIL can indicate that the incoming load should be transported to a cooling cell as soon as possible.

Import at Schiphol is sufficiently fast to prevent (additional) temperature damage to flower cargo. Rather, claims on imported cut flowers are due to circumstances before arrival at Schiphol. For example, the holds of aircraft carrying roses from Kenya are often very hot if the plane had been loaded in the afternoon. In Bolivia flowers are not auctioned, so they lack a quality guarantee. At Paramaribo airport, (flower) cargo may be stored in the open air and sunlight during one day before departure. At Curaçao, it remains very hot till 22 PM, with destructive effects on flower pallets which are not kept in the cooling cell which can contain 6 pallets. Also at many other foreign airports with a hot climate, cooling cells are present, but they may not be utilized in an optimal way and/or have insufficient capacity.

3.3 Conclusions

Sufficient information is available for constructing a simulation system for the Boeing 747-400. The impact of the climatic conditions in the holds on cargo in pallets and containers can be incorporated. The effect of different combinations of ventilation and cooling can be estimated, which may lead to optimization recommendations.

The cargo handling process at Schiphol shows where a sensor system may be employed. Performing measurements on complete pallets or containers at the platform is not feasible. These measurements delay ramp handling and transport. Also, the personnel can not always quickly recognize cut flower boxes, especially when the ventilation holes are sealed off or when they are included on a mixed pallet. Therefore, measurements may best be done at import, export or SPL/FH.

Measurement at import would serve a damage assessment function: the damage has already been done on cargo in import. Opening of boxes can hardly be done by KLM CARGO. Generally, it is not appreciated by the buyer. If nevertheless a few boxes have to be opened, this would have to be under supervision of Customs. Opening boxes after Customs clearance would be easier but seems not feasible because often an agent of the buyer is already present at this stage and any measurement would cause delays.

Measurements at export are feasible and desired because at export cargo acceptance takes place. Figure 3 shows that cargo can be present at export during one hour. A typical cargo intake and acceptance procedure at Schiphol lasts much shorter than this (about 5 *min*). Measurements therefore should be completed in a relatively short time. If indications are obtained that the cargo is in an unacceptable state, additional measurements have to be completed in less than 1 hour.

For export cargo originating from Aalsmeer auction, only a limited set of measurements can be made because the flowers are already palletized and often covered with plastic. If control of cargo from Aalsmeer auction is worthwhile, then measurements should be done at Aalsmeer auction, during or just before pallet construction.

During palletization at Schiphol it may be troublesome to perform measurements. Also, most of the cargo being palletized comes directly from export, and would already have been checked. A routine check may be feasible during pallet deconstruction. This is also desired from a control point of view. For instance, the temperature of the outer layers of a pallet generally raise several *°C* during ramp handling and transport to SPL/FH (Den Heijer, 1996a). The temperature inside the pallet is much more constant. Thus, AA boxes from the outer part of the pallet will not reflect the temperature inside the plane during flight, whereas AA boxes from the center of the pallet will. The only moment when AA boxes from the center can be discriminated from peripheral boxes is during pallet deconstruction.

The measuring moments above may be routine measurements. Random checks of conditions are also useful, especially on cargo on the platform during summer. Thus, on many different locations measurements may be done by different personnel. This means that a sensor used for these measurements should be portable and simple to operate.

4. Aspects affecting the quality of perishables during transport

4.1 Plant life processes

During day light plants in the field form their own biomass from carbon dioxide in the air and water in the soil. The process responsible for this is called photosynthesis. Chemically it amounts to the reaction $6CO_2 + 6H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2$, meaning using solar energy, from carbon dioxide and water the plant forms sugar and O_2. Formation of 1 *mol* of sugar requires 2875 *kJ* of solar energy. From sugar and minerals in the soil, the plant can form its total biomass.

At night, when no energy is available from the sun or another bright light source, life processes in the plant continue, but now the plant has to supply its own energy. This is done in the way common to most living beings: the plant burns its own sugar supplies (respiration). This is the reverse reaction $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$. Burning 1 *mol* of sugar yields 2875 *kJ* of energy. In order to avoid burning all of its sugar supplies it accumulated during day time, at night the plant is 'asleep', *i.e.* its life processes continue, but at a slower rate than at day time. During this 'sleep', the microscopic stomata at the surface of the leaves, the 'lips' of plants through which CO_2 and O_2 can pass to/from the surrounding air, are almost totally closed (Omasa, 1990). During storage and transport, plants are usually in the dark and therefore in the above described 'sleeping' state.

Photosynthesis, respiration and other life processes in plants and specifically in cut flowers can be influeced by factors such as temperature and humidity of the surrouding air, as well as by the concentration of gases like CO_2, O_2 and ethylene. Also micro-organisms can affect plant health. The impact of these aspects on the quality of cut flowers will be described in the following.

4.2 Temperature

During storage and transport, life processes of cut flowers have to be as slow as possible. The reason for this lies in the limited lifetime of flowers. Fast life processes during storage and transport mean a lot of ageing, which reduces the freshness of the flowers at the consumer. Respiration and other life processes can be reduced by cooling. This is reflected by the following approximate empirical expression:

$$\frac{\Delta VALI}{MVALI} = -\Delta t \cdot [0.03 + 0.003T] \qquad (1)$$

$\Delta VALI$ is the loss of vase life (in *days*) at the consumer resulting from storing the flowers at temperature T (in *°C*) for a time period Δt (in *days*). *MVALI* is the maximum vase life (in *days*), i.e. without a storage/transport period. Thus, the remaining vase life is $MVALI+\Delta VALI$. The constants in equation (1) represent an average over different non-tropical flowers from (Van Doorn, 1991). For some flowers the constants are different by 100%.

Equation (1) shows that during transport and storage, the temperature should be as low as possible and the duration of storage and transport should be minimal. For non-tropical flowers the optimal temperature is 2-5 *°C* on average; tropical flowers should be kept at temperatures not lower than 7-8 (Vaughan, 1988). Below these temperatures, chilling injury occurs, expressing itself as wilting, necrosis (dying of tissues), accelerated water loss or susceptibility to disease (Reid, 1991). For many different flowers, optimal storage temperatures and maximal storage durations have been compiled by the Sprenger Institute (1986), Vaughan (1988) and Rudnicki (1991).

For optimization of vase life it is important to minimize the time period during which the temperature is high. For this purpose several pre-cooling techniques are in use, such as forced air cooling and vacuum cooling (Vaughan, 1988; Turk, 1993).

4.3 Humidity

Most fresh harvested flowers contain more than 90% water. This water is needed for their life processes: if plants become too dry, their enzymes cannot work properly anymore. Evaporative water losses of 2-5% can result in wilting of leaves and petals (Reid, 1991). This damage can mostly be reversed by placing the flowers in water after transport. But water losses of 10-15% during transport can lead to unrecoverable damage in many flowers (Sprenger Institute, 1986), due to failure of water conduction in and accelerated senescence of the desiccated tissues .

After 3 days of storage at 4 *°C* and 90% humidity, roses, tulips, freesias and irises typically loose 5-10% of their weight, which is mainly due to water loss. At 99% humidity, the weight loss is only 2-5%. But daffodils only suffer a weight loss of about 1% at both 90 and 99% humidity (Sprenger Institute, 1986). During transport simulations, bouvardias suffered a weight loss of 4-12% after 20 hours and chrysanthemums lost 5-8% after 24 hours. In these transport simulations, the two types of flowers were sleeved and packed in cardboard boxes, and kept at 15 *°C* and 17 *°C*, respectively (Van Gorsel, 1993; Van Meeteren, 1989). This shows that air transports at temperatures of 15 *°C* or higher, which are not uncommon (Den Heijer, 1996a), may result in considerable water losses.

Evaporative water loss during transport is mainly determined by the temperature of the surrounding air and its relative humidity. This is illustrated by the following expression, which is an extension of equation (1):

$$\frac{\Delta VALI}{MVALI} = -\Delta t \cdot [0.03 + 0.003T] - \Delta t \cdot 0.0003 \cdot \left[\frac{100\% - H}{H}\right] \cdot 10^{\left[2.7857 + \frac{7.5T}{237.3+T}\right]} \quad (2)$$

Again, this expression is averaged for several non-tropical flowers (Van Doorn, 1991). *H* is the relative air humidity in %. At 30 °*C*, a humidity of 100% means that air can a concentration of 4.2% of water vapour. At 0 °*C* the is maximum concentration is only 0.6%.

Equation (2) shows that dehydration due to a low humidity is important if the humidity is lower than 93%. In order to minimize vase life losses due to dehydration, humidity should be as high as possible. But a humidity of 100% is not advisable, because at humidities larger than 98%, fungi can germinate (*see* section 4.6).

