QUEST II: REDUCTION OF CO_2 EMISSIONS OF REEFER CONTAINERS

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ABSTRACT

This paper reports on the Quest™ II (QUality and Energy in Storage and Transport) development project run by Wageningen UR Food & Biobased Research, Maersk Line and Carrier Transicold. The aim of the Quest II development project was to improve the control of refrigerated marine container (reefer) units with the objective of maximizing energy efficiency in chilled mode operation without impairing produce quality. Lab testing research on produce quality revealed the limits by which deviations from the optimal transport temperatures are acceptable. Those limits were used in the design of the Quest II algorithm. Quest II control reduces energy consumption in chilled mode operation by 65% compared to non-Quest control. The savings are achieved by replacing continuous throttled compressor operation by an ON/OFF compressor control, and by automatically optimizing internal air circulation with heat load instead of continuous operation at maximum internal air circulation. Extensive produce quality research and hundreds of field trials reveal no adverse effect on produce quality while using the Quest II algorithm.

1 INTRODUCTION

Reefer units have two operational modes: chilled mode for setpoints of -5 °C or above, and frozen mode for setpoints below -5 °C. Table 1 shows some characteristics of an average reefer unit's energy consumption. The numbers in Table 1 are taken from several industrial sources. Many of these numbers are more or less confirmed by Heap & Lawton (1999) and Lawton *et al.* (2010). In Table 1 the 4.0 kW power draw in chilled mode applies to non-Quest operation.

The global installed fleet of reefer containers counts approximately 1,000,000 units. Altogether these cause a yearly CO_2 emission of approximately 4 million tonnes per year. The reefer market has generally realized a compound annual growth (CAGR) of 5%. In view of the growing fleet, rising fuel prices, and growing concerns about greenhouse gas emissions there is an increasing interest in the energy efficiency of reefer units (*e.g.* Fitzgerald *et al.*, 2011).

Lawton *et al.* (2010) justly observe two developments improving the energy efficiency of reefer units: hardware improvements and software solutions. Our Quest II control algorithm is a software solution. Traditional non-Quest control in chilled mode runs the compressor continuously, and always runs the evaporator fans in maximum speed. Quest II aims to improve chilled mode energy efficiency by avoiding inefficient part-load compressor operation and optimizing evaporator fan speed with heat load, without impairing produce quality.

Quest I was released in 2007. Soon after Wageningen UR Food & Biobased Research, Maersk Line and Carrier Transicold started the development of Quest II (patent pending).

This paper reports on the R&D project aimed at developing the Quest II control algorithm in the period Sept. 2008 till Aug. 2010, with the field trial program continuing until June 2011.

Table 1, characteristics of an average reefer unit's energy consumption.

number of trips	4	trips/year
avg. duration of trip	21	days/trip
chilled mode power consumption	4.0	kW
frozen mode power consumption	2.4	kW
frozen mode shipments	50	(% of all shipments)
Specific Fuel Oil Consumption	230	g/kWh
electricity price	0.11	USD/kWh
electric energy usage	6451	kWh/year
fuel oil consumption for electricity	1562	(L fuel oil)/year
CO2 emission	4139	(kg CO2)/year
fuel oil costs	688	USD/year

2 THEORY

Figure 1 schematically depicts the layout of a reefer container. When cooling is ON the compressor (not shown) cools the evaporator. Air circulation is maintained by internal evaporator fans with three possible operation modes: OFF, HALF or MAX (maximum) speed. Air passing over the evaporator cools, after which it is supplied to the cargo hold at a supply air temperature T_{sup}. It absorbs heat from the cargo after which it returns into the reefer unit with return air temperature T_{ret}. Heaters are used and cooling is OFF during conditions with relatively high setpoints and low ambient temperatures.