Since at 8-10 *km* height the atmosphere is very dry (absolute humidity less than 10^{-4} kg/m^3), due to ventilation the relative humidity in the plane in general will be lower than optimal (the relative humidity of ventilation at 0 °*C* is about 1.5% and at 10 °*C* about 0.9%). Perishables therefore might dry out considerably: at 10 °*C*, per cubic meter ventilation an amount of about 42 gram of water can be evaporated (at 0 °*C* about 23 gram).

In practice, indeed a decrease of humidity during flight can be seen. During flight KL750 (AWB 074-64903053) from Ecuador to Amsterdam (GYE-CUR-CUR-AMS), the humidity near the flowers could fall to less than 70% (Den Heijer, 1996a). Equation (2) applied to the temperature and humidity data measured for a pallet at loading position a/c 22 shows that during the flight a vase life reduction of 10% in the middle of the pallet to 20% on top of the pallet could have been accumulated, within 17 hours. For another flight, GYE-MIA with a freighter, MIA-AMS with MP644/5nov (AWB 074-64903215) a vase life reduction of about 30% within 40 hours was estimated. If the humidity would have been 95% during both flights, the vase life reduction numbers would have been at least two times smaller.

To avoid dehydration, cut flowers could be transported in water containers (Aqua-packs). A major shortcoming of this method, as compared to dry transport in boxes, is that in Aqua-packs a smaller amount of flowers per cubic meter can be transported, while the total weight to be transported increases. More specifically: in Aqua-packs one can transport some 55 *kg* flowers per m^3 loading space compared to about 86 kg/m^3 when packed in AA-boxes (a box of 120x45x28 *cm*). One Aqua-pack further typically contains 3.5 *kg* cut flowers and 1 *kg* water.

4.4 Ethylene

Many plants can communicate their state of ageing and/or stress to other plants by emitting gaseous plant hormones into the air. One of these plant hormones is ethylene. For many flowers and fruits ethylene is a signal of ripening, which promotes ripening in other flowers or fruits. Since ripening means termination of flowering, ethylene concentration has to be kept low where ethylene sensitive cut flowers are present.

Typically, flowers do not response to ethylene presence as long as the ethylene concentration is below a threshold of about 0.01 ppm (1 ppm means 1 ethylene molecule per one million air molecules). Half of the maximum response is typically seen at 0.1 ppm and 90% of the maximum effect at 1 ppm of ethylene. Ethylene damage becomes apparent within hours or days (Abeles, 1985).

In rural areas, where the ethylene concentration is less than 0.005 ppm, there need be no ethylene effects as long as flowers are not kept near ethylene producing produce, which may be other flowers. But in cities and near roadways, the ethylene concentration may be 0.01 ppm to 0.1 ppm or even higher, which can cause markedly speed up ageing of flowers. This is due to exhaust gases, which contain ethylene. In an auction hall where products were being transported in and out, due to exhaust gases an ethylene concentration of 0.2 ppm has been measured (Sprenger Institute, 1986). Also at airports, there may be sites where the ethylene concentration is too high and where perishables like flowers should not be placed for a prolonged period of time.

Even if the ethylene concentration is high, there may not be very large effects on flowers. First, some flower races, such as roses, are almost insensitive to ethylene (Van Doorn, 1991). Ethylene-sensitive flowers, such as carnations can be made insensitive by putting them on a solution containing silver salts shortly after harvest. Cooling also has a pronounced effect on ethylene sensitivity. This is illustrated in Table 1, which shows the threshold ethylene concentrations at several temperatures and for three storage durations. The flowers are exceedingly insensitive to ethylene if held at 6 *°C*, whereas 48 hours of storage at 24 *°C* in the auction hall mentioned above would be detrimental to flower quality.

Table 1. Threshold ethylene concentrations for mini-cymbidium flowers (Sprenger Institute, 1986)

storage period (hours)	storage temperature (*°C*) 6	12	18	24
12	100	40	0.3	0.1
24	50	1	0.1	0.05
48	20	0.2	0.05	0.05

In cases where ethylene damage can not be avoided by other means, commercial sachets containing potassium permanganate are available, which absorb ethylene chemically. This may require a sufficient amount of air circulation in order to avoid air 'pockets' that do not come into contact with the sachets (Nichols, 1985). Unfortunately, the sachets become less effective at humidities above 90% and they can only be used once (Schouten, 1985).

4.5 Oxygen and carbon dioxide

Since the respiration involves both O_2 and CO_2, changing the O_2 and CO_2 concentrations in the air during transport can in principle reduce respiration, thus limiting ageing effects during tranport. At 10 *km* height the composition of air in the atmosphere hardly differs from that at sea level, except for water contents. Therefore, eventual changes in the O_2 and CO_2 concentrations would have to be artificial and due to the presence of dry ice or special kinds of packaging, for instance. For many flowers lowering the O_2 concentration to 0-1% (in normal air: 21%) is a good way to cut down respiration and limit ageing (Sprenger Institute, 1986).

The CO_2 contents of normal air is only 0.03%. In a controlled atmosphere containing 3% O_2, increasing the CO_2 content up to 7% or more did not have very clear effects on several cultivars of roses and carnations (Sprenger Institute, 1986). But cut flowers are seldomly air-freighted in a controlled atmosphere package. Rather, the atmosphere surrounding the flowers will resemble the atmosphere in the holds of the aircraft and contain the normal amount of 21% O_2 and a maximal amount of 0.5% CO_2 (*see* section 3.1.4). In such atmospheres some CO_2 effects may be expected. In buttercup flowers, CO_2 has been shown to regulate the production of ethylene. At room temperature, the ethylene production of these flowers increased proportional to the CO_2 content if the CO_2 content was increased from the normal value of 0.03% up to 0.1%. Beyond 0.1%, the ethylene production stayed approximately constant. Damage effects which may arise due to ethylene formed at these elevated CO_2 concentrations are partly canceled because CO_2 also slightly reduces the sensitivity to ethylene (Horton, 1985), but an effect remains.

4.6 Bacterial and fungal infections

Fungi and bacterial infections can strongly reduce vase life. The extend to which this will happen depends on the treatment given by the producer and by the consumer. One may think of hygienic conditions, desinfection methods etc. Often, bacterial infections are prevented by the producer and the retailer by recutting the stems and placing the flowers in water containing anti-bacterial agents (Sprenger Institute 1986; Vaughan, 1988).

Botrytis is one of the most common fungal infections. On roses, for instance it shows as small white spots on the buds, which turn black in a later stadium. Botrytis can germinate if the humidity is higher than 98% (Van Doorn, 1991). This can occur if flowers are very well shielded against dehydration by plastic sleeves and the temperature shows large variations during transport. In a cooling phase, water condense can form, meaning that the humidity is 100%. In a subsequent warming phase the Botrytis spores which have just germinated, may grow rapidly (Reid, 1991).

4.7 Conclusions

From the preceding sections it is clear that temperature and humidity can have important impacts on cut flower transport. Also ethylene can lead to quality deterioration in flowers that are sensitive to it. But even flowers almost insensitive to ethylene, like roses, produce more ethylene if they are ageing than when they are fresh (Sprenger Institute, 1986), meaning that also for these flowers an ethylene detection could yield information concerning their freshness.

O_2 effects are expected if flowers are packed in CA (Controlled Atmosphere) packages, but this can not be influenced by the air transporter. CO_2 can indirectly influence flower quality by affecting ethylene production. But detecting ethylene itself instead of CO_2 gives a better indication of the probability of ethylene damage in the produce. Still, detection of O_2 and CO_2 concentrations may be useful if ventilation inside the package is limited. In this case due to respiration, the main process in the dark, the O_2 concentration will get lower and the CO_2 concentration will increase during storage. This effect will be most pronounced if the flowers have been packaged a long time ago and/or stored at high temperatures.

Bacterial and fungal infections can not be influenced by the air transporter. The responsibility for avoiding these infections lies at the producer and retailer level. A starting Botrytis infection can usually be seen only with a trained eye, which limits the usefulness of such a detection method during the freight acceptance procedure.

The above suggests that a quality control system for cut flowers should mainly rely on detection and control of temperature, humidity and ethylene. A measurement of O_2 and CO_2 at acceptance might be useful for estimating how long ago a flower load was packed. This is only worthwhile if ventilation in the package is limited.

5. The sensor system

5.1 Climate sensing

At the moment a cut flower cargo load is offered for transport, and also during or even after transport, the climate inside the flower packages can be measured by several means. Below, we follow the conclusions from chapter 4 and discuss sensor techniques for detecting temperature, humidity, ethylene, O_2 and CO_2.

5.1.1 Temperature

Temperature sensors are commercially available from numerous manufacturers. Three types of temperature sensor are given in Table 2. Typical values are included for the temperature detection accuracy and the 99% response time, which is the time at which the sensor has bridged 99% of the temperature difference between the end temperature and the temperature denoted at the start of the measurement. For instance, if one measures an object of 10 *°C* while the air temperature is 20 *°C*, after the 99% response time the sensor will indicate 10.1 *°C*. Also an indication of typical prices, in Dutch guilders, is given. The data are indications, considerable differences are found between different sensors.

Table 2. Typical temperature sensors

sensor	accuracy at 20 *°C* (*°C*)	99% response time (*s*)	cost (*f.*)
Infrared imaging camera	0.1	0.04	65 000
Infrared spot thermometer	1	0.5	1 500
Contact thermocouple	1	150	400

Infrared cameras are like visible CCD cameras, but instead of silicon CCD detectors they are equipped with infrared sensitive detectors made of mercury-cadmium telluride or indium antimonide. The operation is based on the fact that all objects emit infrared radiation, which is more intense if the temperature of the object is higher. By collecting this radiation, long distance infrared cameras can form two dimensional images of the temperatures at the surface of the objects under study. The cameras can make images of objects as close as 20 *cm* or as distant as 1 *km*. Most of these cameras are rather voluminous and not more than semi-portable. Because of the expense of the detector, the liquid nitrogen cooling often involved, and the data processing equipment, this kind of temperature sensor is expensive.

Infrared spot thermometers do not create images, but measure the temperature at one spot. Commonly used infrared detectors for these thermometers are pyro-electric cells or non-contact thermocouples. Depending on the lensing or mirror system included in these thermometers, they can be used in for non-contact temperature measurement at a few *mm* distance up to several hundreds of meters. A common feature of them is their limited size, which gives them excellent portability. Most of these thermometers are less accurate than infrared imaging cameras, but the more expensive types can compete with such cameras.

Contact thermocouples are the simplest temperature sensors. In contrast to the non-contact types described above, they need to be in thermal contact with the object to be measured. Due to this contact, the thermocouple assumes the temperature of the object, which can be measured by a voltmeter connected to it. It takes a while before a thermocouple reaches its final temperature, as is evident from Table 2. Thermocouples have good portability and are not expensive. The accuracy of the best thermocouple sensors is about 0.3 *°C*.

Another contact temperature probe makes use of fiber optics. The probe is very thin, 0.6 *mm*, and can have an accuracy of 0.02 *°C*. It has been designed for medical applications and is rather expensive (Grattan, 1995).

5.1.2 Humidity

Sensors for relative humidity are commercially provided by many manufacturers. One type is based on a capacitive effect which depends on the relative humidity of the air. Another type employs materials which can absorb water, which leads to change in electrical conductivity. Humidity detection accuracies of about 2% can be obtained.

A special type of capacitive humidity sensor is the dew-point sensor. The temperature of the capacitive sensor is lowered (or raised) by a small Peltier cooling element. At a certain temperature water starts to condense (or evaporate), which leads to a pronounced signal in the capacitive sensor. The temperature at which this happens is directly related to the water contents of the air. A typical sensor of this type has a temperature measurement accuracy of 0.5 *°C*. At temperature between 0 and 30 *°C*, this translates into a humidity detection accuracy of 4 to 3%, respectively.

Besides separate humidity probes, combinations of a humidity sensor and a thermocouple in one probe are quite common. The size of these probes is determined by the size of the humidity sensor. Combined temperature/humidity sensors can be bought for *f* 500.

5.1.3 Ethylene

In greenhouses, increasing the CO_2 content can promote photosynthesis and growth. CO_2 is often obtained from the exhaust gases emerging from the greenhouse heating system. Since exhaust gases can also contain ethylene, which may impede the formation of flowers cultivated in the greenhouse, the ethylene content of the exhaust gases needs to be monitored. A typical commercial climate monitoring system for this purpose is based on infrared absorption by ethylene. With a typical size of 50 *cm* in height and a 20 *kg* weight, it can analyze 1 litre of exhaust gas per minute. The lowest detectable ethylene concentration is about 5 ppm. For exhaust control these specifications may be good, but ethylene concentrations in flower boxes will rarely get as high as 5 ppm (see section 4.4).

At ATO-DLO, ethylene concentrations as low as 0.02 ppm can be measured using a gas chromatograph after taking samples in the field, but this is typically a laboratory technique. Another sensitive technique has been described by Woltering *et al.* (1989). Their technique was based on the photo-acoustic effect, induced by absorption of infrared radiation from a CO_2 laser due to the presence of ethylene. The technique permitted the detection of ethylene concentrations as low as 0.00003 ppm. The necessary equipment was not portable.

5.1.4 Oxygen and carbon dioxide

Greenhouse climate monitoring systems can detect a whole range of gases and not only ethylene. Carbon dioxide is detected by the same method as ethylene. CO_2 concentrations as low as 0.3 ppm may be detected. This is much lower than the natural CO_2 concentration of 30 ppm. O_2 can be detected because of its rather unique property that is attracted by magnetic fields (paramagnetism). Employing this property a concentration near 21%, the normal concentration in air, can be measured with an accuracy of 0.6%=600 ppm.

The above shows that greenhouse climate monitoring systems would have no problem detecting CO_2 concentrations in flower boxes. The detection accuracy for O_2 would probably not be sufficient[1]. But again, these systems are big, not portable and relatively expensive (about *f* 20 000).

Hand-held commercial detectors for gases like O_2 and CO_2 are based on electro-chemical cells, semiconductor gas sensors, or infra-red absorption measurement. Electro-chemical cells are commercially available for gases like O_2, whereas infra-red absorption techniques are being employed for detection of CO_2. Hand-held CO_2 sensors for the range 0-5000 ppm, i.e. the range relevant to air transport, can be bought for about *f* 1000.

[1] Ranunculus leaves put into a sealed flask initially containing normal air (21% O_2 and 0.03% CO_2) and then held in the dark, were not able to produce additional CO_2 after the CO_2 concentration had risen to 0.1%. (Horton, 1985). Since for each molecule of CO_2 produced, one molecule of O_2 is absorbed and *vice versa* (*see* section 4.1), then the O_2 concentration has dropped by 0.1%, which is much less than 0.6%.

5.2 Quality sensing

Several sensors which can be used for assessment of the climate within flower boxes have been mentioned in section 5.1. These sensors do not give any direct information concerning the status of the flowers at the moment they are offered for transport. This can be a disadvantage in many cases. For instance, if one measures a humidity of 90% in the box, this may be due to several causes. In a first case, the flowers may have been harvested and packed only one hour ago and since then, due to evaporation from the flowers, the humidity inside the box has been rising from an initial value of 60% to 90%. In a second case, The flowers may have been packed one day ago. Since then the humidity has been rising to almost 100% and subsequently falling back to 90% due to dehydration of the flowers.

In case one, the flowers are very fresh. But in case two the flowers have acquired a considerable drought stress and they may not survive a subsequent air transport. A sensor which directly determines the amount of drought stress in a flower would be able to distinguish between case one and two. Below, we discuss sensor systems for temperature stress or for drought stress.

5.2.1 Temperature stress

Temperature stress in a plant can be detected using a technique called chlorophyll fluorescence (CF). By this technique the efficiency of the photosynthesis process is probed under a controlled illumination. Typically, a CF instrument consists of an electronic part containing a light source and a probe that has to be clipped onto a leaf of the flower under consideration. Light from the light source is transferred to the probe via a fiber optic bundle. The bundle ends directly on the surface of the leaf. The leaf responds to the illumination by returning infrared radiation back through the fiber optic bundle to a detector included in the electronic part. The intensity of the infrared radiation detected during controlled illumination gives information about the how fast and how efficiently photosynthesis and competing processes react to the illumination.

Commercial CF instruments are available in two varieties. We will refer to them as the 'basic CF meter' and the 'pulse modulated CF meter'. The two instruments differ by their way of illumination. The pulse modulated CF meter can measure everything that a basic CF meter can, but it can do more. This is also reflected in the price and portability. A basic CF meter is typically hand-held and can be bought for *f* 2000, whereas a pulse modulated CF meter is semi-portable and costs about *f* 35 000.

A measurement done with the basic CF meter is only reliable when performed on a dark-adapted leaf. The leaf has to be held in the dark for about 20 minutes. After this the measurement may be done, which takes only a few minutes (Harbinson, 1995). For flowers at an airport the measurement may be started almost immediately, since only little light can enter a box of flowers and dark adaptation has already taken place. How a basic CF meter can detect heat stress is illustrated in (Schreiber, 1987). Leaves of *Arbutus unedo* (a shrub) were held at an elevated temperature in the dark for 5 minutes, and were returned to ambient temperature, 22 *°C*. Another 5 minutes later, CF measurements were performed. The decay time of the CF effect was markedly decreased after heat treatment. If the decay time after a 22 °C treatment (no heat treatment) was 1, then treatments of 36, 40 and 44 °C resulted in decay times of 0.7, 0.6 and 0.3 respectively.