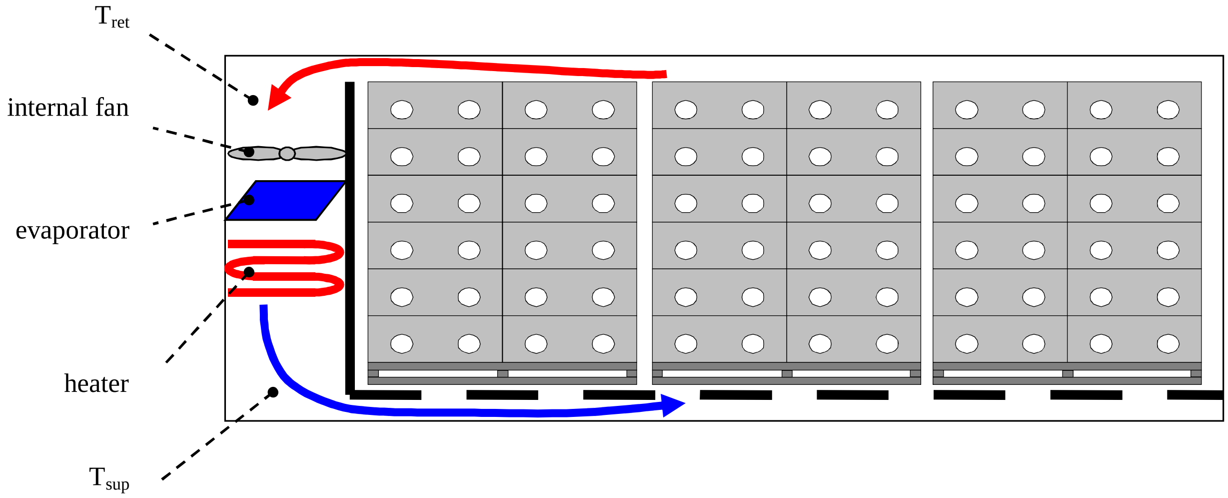

Figure 1, main outline of a reefer container.

Non-Quest chilled mode operation has two important sources of energy inefficiencies:

1. The 1.6 kW evaporator fans always run at maximum speed, regardless of the heat load.
2. During part-load operation throttling the compressor reduces the efficiency of the refrigeration cycle.

With respect to issue one: the evaporator fan air flow in reefer containers suffices for temperature pulldown of hot-stuffed containers. Full fan air flow is usually not needed after pulldown. With respect to issue two: in part-load operation, the continuously running compressor is throttled in order to manipulate the evaporation temperature such that supply air temperature T_{sup} equals setpoint. This throttling causes efficiency losses.

3 METHODOLOGY

The Quest II project team aimed to develop a control algorithm that maximizes energy efficiency without impairing produce quality. The means of addressing the two inefficiencies listed above are:

1. Fan speed control logic that adjusts internal air circulation with respect to internal heat load.
2. Compressor control that replaces inefficient throttled part-load compressor operation with unthrottled compressor ON-OFF operation, accepting some controlled supply air temperature variations.
3. Indirectly controlling produce temperature by controlling the average of T_{sup} and T_{ret} to setpoint, instead of just controlling T_{sup} to setpoint. Freezing or chilling injury is avoided by applying a minimum constraint to the time-averaged T_{sup}.

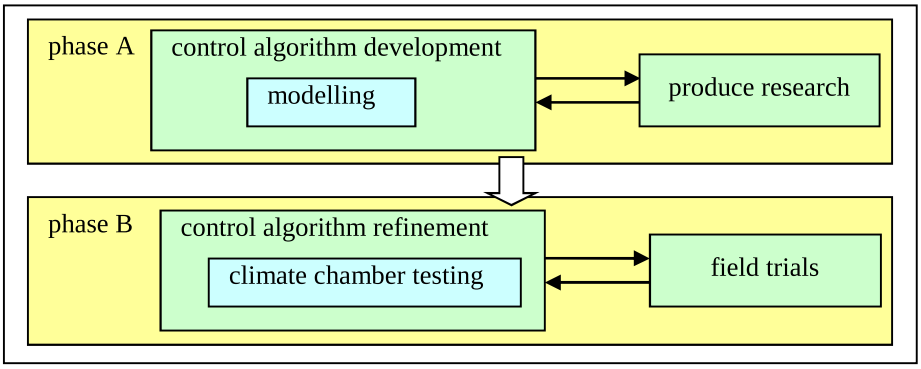

Figure 2, schematic representation of main activities within the project.