A practical example of the merits of the basic CF meter can be extracted from the data given by Moffat *et al.* (1990). They utilized a basic CF meter for assessing the effects of high temperature stress on six different wheat cultivars. Young plants were allowed to grow for five days and after this, one half was held at 25/20 °C day/night temperatures, whereas the other half was subjected to elevated temperatures of 37/25 °C. CF measurements were done 3 and 10 days later. A CF parameter called F_v turned out to be a good indicator of the temperature at which the plants were held. If we define a threshold value for F_v such that all not drought stressed plants would be classified correctly by the CF test, then in 60% of the cases (different cultivars, different stress durations- 3 or 10 days), drought stressed plants would be recognized as such. 40% of the CF-tested drought stressed plants would be classified as not drought stressed. This gives an indication of how accurate a basic CF meter test for temperature stress might be for other plants, like cut flowers.

As for the basic CF meter, usually a measurement with the pulse modulated CF meter is also done on a dark adapted leaf. Nevertheless, methods exist in which leaves exposed to light can be used after an adaptation period of only 5 minutes (Van Kooten, 1991). The data given by Schreiber and Bilger (1987) suggest that the pulse modulated CF meter can detect how high the temperature has been in the past (10-5 minutes ago in the experiment described by Schreiber and Bilger (1987)). We estimate that the accuracy of this determination would be about 5 °C for temperatures between 20 and 50 °C. If the same holds for longer periods of elevated temperature longer ago, this technique would be a good means for signalling high temperature storage of cut flowers between harvest and the moment of checking in at the airport.

5.2.2 Drought stress

Like temperature stress, also drought stress can be detected by basic CF meters. In *Arbutus unedo* leaves, at weight losses from 5% to 29%, a significant change in the response signal 1 minute after starting the measurement can be observed. At higher losses, 40% or 64%, also the signal obtained during the first minute shows marked changes: respectively, the CF decay time is 75% or 850% larger (Schreiber, 1987).

Pulse modulated CF meters can measure the efficiency of the photosynthesis process and the efficiency of competing processes (Schreiber, 1987). If roses are stored dry for 36 hours, photosynthesis becomes slightly less efficient, whereas competing processes become appreciably more efficient. The changes were not very significant within the first 12 hours of storage, but the increase of efficiency of competing processes exceeded the standard deviation due to differences between individual flowers by a factor of 10 at the end of the 36 hour dry period (Van Kooten, 1991). This is consistent with the observation in section 4.3 that dangerous dehydration levels can be reached after about one day of dry storage.

In a dehydration experiment on *Arbutus unedo* leaves by Schreiber and Bilger (1987), also marked increases of the efficiency of competing processes were found as long as the water loss did not exceed 20%. Beyond 20% dehydration competing processes did not become more efficient but photosynthesis efficiency decreased. In combination with these data, we estimate that a pulse modulated CF measurement would be able to determine the water loss with an accuracy of ±4%.

As an alternative to detecting drought stress using a CF meter, a second detection method exists. In this method the water contents of a plant is probed by measuring the so-called water potential. This can be done by several techniques (Kramer, 1990). Most of these are elaborate or require a careful calibration prior to use, which makes them only suited for laboratory use. But one popular method is suited for use in the field. This is the pressure equilibration method, in which a leaf or twig is taken from the plant and sealed in a pressure chamber which the cut end protruding. From a portable tank of compressed gas (*e.g.* divers equipment), pressure is applied to the chamber and at a certain pressure water starts coming out. The water potential is minus this pressure. A dehydrated leaf would require a large pressure and therefore has a low water potential.

Under natural conditions in Portugal, the water potential potential of *Arbutus unedo* leaves shows clear signs of drought stress (Lange, 1987). In April, at 22/8 *°C* day/night temperatures, the leaf water potential was about -15 *bar* at noon and -7 *bar* at night. This illustrates the drought stress induced by transpiration during the day. In August, at temperatures of 32/17 *°C* and at the end of a hot summer, the water potential was even about -40 *bar* during day and night.

Field grown maize plants have a typical leaf water potential between -14 and -18 *bar*, depending on irrigation conditions. The plant-to-plant variability is ±1 *bar* (Tardieu, 1993). Van Meeteren (1989) reported changes in the water potential of cut flowers. During a 24 hour transport simulation of sleeved chrysanthemums in cardboard boxes at 17 *°C*, the water potential of the flower stems decreased from -2.6±0.7 *bar* to -7.6±0.4 *bar*. After an additional day the stem water potential was -9.5±0.5 *bar*. At this time, the water potential of the leaves varied between -9 and -12 *bar*, and the flowers had lost between 9 and 14% of their initial weight. This suggests that a leaf water potential difference of -1 *bar* corresponds to a 1% water loss. A plant-to-plant variability of 1 *bar* and an experimental error of less than 1 *bar* suggest that the pressure equilibration method would be able to detect water loss with an accuracy of ±1.4%.

A third drought stress test is based on the fact that during drought stress, in water conducting vessels air bubbles can be formed (air embolism). As shown above, the water potential in plants is negative. This means that the water in water conducting vessels in the stem and the leaves is under tension. Under drought stress this tension becomes progressively higher (the water potential falls). At a certain moment, locally the tension can get so high that the water column in the vessel breaks. The resulting vacuum is subsequently filled by air diffusing in from the surrounding tissue (Jones, 1989). At the moment the water column breaks, an acoustic signal is emitted. Using commercially available ultrasound sensors attached to the trunk, in young trees that were not watered, 7-60 'clicks' were detected per minute. The trees were only moderately stressed, because their leaf water potential was reduced by only one *bar* (Jones, 1989; Grace, 1993).

The presence of air embolism was also suggested in roses (Van Doorn, 1989). It may be expected to be present in many cut flowers and because they are often considerably more stressed than the trees mentioned above, a one minute measurement duration may be enough for an accurate measurement. Measuring air embolism is very attractive because of the ease of use of ultrasound sensors. But the method only allows detection of the *proceeding* of dehydration, not dehydration itself. After a short period at high humidity, dehydrated flowers may not emit many 'clicks' anymore. Another point of concern is that 1 MHz ultrasound can not reach very far in air. At a distance of 1 cm in air, the intensity of ultrasound is only 6% of the intensity at 0 cm from the source. Of course, this is also an advantage because this means that ultrasound coming from the surroundings (aircraft etc.) is negligible. But it means that in an ultrasound measurement, one should press the ultrasound detector against the bunch of flowers. Ultrasound detection will not require opening of the flower boxes, which is an advantage relative to CF meters and pressure chambers.

5.3 Conclusions

With regard to climate sensing, in a cut flower quality control system, non-contact thermometers may be used for quick detection of hot spots in the load. Since these thermometers detect the surface temperature of objects, this will only give a rough indication of which flower boxes might contain flowers at too high a temperature. Detailed information on the temperature (profile) inside a box of flowers is only possible by inserting a probe into the box. Thermocouple probes are very suitable for this purpose because they are typically a few *mm* in diameter and can be inserted into a box without causing much physical damage. Commercially available infrared spot thermometer probes are 1 *cm* thick at least, which makes them less suitable for insertion into a box of flowers.

Most humidity probes are more than 1 *cm* in diameter, which can be a disadvantage if one intends to measure the humidity inside a box of flowers. We are continuing the search for smaller humidity sensors.

The sensors discussed up to now are commercially available for less than *f* 2000, are hand-held and are sufficiently accurate for application in a quality control system. For the detection of gas concentrations inside a flower box, this is not always the case. A portable and sufficiently accurate sensor for ethylene is not currently available. We have indications that a miniaturized sensor system combining aspects from the greenhouse climate monitoring system and the photo-acoustic system (see section 5.1.3) might result in a practical sensor. A definite answer to this question can only be given after eventual prototype design and testing procedures.

As far as we know, a sufficiently accurate O_2 sensor is also not commercially available. On the other hand, hand-held CO_2 sensors which are probably accurate enough can be bought for about *f* 1000.

Regarding flower quality sensing, the inexpensive basic CF meter can be a valuable tool in assessing high temperature stress which has occurred before arrival at the airport for checking-in. The same is even more true for the pulse modulated CF meter, but its price is a drawback.

Only severe drought stress can be detected accurately using a CF meter. The pressure chamber technique is more precise and allows also measurement of drought stress induced by 'normal' flower handling practices. But it requires more handling by the user (cutting a leaf, insertion and fixation into the pressure chamber).

A disadvantage of both the CF meter and the pressure chamber is that they require access to the flower leaves. Often, flower boxes have holes which allow this access. But sometimes it would require (partial) opening of the box, which has to be done in consultation with the Customs. This disadvantage is not shared by ultrasound measurement, which does not require opening the entire box of flowers. Probably, the ultrasound sensor will have to be inserted into the box, but this can probably be done through a small hole.

In conclusion, for climate sensing we suggest focusing on temperature, humidity and CO_2 sensors, which can immediately be bought and tested under practical and simulated conditions. Development of an ethylene sensor which meets the requirements would be very worthwhile, but may take some time. In order to pre-assess the use of such a sensor in practice, we suggest taking ethylene samples from the ambient air at different places at the airport, as well as from the air inside flower boxes. The samples may be analyzed at ATO-DLO using the gas chromatography technique.

For quality sensing we suggest focusing on the basic CF meter. A pre-assessment of its usefulness may be done using the more complete pulse modulated CF meters present at ATO-DLO. Also we suggest performing feasibility tests for ultrasound detection.

6. The simulation system

6.1 Previous measurements and literature

Insight in the distribution and time-development of for instance temperature and humidity in the loading room of an aeroplane is crucial if one wants to predict the quality of the transported perishables. However, the amount of published measurements of for instance temperature and humidity in an aeroplane is limited. Here a brief overview of found literature is given, in chronological order.

Harvey and Harris (1976) measured temperatures during transport of strawberries from California to Hong Kong and from California to Tokyo in the top and middle layers of a pallet. Transport respectively took about 50 and 33 hours, of which about 30 to 40% was spent on a plane, and about 40% was spent at airports. Both during flight as during stay, the temperature of the load increased, in the top of the pallet at an average rate of about 0.5 *°C* per hour, in the middle of the pallet at a rate of about 0.1 *°C* per hour. When dry ice (3 to 4 *kg*) was included, essentially the rate of temperature increase did not change, except for the first 5 hours, when the load was still in California. Unfortunately, it is not clear under what conditions the load was stored in the plane.

Bye and Bleasdale (1985) argue that perishables transported by air should be loaded in refrigerated containers (like their own). They give a brief overview of refrigerated containers used in air-fright, most of which were no success. In general the containers use dry ice as a cold source. Bye and Bleasdale think that the development of a light weight thermostat/battery container could improve the situation. They emphasize, however, that the perishable cargo must be pre-cooled to the desired transit temperature.

Sharp and Spraggon (1988) measured temperatures at several places in a LC3 container during transport of fruit (mostly peaches) from Sydney to London. Also the temperature outside the container (in the loading room) was registered, and showed to vary between 35 *°C* and 7 *°C*. Especially during stay at the several airports (about 35% of the total transport time), the loading room temperature showed to increase substantially (typically 5 *°C* per hour), while it decreased with about 3 *°C* per hour during flight. These large temperature changes were hardly noticed in the insulated container. In the top layer of the container, near the place were 20 *kg* dry ice was placed, the temperature gradually decreased from 20 *°C* to 12.5 *°C*. In the centre of the stow, the temperature slowly increased from 6 *°C* to 11 *°C*. It is advised to use insulated containers for transport of perishables. Use of dry ice is not recommended, better is to pre-cool the products

Den Heijer (1996a) measured temperatures and humidity in a box of cut flowers both in the middle and upper layer of a pallet during transport from Curaçao to Amsterdam. At the warehouse and during ramp-handling the temperatures increased to unacceptable heights. During flight the temperatures decreased, as shown in Figure 5, with a typical rate of 1.2 *°C* per hour. Figure 6 shows that also the relative humidity decreases, which might be due to ventilation, as discussed before.

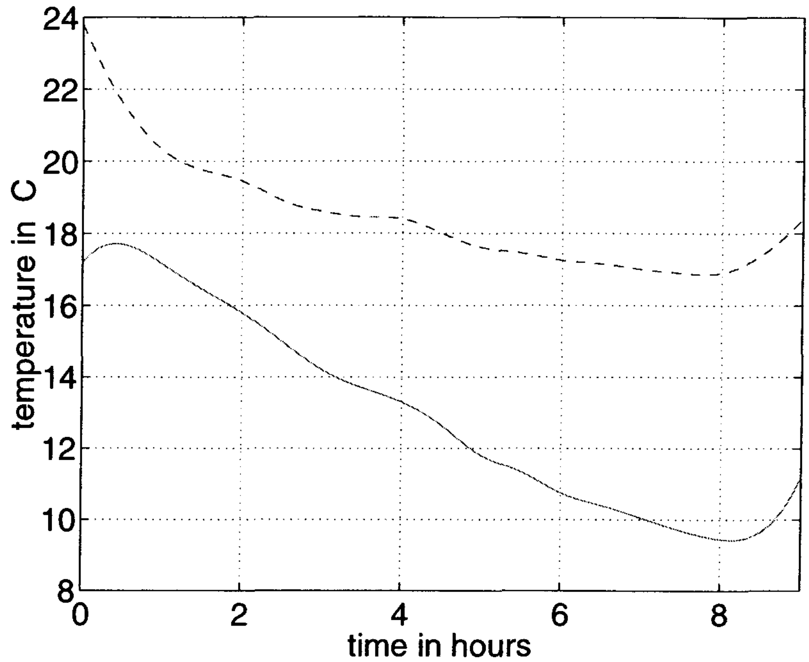

Figure 5. Measured temperature in a pallet of cut flowers during flight from Florida to Amsterdam.

———: box in middle layer, ------: box in upper layer.

It is interesting to notice that the temperature in the upper layer is higher than in the middle layer. This points at effects of natural convection in the pallet, due to which warmer air flows upwards and accumulates at the upper layer. It is clear that the condition experienced by the cut flowers are far from optimal in the considered case. The temperature is far too high during the total duration of the transport and the relative humidity is sub-optimal during the major part of the flight.

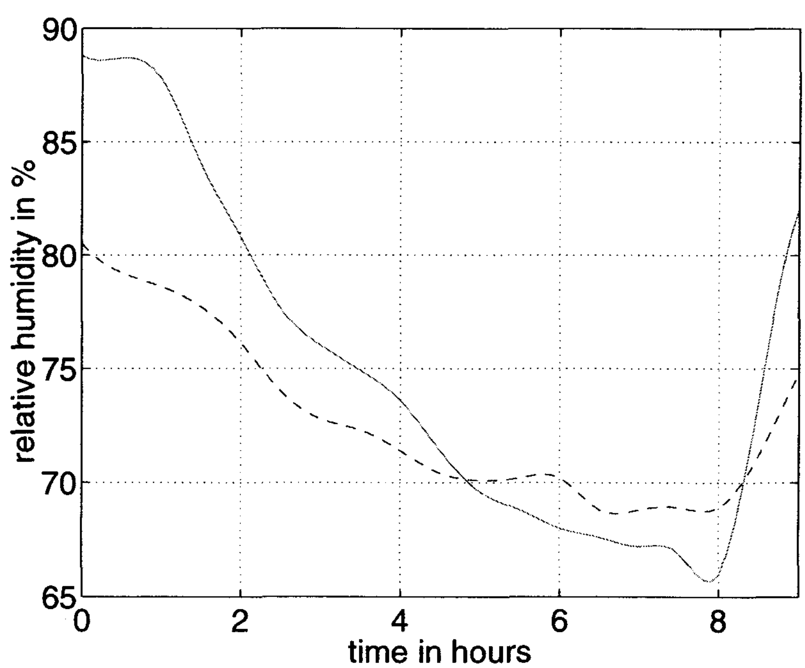

Figure 6: Measured relative humidity in a pallet of cut flowers during flight from Florida to Amsterdam.

———: box in middle layer, ------: box in upper layer.

6.2 Climate simulations

It may be clear that the quality development of perishables during air transport largely depends on the climate inside the hold in which they are loaded. Insight in the climate during flight is based on a limited amount of measurements and is by far sufficient. The temperature in a hold was found to vary considerably, and it is necessary to gain knowledge about the physical mechanisms by which these variations in climate are caused. Especially in relation to the quality of perishables, and the interaction of perishables with the hold climate (e.g. via heat production and evaporation), numerical modelling seems a valuable research tool to gain the necessary insights.

The following strategy could be followed:

- Obtain the necessary information of the geometry of the hold, the ventilation rates and temperature and the location of the inflow and outflow. Also isolation values of the wall material and further information of the surroundings are of importance. This information gathering part largely has been carried out.
- Modelling of the flow resulting from the ventilation in the hold. Consider the containers and pallets to be rigid, perfectly insulated bodies. Validation of the flow pattern in a perspex model of the hold and loading might be necessary.
- Implementation of thermodynamical models of the produce to model heat generation in respect to the temperature distribution in the pallet.
- Modelling the flow, heat and mass transfer in the hold. Validation by measurements during transport in the plane. For this a monitoring system has to be set up.
- Use the obtained insight to develop less advanced, but more practical, thermodynamical models predicting temperature and water loss of the produce during flight.