The main outline of the Quest II project is depicted in Figure 2. In the first year of the project (phase A) two research lines ran in parallel, mutually influencing each other: control algorithm development and perishable produce research. The lab testing produce research was conducted to learn the relevant temperature tolerances of sensitive perishables. Phase A was concluded with a control algorithm which performed well in a computer simulation environment and was safe for produce quality according to the information collected in the produce research. In the remainder of the project (phase B) the control algorithm was further refined, based on results collected during climate chamber tests. Concurrently a program with hundreds of field trials was started to test and verify the proper functioning of the control algorithm in a range of practical conditions. Control algorithm refinements gave rise to specific field trial set-ups, while field-trial results revealed weaknesses in beta-versions of the control algorithm, which were then addressed by further refinements of the algorithm.

3.1 Control algorithm development and refinement

The control algorithm development in phase A was started with the formulation of a static reefer unit model and a dynamic model describing the main climate dynamics in the container. Both models and the control algorithm were then programmed and mutually connected in the Matlab programming environment. The control was then simulated in Matlab in a large range of conditions. This led to an iterative process of simulating and redefining the control algorithm.

At the start of phase B the main outline of the Quest II algorithm already existed. In phase B the control algorithm was programmed in Carrier's MicroLink 3 controller and its performance tested in a series of climate chamber tests. These climate chamber tests in conjunction with the field trials revealed the differences between the container model and the true reefer unit dynamics, thereby proving the need for further algorithm enhancements.

3.2 Produce quality research

The three sub-goals of Quest II, listed at the beginning of section 3, give rise to three produce quality related questions:

1. Would reduced air circulation lead to elevated produce temperatures at the container's door end, how would that affect produce quality?
2. Do variations in T_{sup} negatively affect quality?
3. If average T_{sup} is below setpoint, what is the risk of inducing chilling/freezing injury?

The above questions have been answered by simulating the long distance transport of selected batches of banana, pineapple, kiwi, grape, iceberg lettuce, chilled lamb meat and lily bulbs in small climate rooms at four different temperature regimes:

1. Reference temperature – 3 °C.
2. Reference temperature + 3 °C.
3. Profile 1 (severe variation): min/mean/max = reference – 3.0 / reference / reference + 1.0 °C, with a 60 minutes cycle period.
4. Profile 2 (extreme variation): min/mean/max = reference – 6.0 / reference / reference + 1.5 °C, with a 180 minutes cycle period.

Afterwards the quality of these four batches is compared to the quality of a fifth batch stored at the reference temperature. Reference temperature is chosen equal to the setpoint temperature at which the produce is usually transported. The typical stepwise procedure in all lab testing experiments is depicted in Figure 3.

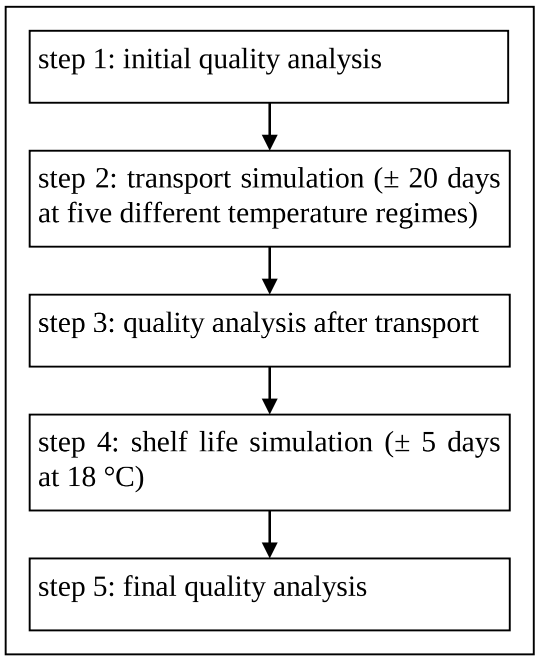

Figure 3, typical chronological steps in produce quality experiments.

In all lab testing experiments, the produce is selected:
- to originate from one batch (same harvest date, same origin),
- to be packed as usual during container transport and
- to be a temperature-sensitive cultivar.

3.3 Field trial program

Objective of the field trials is threefold: 1) collect information in a range of operating conditions which may be used to further refine the control algorithm, 2) gain insight in the real-world energy savings, 3) prove that produce quality is not impaired. Setpoints during the trials ranged from -3 °C up to +22 °C and ambient temperature ranged from -5 to +52 °C. Especially sensitive cargos were selected for trials. In all field trial shipments the intended trial set-up was:

- Ship two identically loaded containers, one Quest II and one non-Quest, at the same time.
- Position the two containers in all supply chain links as close as possible to each other.
- In each container register hourly readings of air temperatures in four cartons: unit-end lower tier, halfway lower tier, three quarter of length middle-tier, door-end upper tier.