6.2.1 A rough temperature simulation model

In order to gain a basic insight in the temperature characteristics of cut flowers stored in hold 1-2 of a Boeing 747-400, a global heat balance is set up, based on the following assumptions and data:

- The loading consists of 5 pallets of cut flowers. Per pallet a total mass M_b of 1000 *kg* flowers is stored. The specific heat capacity of cut flowers c_{pb} equals 4.2 *kJ/(kgK)*.
- Respiration by cut flowers leads to heat production. The heat production per kilogram of cut flowers Q_b depends on temperature and is different for each flower race. Tulips at 5 *°C* produce 0.1 *W/kg*, whereas roses at 25 *°C* produce 1.3 *W/kg*. Heat production data were taken from (Sprenger Institute, 1986).
- The ventilation rate ϕ_v of hold 1-2 equals 0.43 m^3/s. The temperature of the ventilation air T_a equals 4 *°C*, the specific heat c_{pa} equals 1.011 *kJ/(kgK)* and the density ρ_a is 1.25 kg/m^3.
- The hold is perfectly insulated and the ventilation is perfect, so that the temperature of the air in the hold and the temperature of the load are instantly equalized. There are no temperature gradients inside the pallets. The flowers do not dry out.

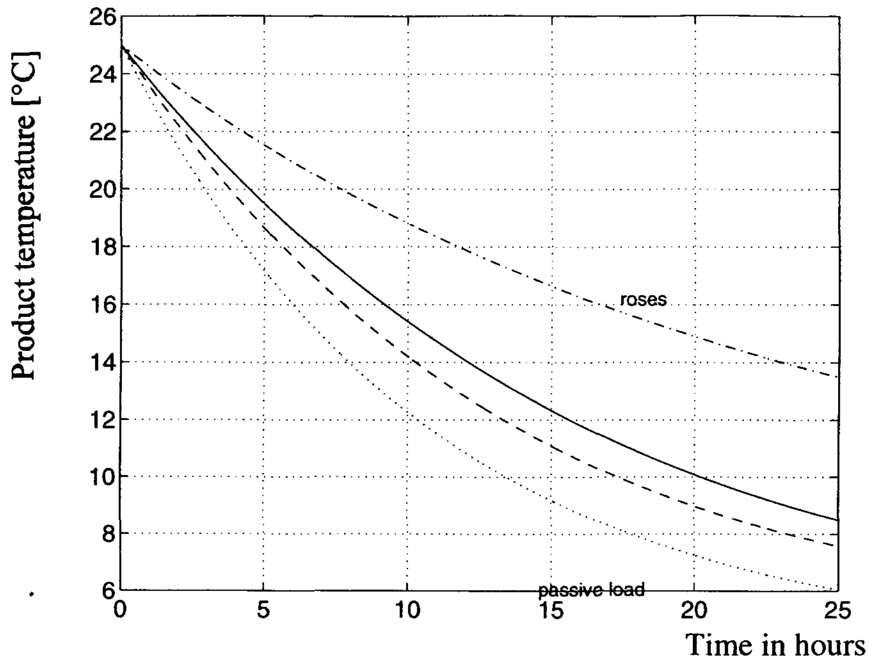

Figure 7: Computed temperature development during transport of cut flowers in hold 1-2

These assumptions yield the following equation for the development in time of the temperature in hold 1-2:

$$M_b \cdot c_{pb} \cdot \frac{dT}{dt} = \phi_v \cdot \rho_a \cdot c_{pa} \cdot (T_a - T) + M_b \cdot Q_b \qquad (3)$$

where T is the temperature of the cut flowers and t denotes time. Integration of equation (3) gives an impression of how the temperature of cut flowers decreases in time in hold 1-2. The result is shown in Figure 7, where the initial temperature of the flowers is taken to be 25 *°C*.

Figure 7 shows the temperature development in four different cases. The dashed line shows the case where the flowers do not produce any heat. The dashed line indicates the case of transport of tulips, the solid line refers to transport of irises and the dash-dot line refers to roses, which produce a relatively large amount of heat. Tulips and irises are cooled from 25 *°C* to 10 *°C* in about 20 hours. Roses are only cooled down to about 15 *°C* in this period. Comparing this result with the measurements performed by Den Heijer (Figure 5, 1996a) it is observed that already a remarkable agreement is found: the rate of temperature decrease is at a similar level and a temperature decrease of 5 *°C* is achieved in typically 5 hours.

The rate of temperature decrease is shown in Figure 8 for the several cases considered. When the temperature difference between the ventilation air and the flowers is high, the rate of temperature decrease is correspondingly also high. Important is that, although the heat production of flowers increases with temperature, the ventilation rate is sufficient to inhibit heating of the load. At lower temperatures, the temperature difference between the load and the ventilation air becomes lower and thus the rate of temperature decrease is limited. For roses it is observed that the temperature decrease rate equals 0 *°C/h* at a temperature of about 7 *°C*, and according to this model, further cooling is thus not possible. Ventilation of hold 1-2

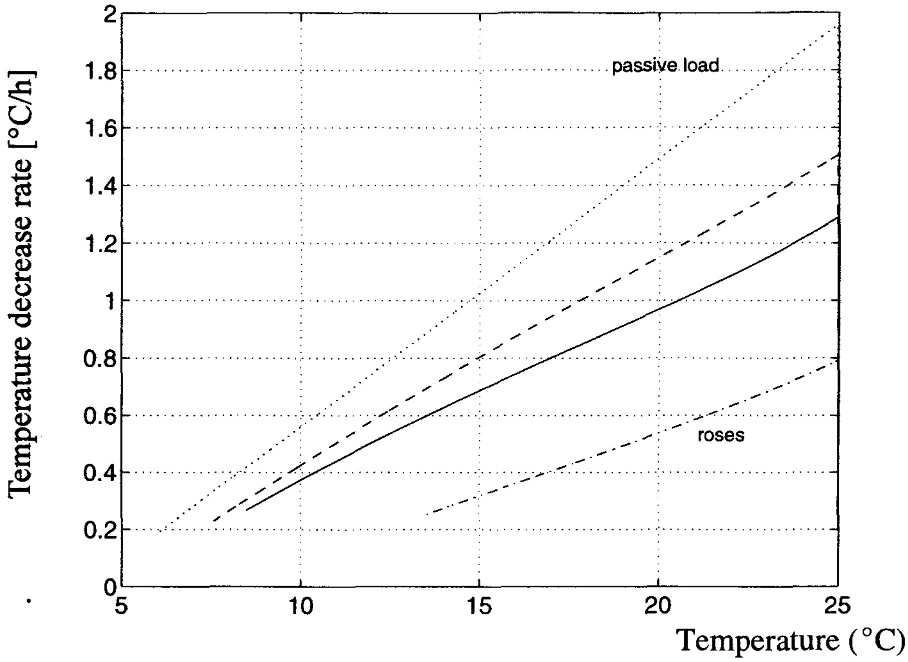

Figure 8: Computed temperature decrease rate during transport of cut flowers in hold 1-2

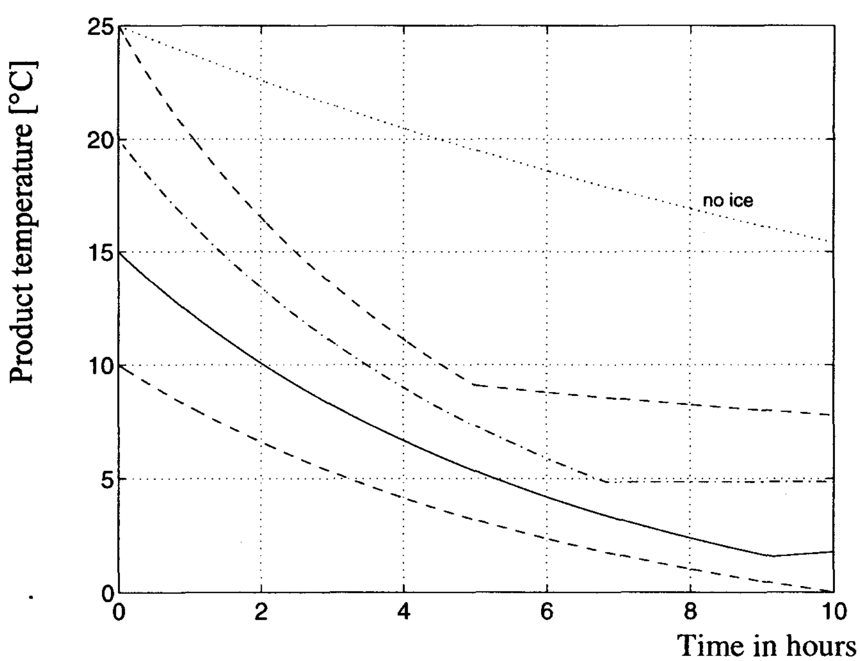

Figure 9: Computed temperature development during transport of cut flowers in hold 1-2, including cooling effects of ice.

is sufficient to cool tulips and irises to less than 5 °*C*, although the period in which cooling down is achieved is far too long when the initial temperature is above 10 °*C*.

6.2.2 Effect of additional cooling using wet ice

Suppose now that wet ice can be introduced such that the relative humidity of the ventilation air increases from 0% to 90%. The latent heat of melting and evaporation is withdrawn from the ventilation air and from the load (an energy sink term is introduced in equation (3) which accounts for this). Suppose that 100 *kg* of wet ice is introduced in hold 1-2 and that the load consists of 5000 *kg* irises. Figure 9 shows the temperature inside the hold as a function of time for several initial temperatures of the hold. As a reference also the situation without ice is depicted as the dotted line.

It is obvious that due to the 100 kg ice the temperature of the load potentially decreases at a considerably higher rate than in the case without wet ice. The remarkable discontinuity in the curves indicates the time where the ice is fully evaporated. For the considered situation, 100 kg wet ice seems to be quite appropriate. Note that a larger quantity of ice does not increase the rate of temperature decrease in this basic model, but only affects the period of ice-increased temperature decrease rate.

It should be kept in mind that the model described in this section is based on the assumptions listed above. Especially two of these may be doubted. The first is the assumption that the ventilation air completely warms up to the hold temperature. This is certainly not the case since heat inside a pallet has to be transported to the outer layer of the pallet before it can be transferred to the ventilation air. Time scales involved in this process are presently not known, but may be of the order of hours, whereas the time scale of ventilation is of the order of one minute. This mechanism needs further study before it can be implemented in an improved load model. The second questionable assumption is that the relative humidity of the ventilation air can be increased to 90%. This again is dependent on the residence time of the air in the and on the manner in which the ice is distributed over the load. Further it is largely dependent on the temperature distribution in the load, which was assumed to be homogeneous.

6.2.3 A two-dimensional diffusion model

To gain insight in the temperature distribution and in the local temperature characteristics of cut flowers stored in hold 1-2 of a Boeing 747-400, a two dimensional heat diffusion model is set up, based on the following assumptions:

- The heat flux in the pallet can be described by a thermal diffusion model, using some uniform effective heat conductivity (λ_e). Convective effects and thermal barriers (like the box material) inside the pallet are attributed to the effective conductivity.
- Similarly, a uniform effective heat capacity (c_{pe}) and an effective density (ρ_e) can be defined for the pallet load.

- Like in the global model, the heat production per kilogram of cut flowers Q_b is temperature dependent, and is based on the data given in (Sprenger Institute, 1986).
- The ventilation rate ϕ_v of hold 1-2 equals 0.43 m^3/s. The temperature of the incoming ventilation air T_a equals 4 °C, the specific heat c_{pa} equals 1.011 $kJ/(kgK)$ and the density ρ_a is 1.25 kg/m^3.
- A cross-section of the hold is representative for the whole load. That is: a two-dimensional approach suffices.
- Initially the pallet is uniform in temperature (T_0).

The following heat equation describes this situation:

$$\rho_e \cdot c_{pe} \frac{\partial T}{\partial t} = \lambda_e \cdot \nabla^2 T + Q_b \qquad (4)$$

The appropriate boundary conditions are sketched in Figure 10, in which a cross-section of hold 1-2 is given. The situation is supposed to be symmetric, thus only half of the pallet has to be modelled (*see* Figure 2*b*). The dotted area represents the pallet loading, which actually is described by the heat equation. The dashed area indicates the boundaries with no heat flux. At boundaries I and II a convective heat flux is prescribed, using ventilation data (local average velocity and temperature) of the considered hold. The local heat transfer rate is computed at each time step using the local temperature difference between the pallet boundary and the surrounding ventilation air.

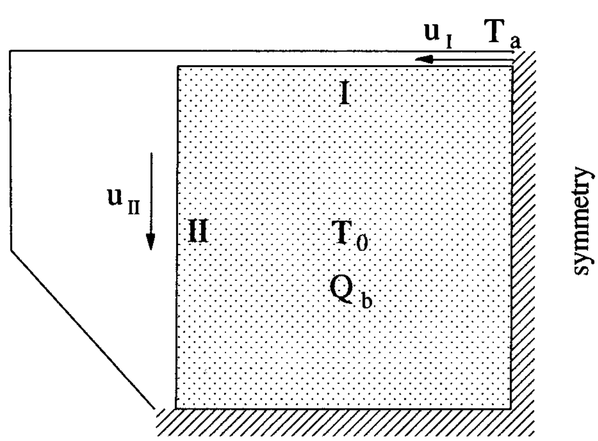

Figure 10. Considered geometry for the 2D diffusion model.

The spatial derivatives in equation (4) are discretized by a second order finite difference method. The time-derivatives are solved using the second order accurate Cranck-Nicholson scheme (Hirsch, 1988). The convective heating of the ventilation air is treated in an inner loop, in which the air volumes adjacent to the pallet are conveyed to the subsequent position during which each individual air volume is uniformly heated by the locally evaluated heat flux.

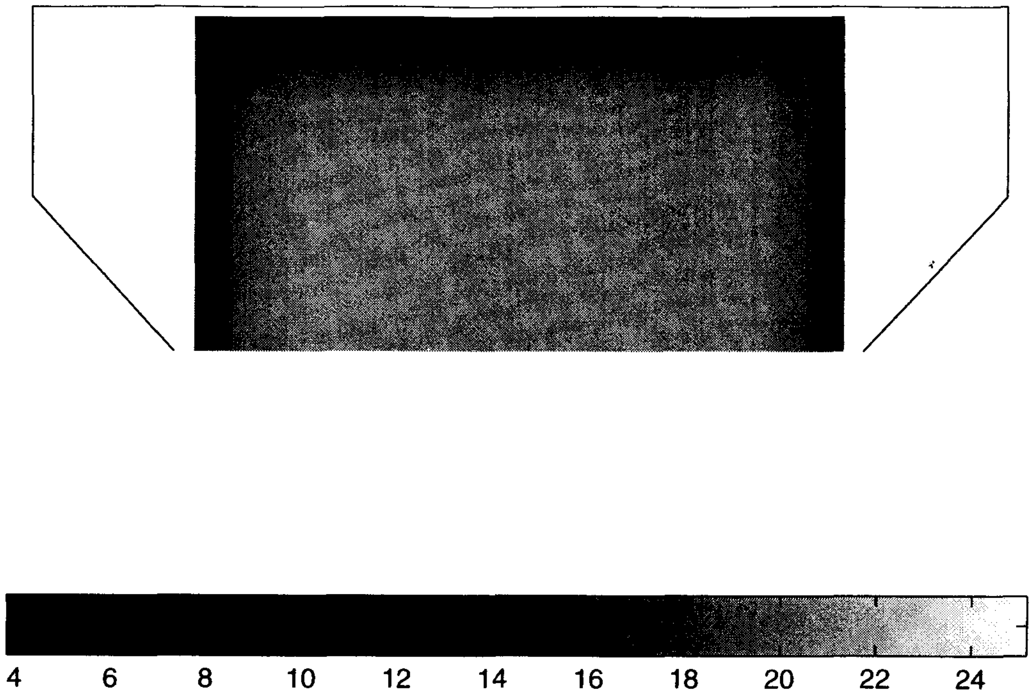

Figure 11. Computed temperature distribution in a pallet of cut flowers (Roses) after 10 hours flight in hold 1-2. Initial temperature was set to 20°C.

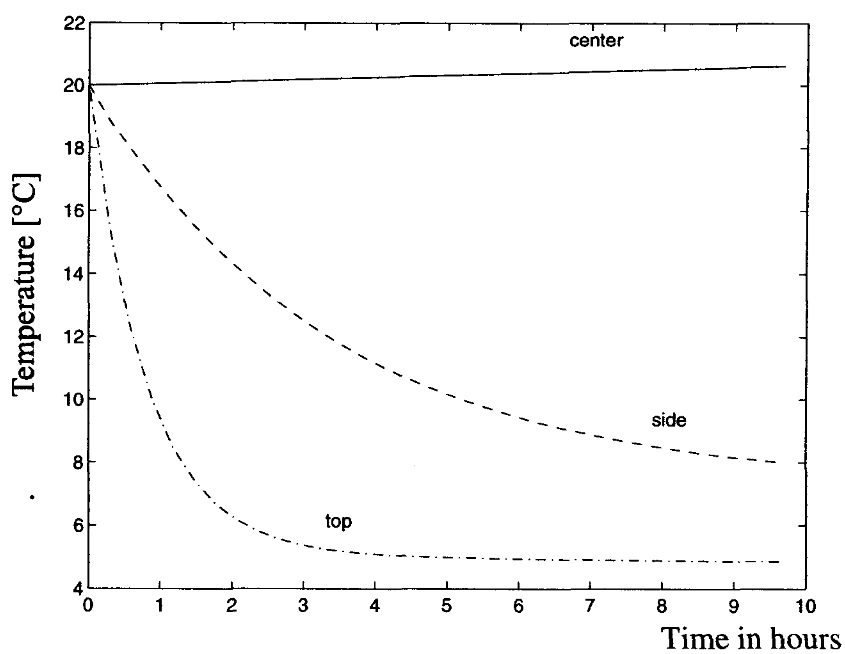

Figure 12. Temperature development in loaded pallet on three different locations.