Specifically for these trials the reefer unit's data acquisition program was programmed to collect information with respect to all relevant controls and temperatures. Each reefer unit was equipped with an electric energy meter, which was read on a daily basis. Both at stuffing and unstuffing of the container, third party surveyors analyzed the produce quality. Products used in the field trials: banana, melon, onion, apple, pear, pineapples, plums, chocolate, garlic, printer cartridges, potted plants, chilled meat, various kinds of citrus.

4 RESULT: THE QUEST II CONTROL ALGORITHM

The Quest II algorithm adjusts evaporator fan speed to heat load, avoids inefficient throttled part-load compressor operation, and indirectly controls cargo temperature instead of just supply temperature. The remainder of this section presents the main characteristics of the algorithm.

A key variable in the Quest II control algorithm is the Temperature-Error Integral TEI(t). The variable TEI(t) [°C.min] is calculated by

$$TEI(t)=\max(TEI_{min},\min(TEI_{max},TEI(t-1)+ (T_{sup}(t)-T_{sq}(t)) \times t_s)) \qquad [°C.min] \quad (1)$$

where t_s is the sampling interval, with a value of 1/60 minutes, and T_{sq} is the Quest-setpoint temperature, which will be explained further down in this section. The algorithm arguments, max(…,min(…,…)) prevent the integral from getting excessively large during periods when cooling/heating capacity is insufficient to control T_{sup} around T_{sq}.

A starting value $TEI(t_0)$ for TEI is determined anytime Quest II starts to operate. After running the evaporator fans at MAX speed for 15 seconds the initial value of TEI is then calculated using:

$$TEI(t_0) = \max(TEI_{min}, \min(TEI_{max}, 40 \times (T_{ret}(t_0)-T_{sq}(t_0)) + 30)) \qquad [°C.min] \quad (2)$$

Crucial in Quest II is control of the cycle-averaged T_{sup} to T_{sq} by controlling TEI within bounds. The notions of cycle (1) and T_{sq} (2) are explained below. Subsequently the control of operation mode (3) and fan speed (4) is defined.

<u>1. Cycle</u>: A cycle is a period of time starting at the end of the previous cycle and ending when one of the following conditions apply: cooling switches ON, heater switches OFF, or last cycle ended more than 1 hour ago. Usually a cycle consists of a compressor-ON period followed by a consecutive compressor-OFF period.

<u>2. Quest setpoint T_{sq}</u>: Temperature to which average T_{sup} is controlled. The Quest setpoint T_{sq} deviates from T_{set} with the objective to control the average of T_{sup} and T_{ret} to the setpoint. By allowing the average T_{sup} to be below T_{set} the average produce temperature in the container will be closer to T_{set}. When Quest II starts T_{sq} is initialized as T_{set}. Following this initialization, T_{sq} is calculated at the beginning of each subsequent cycle according to:

$$T_{sq} = \max(T_{sq,min}; (1-0.2\times t_{cycle}/60)\times T_{sq} + 0.2\times t_{cycle}/60\times (2\times T_{set} - \bar{T}_{ret})) \qquad [°C] \quad (3)$$

Where

t_{cycle} = duration of the preceding cycle [minutes].

$\bar{T}_{ret}$ = return air temperature averaged over the last cycle [°C].

$T_{sq,min}$ = lower constraint on T_{sq}, meant to avoid freezing or chilling injury, given by:

$$T_{sq,\min} = \begin{cases} T_{set} \ {}^{o}C & \text{for} \quad T_{set} < 1.2 \quad \text{or} \quad 12 \le T_{set} < 15\ {}^{o}C \\ T_{set} - 1\ {}^{o}C & \text{for} \quad 1.2 \le T_{set} < 12 \quad \text{or} \quad T_{set} \ge 15\ {}^{o}C \end{cases} \qquad [°C] \quad (4)$$

3. Operation mode control: Operation switches between five possible modes: cooling, circulation, heating stage 1, heating stage 2, and heating stage 3. The instantaneous value of TEI determines the desired unit control mode as illustrated in Table 2. Additionally the value of any of the three controls (compressor, evaporator fan, electric heater) may only change if none of them changed during the last three minutes, the compressor is even forced to stay ON for at least four minutes. The primary reason for introducing these minimum durations is protection of unit hardware including compressor lubrication and contactor wear. In circulation mode additional rules apply to decide on fan speed, which may be OFF, HALF or MAX.