In Figure 11 the temperature distribution as predicted by the model is visualized by a grey scale plot. As indicated by the horizontal bar, a dark tone represents the lower temperatures and a bright tone represents the higher temperatures. The considered case is a pallet of Roses after 10 hours of transport in hold 1-2. The initial temperature of the pallet was set to 20 *°C*. Due to heat production of the produce the temperature in the center of the pallet rises above the initial temperature. As the sides of the pallet, where convective cooling takes place, the temperature has decreased considerably in a relatively thin layer of the pallet. This also is observed in Figure 13 where the temperature development in time at three locations in the pallet is shown. Here it is also seen that the top layer is cooled relatively fast. The temperature in the center of the pallet reaches a value of about 20.5 *°C* after 10 hours of flight, but the temperature still increases. In the hypothetical case of transport during 50 days in hold 1-2, the temperature in the center stabilizes at 38.4 *°C*. Due to breathing of the produce it therefore is not possible to cool the center of a pallet of Roses in hold 1-2.

Of course temperature development is no direct measure for the quality development of the cut flowers during transport. However, it is possible to quantify quality by means of residual vase life, the number of days the flowers can be kept in a vase by the consumer. Using the experimental data of Boer and Hilhorst (1978), Van Doorn and Tijskens (1991) set up a generic model for the development of the residual vase life under storage and transport conditions. This model is implemented in the 2D heat transfer model described above, and thus a tool has been developed to model quality of cut flowers during flight in hold 1-2. So far only effects of temperature have been taken into account, although the model of Van Doorn and Tijskens also describes effects of relative humidity, ethylene and contamination.

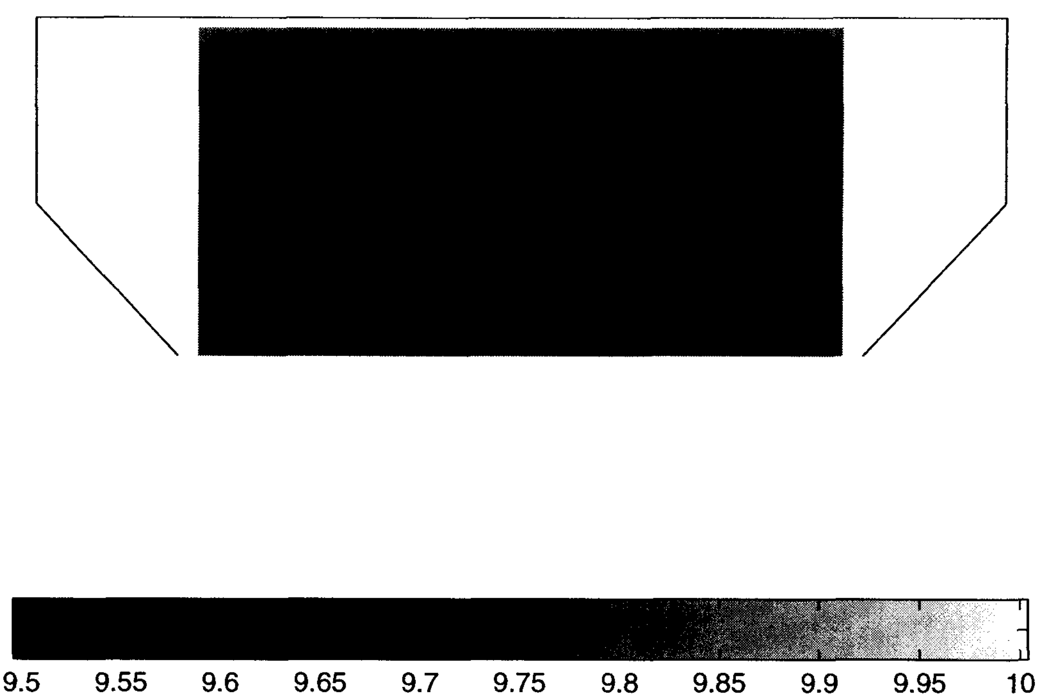

Figure 13. Computed residual vase life distribution of a pallet of Roses after 10 hours flight.

In Figure 13 the residual vase life of Roses after transport in hold 1-2 is visualized. The initial vase life was 10 days and the initial temperature 20 *°C*. It is observed that on the whole the residual vase life is reduced by about one third of a day. Due to better cooling the reduction in residual vase life near the outside of the pallet is less. It however must be emphasized that effects of water loss until now not have been taken into account. It is expected that at the sides of the pallet the flowers may loose a considerable amount of water, due to which the residual vase life of the flowers near the outside is likely to be reduced more.

At present the model was designed to describe the temperature distribution due to convective cooling in hold 1-2 of a Boeing 747-400. However, it is relatively easy to implement other convection parameters or radiative heat transfer to the pallet. The latter for instance could be used to model the stay in the sun at the loading platform. By changing the convection parameters, cooling in other aeroplanes could be modelled.

A major issue at this moment is the validity of the model. It was assumed that the heat transport in the pallet could be described by a diffusion process. The problem which then arises is how to quantify the effective conductivity and heat capacity of the pallet. For the time being the conductivity is chosen to be equal to the conductivity of air, whereas the heat capacity is chosen to be equal to the capacity of flowers. This apparent inconsequency is based on the considerations that flowers do not form a continuity, whereas air/cartons do. On the other hand, the heat capacity of air is negligible compared to the heat capacity of flowers and thus the latter is dominant. Secondly it was assumed that the heat loss to the ventilation air could be described by heat transfer correlations, which only have a limited accuracy. Thirdly the two dimensionality of the processes may be doubted, and further the models of heat generation and quality loss of cut flowers only are approximations (unfortunately this is inherent to modelling agricultural products).

To check and improve the validity of the model, two types of investigations have to be conducted. First, experiments have to be performed to monitor both temperature and relative humidity in a pallet with cut flowers during transport in hold 1-2. The development of these parameters in time and space yields a direct way to judge the accuracy of the model. When a sufficient number of recorders is adequately placed in the load, a fair insight in the temperature distribution (and thus for instance of the two-dimensionality) can be obtained.

Apart from experiments, more advanced numerical modelling (Computational Fluid Dynamics: CFD) is a valuable tool to gain insight in some of the physical aspects of the transport. Numerical modelling of the ventilation in the hold can give information on the validity of the employed heat transfer correlations, and improve the used heat transfer characteristics. Further by detailed modelling a better understanding of processes in the pallet is obtained, which yields a better estimate of the effective conductivity and heat capacity of the load. Due to local temperature differences in the cartons natural convective heat transfer mechanisms are likely to increase the effective conductivity. This might be accounted for by adding a turbulent conductivity to the conductivity of air. Besides a pallet of cut flowers in fact is a multi-phase system, which correspondingly can be described by CFD. Further until now only temperature effects have been considered. Using more advanced models, also effects of relative humidity (evaporation and the resulting quality loss) can be described.

6.3 Conclusions

A global heat balance model for cut flower transport in hold 1-2 of the Boeing 747-400 has been developed, which has shown to yield a fair agreement between the predictions and the measurements. But for gaining insight into the temperature distributions during flight a 2D model (or eventually a 3D model) has to be utilized.

We have developed a 2D diffusion model incorporating ventilation data of hold 1-2 and also product characteristics. The model has been coupled to a cut flower quality development model. Preliminary results show that in hold 1-2, mere ventilation is not able to sufficiently cool the bulk of a pallet of cut flowers.

In order to judge the validity of the 2D model, a set of experiments in hold 1-2 will have to be performed. Also more sophisticated (3D, including convection effects) model is required for being able to improve the 2D diffusion model.

In order to be practically applicable in a quality control system, the 2D diffusion model will not only have to be able to simulate flower quality development in hold 1-2, but also at different locations and stages in the distribution chain. Thus, also the situation during stay at the platform or in a cooling cell will have to be included. In the end, the model should be able to adequately describe temperature, humidity and quality development of perishable products like cut flowers during different phases of air transport and handling.

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