Table 2, desired mode(s), and value of control variables, as a function of TEI [°C.min].

TEI range	< -30	[-30, -10]	[-10, 0]	[0, 70]	≥ 70
mode	Heating stage 3	Heating stage 2	Heating stage 1	circulation	Cooling
controls	heater ON fans MAX cooling OFF	heater OFF fans MAX cooling OFF	heater OFF fans HALF cooling OFF	heater OFF fans OFF/HALF/MAX cooling OFF	heater OFF fans MAX cooling ON

4. Evaporator fan speed control in circulation mode: a complex algorithm controls the changing of fan speed between OFF, HALF and MAX. The algorithm is designed to run fans in MAX speed during periods of high heat load, to alternate fan speed between MAX and HALF at moderate heat loads, and to alternate fan speed between OFF and HALF during periods of very low heat load. The most important inputs to the fan speed control algorithm are:

- Duration of compressor OFF periods: short compressor OFF periods indicate high heat load, and hence fan speed stays MAX.
- Changes in return air temperature during compressor OFF periods:
  - increase fan speed one step during a period with fan speed OFF or HALF if T_{ret} changes more than 0.4 °C since the start of the current fan speed.
  - reduce fan speed one step after five minutes of HALF or MAX fan speed in case the current T_{ret} changed less than respectively 0.01 or 0.04 °C/min since an earlier registered T_{ret}.
- After 20 minutes of fan speed OFF or MAX change to fan speed HALF.
- After 40 minutes of fan speed LOW change to OFF.

Figure 4 through Figure 6 present real data collected in an empty container for different heat loads. At high heat load (Figure 4) the duration of compressor OFF periods equals the minimum required 3 minutes, evaporator fans run MAX speed all the time. Supply temperature during compressor ON periods drops only about 1 to 3 °C below setpoint. High heat load typically occurs during the first two days of a shipment with hot-stuffed cargo, like common practice in banana shipments. At moderate heat load (Figure 5) the duration of compressor ON periods equals the minimum required 4 minutes and OFF periods are longer, while evaporator fans alternate between HALF and MAX speed. During compressor ON periods supply temperature drops about 3 to 4 °C below setpoint. Moderate heat load covers about 70% of all operation time. At low heat load (Figure 6), occurring during less than 10% of operating time, compressor ON periods are 4 minutes and OFF periods longer than 40 minutes, while evaporator fan speed in circulation mode alternates between HALF and OFF. In these circumstances supply temperature during compressor ON periods drops more than 4 °C below setpoint.

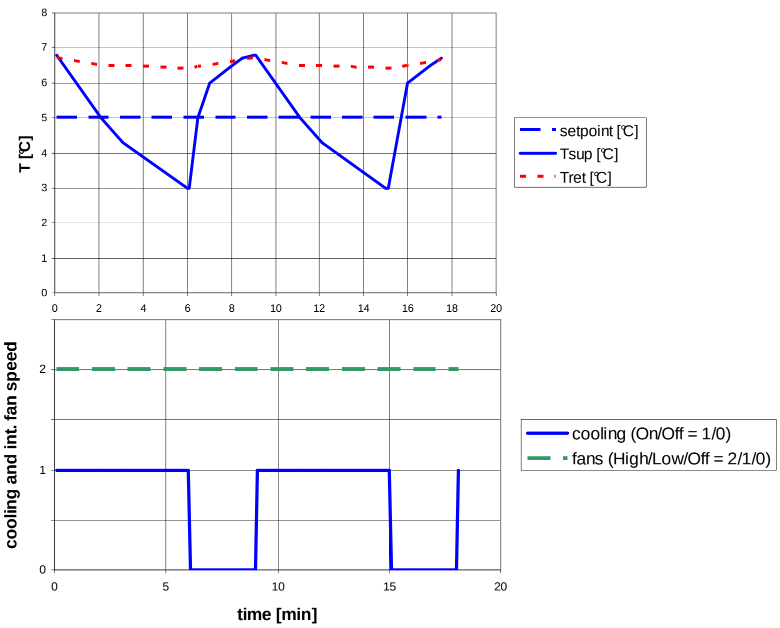

Figure 4, temperatures and controls at high heat load.

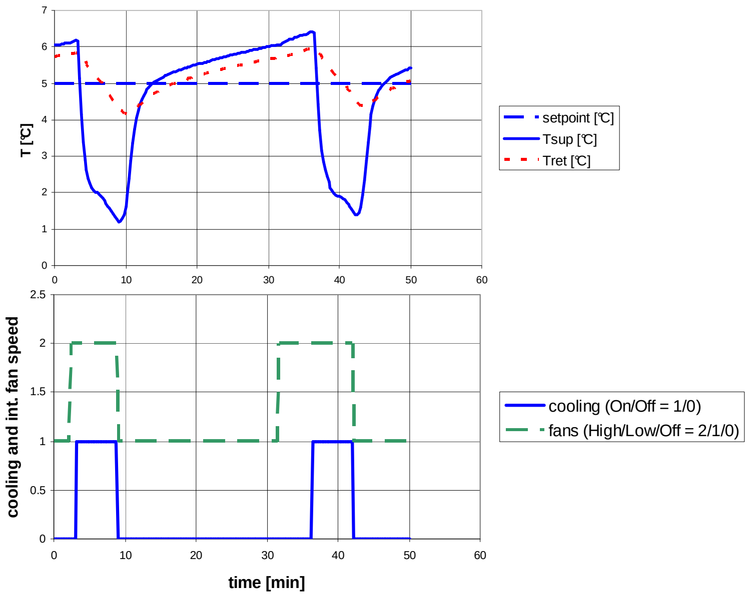

Figure 5, temperatures and controls at moderate heat load.

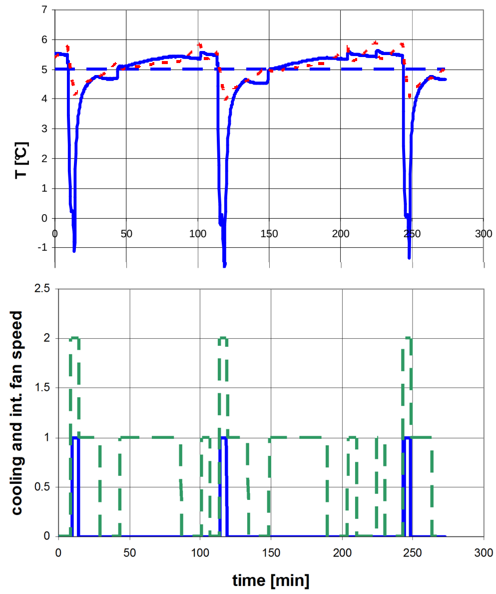

Figure 6, temperatures and controls at low heat load.

4.1 Produce quality

Table 3 summarizes the results of the produce quality research. Unsurprisingly constant temperatures of 3 °C above the reference temperature have a distinct adverse effect on produce quality (Table 3, last column). Similarly, 3 °C below the reference temperature yields adverse results (Table 3, column 3). The extreme temperature profile (profile 2) has a negative effect on the quality of lily bulbs and pineapple (Table 3, column 5). The severe temperature profile (profile 1) shows a statistically significant negative effect only on grapes (Table 3 column 4), while iceberg lettuce benefits. Remarkably, grapes are not adversely affected by the extreme temperature profile. The main reason for the limited effect of the severe temperature profile is that temperature oscillations inside the cartons are largely dampened by the produce's own thermal inertia.
The findings with respect to produce quality have been used to design the Quest II control:

1. In order to avoid hot spots Quest II only reduces the internal air circulation if heat load is low.
2. Quest II temperature variations are milder than the severe variation (profile 1) used in produce quality research. Quest II uses much shorter cycle periods than profile 1. Due to the much higher frequency the Quest II cycles are better dampened by the packaging's thermal inertia.
3. Quest II aims to control the average of supply and return temperature to the setpoint or reference temperature, because both too high and too low temperatures harm produce quality. A lower constraint is added to the time-averaged T_{sup} (eqn. 4) to avoid freezing or chilling injury.

Table 3, summary of results of lab testing produce quality research.

produce	**T_{ref} [°C]**	**T_{ref} - 3 °C**	**profile 1**	**profile 2**	**T_{ref} + 3 °C**
Lily bulb (cv. Simplon, Tiara, Conca d'Or)	-1.5	Freezing		Leave burn after planting	Sprouting
Lamb shoulder cuts	-1.5	Freezing			Microbial count ↑
Kiwi (cv. Hayward)	+0.5	Freezing			
Grape (cv. Victoria)	+0.5	Freezing	Stem browning		Greener stem
Iceberg lettuce	+0.5	Freezing	Wilting ↓		
Pineapple (cv. MD2)	+6.5			Firmness ↓, external yellowing	Firmness ↓, external yellowing
Banana (cv. Cavendish)	+13.5	Chill injury			

meaning of colours in the table above:	Green = no statistical difference as compared to reference temperature.	Red = statistically significantly worse than reference temperature.	Bright green = statistically significantly better than reference temperature.

4.2 Field trial program

Figure 7 and Figure 8 show the trajectories of T_{sup} and T_{ret} registered during two informative trial shipments. It concerns containers with Carrier ThinLine units making the same journey simultaneously. The containers both carry a load of hot-stuffed citrus. The high initial cargo temperature causes high return air temperatures during the initial days of the voyage. Figure 7 shows the trajectories of T_{sup} and T_{ret} registered in a non-Quest container, while Figure 8 displays the recorded T_{sup} and T_{ret} in a Quest II container. As seen in Figure 7 non-Quest just controls T_{sup} to T_{set}. Note that the persistent 0.2 °C offset between T_{sup} and T_{set} is a consequence of a difference between the return air temperature recorder sensor (shown in Figure 7) and the return air temperature controller sensor (not shown). Quest II though (Figure 8) responds to the high initial T_{ret} by reducing T_{sq} (not shown, but approximately equal to T_{sup}) to its lower bound. Consequentially the pulldown of T_{ret} is faster. Later on T_{ret} comes ever closer to T_{set}, while the Quest II algorithm gradually rises T_{sq} with the obective to control the average of T_{sup} and T_{ret} to T_{set}. In Figure 8 a minor jitter is observable on T_{sup}, which results from the hourly averaging of T_{sup} which varies in cycles unequal to one hour. Evaporator fan speed (not shown) in non-Quest (Figure 7) is always MAX. In this trial in Quest II (Figure 8) evaporator fan speed in circulation mode remains MAX till about 18 Dec. 2009 12:00 (091218-12 on the horizontal axis), after that it is mostly HALF. From about 5 Jan. 2010 0:00 (100105-00) on fan speed cycles between HALF and OFF.

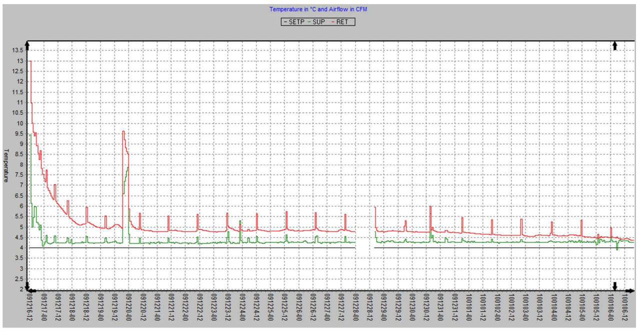

Figure 7, non-Quest citrus trial shipment: T_{set} (black), hourly averaged T_{sup} (green) and T_{ret} (red).

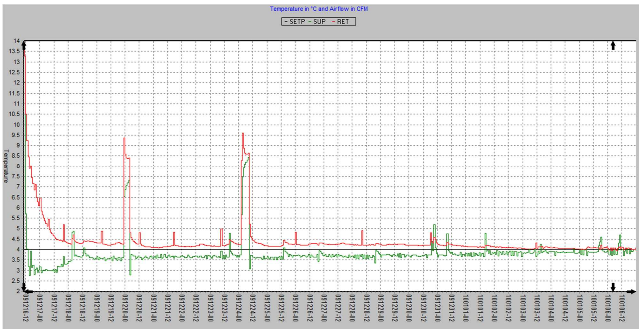

Figure 8, Quest II citrus trial shipment: Tset (black), hourly averaged Tsup (green) and Tret (red).

In field trials the observed cargo temperature gradient inside the container is only about 0.2 °C larger for Quest II as compared to non-Quest. This number is an average over the observations from 48 field trials conducted with the final version of the Quest II algorithm.
None of the field trials executed with the final version of the Quest II algorithm revealed adverse effects on produce quality. The final version of Quest II saves around 65% energy. Typically the savings percentage is highest at low heat load. Table 4 provides some representative observations. In Table 4 two consecutive lines with the same shading colour concern two containers making the same journey at the same time.

Table 4, summary of some of the field trial results. Meaning of abbreviations in this table: PL = Carrier PrimeLine, EL = Carrier EliteLine, TL = Carrier ThinLine, nQ = non-Quest, QII = Quest II, UK = United Kingdom, NL = The Netherlands, SA = South Africa, tC = percentage of time the compressor is ON, tMS = percentage of time the evaporator fans run at Maximum Speed.

Unit	**control**	**origin**	**destination**	**Duration [days]**	**product**	**T_{set} [°C]**	**Avg. el. power [kW]**	**tC [%]**	**tMS [%]**	**Energy savings [%]**
PL	QII	Australia	Japan	15	Beef	-1.0	1.6	18%	38%	47%
PL	nQ	Australia	Japan	15	Beef	-1.0	3.0			
TL	QII	SA	UK	17	Apples	-1.0	2.3	23%	26%	56%
TL	nQ	SA	UK	17	Apples	-1.0	5.2			
TL	QII	SA	Portugal	15	Citrus	+4.0	0.6	14%	27%	74%
TL	nQ	SA	Portugal	15	Citrus	+4.0	2.2			
PL	QII	Ecuador	NL	18	Banana	13.3	1.1	12%	27%	63%
PL	nQ	Ecuador	NL	18	Banana	13.3	3.0			
EL	QII	Ecuador	NL	19	Banana	13.3	2.0	21%	27%	63%
EL	nQ	Ecuador	NL	19	Banana	13.3	5.5			

5 DISCUSSION

The main effects of the Quest II control algorithm, as compared to traditional non-Quest chilled mode operation, are:

1. Approximately 65% energy savings as compared to non-Quest.
2. Increased rate of temperature pulldown, especially for setpoints where T_{sq} is allowed to decrease to 1 °C below setpoint.

The 65% energy savings is an average: the observations range from 0% savings during the initial stage of temperature pulldown, where the unit cools at maximum capacity (for example during the first hour in Figure 8) till over 90% at very low heat load in situations where cargo temperatures are in steady state while ambient temperature is close to setpoint (for example during the last two days in Figure 8). Table 4 presents some of the field trial results. The last column presents trip-averaged savings percentages of Quest II as compared to non-Quest. Clearly, the most modern unit type (PrimeLine) is a lot more efficient than the older unit type (ThinLine). Yet there is no clear correlation between savings percentage and unit type. The lowest observed saving is 47% in a shipment where evaporator fans run high speed 38% the time, while the compressor is ON during 18% of time. The highest observed saving is 74% in a shipment of nicely precooled citrus. That saving is achieved by reducing the compressor ON time to 12% and the time the evaporator fans run in max. speed to 27%.
The improved temperature pulldown is illustrated in Figure 8: because return air temperature is distinctly above T_{set} eqn. 3 reduces T_{sq}, and hence time-averaged T_{sup}, to T_{set} – 1 °C during the first day of the shipment. In non-Quest control T_{sup} is controlled to T_{set} (Figure 7) and hence it takes longer for T_{ret} to come down.

6 CONCLUSION

The Quest™ II control algorithm (patent pending) saves approximately 65% energy as compared to non-Quest in chilled mode. This is achieved by:

1. Replacing continuous throttled compressor operation with ON/OFF compressor operation.
2. Optimizing evaporator fan speed with heat load: at high heat load evaporator fans run at maximum speed similar to non-Quest operation. However, when heat load reduces, evaporator fan speed starts to alternate between maximum and half speed, or between half speed and OFF at very load heat load.

Quest II achieves faster temperature pulldown by allowing supply air temperature to drop below setpoint in periods where return air is above setpoint (see first day in Figure 8).
Analysis of over 200 field trials revealed no adverse effect on produce quality while using the Quest II control algorithm.

7 ACKNOWLEDGEMENTS

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