Supervision of transport and ripening of bananas by the Intelligent Container

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Abstract: The ripening of bananas inside a container during transportation can provide for large economical benefits. However, it only will be feasible if the air flow and thereby the cooling is improved. This paper introduces a model for estimation of the rate of heat flow and of the heat generated by fruit respiration from recorded temperature curves. Different measures for improving air flow conditions inside and outside the pallets loaded to the container were evaluated in field tests, including overseas transport, simulated setups ashore and container ripening of 8 pallets.

1. Introduction

The intelligent container provides a system for remote supervision of transports of perishable goods in trucks and containers. A special focus of the project has been set on containerized transports of bananas, with the final goal of providing required control mechanisms to carry out the ripening process directly in the container. Container ripening brings economical benefits but also involves higher risks than ripening in specialized chambers ashore. The ripening process itself creates a tremendous amount of heat, which can lead to total loss if not channelled away.

This paper first introduces a modelling approach to identify parameters from temperature over time curves during transport. The first model parameter gives an index value for effective cooling performance at different sensor positions. The second parameter describes the amount of generated respiration heat. The temperature model can be applied to supervise containers during transport and to detect critical states. Furthermore, it can be combined with a green life model in order to predict the remaining green life at the expected time of arrival.

Several spatial temperature profiles were recorded during transports of bananas from Costa Rica to Europe and in simulated setups close to a banana ripening facility in Germany. The effects of different box designs, loading schemes and gaps between pallets were evaluated by calculation of the index value for effective cooling performance. Two pilot tests were carried out for container ripening subsequent to an overseas transport. Ripening was triggered by gassing with ethylene. In the second test it was managed to keep the box temperature stable within the recommended range by using an improved packing setup.

2. The Model

Over the past three years spatial temperature profiles of banana containers were recorded in various tests ashore and offshore. Between 16 and 50 data loggers were placed in the centers of bananas boxes. Large variations in the speed of temperature changes in the box centers could be observed. **Fig. 1** shows an example for measured temperatures during a transport from Costa Rica to Antwerp, which provides an example for high temperature variations inside a container.

A simple curve fitting by an exponential function leads to high inaccuracies, especially if the air supply temperature changes over time. Therefore, we started to develop a dynamic model for the temperature T in the centre of a banana box. A temperature change ΔT results from two factors: The heat generated by fruit respiration causes an increase of temperature by ΔT_{Resp}. Depending on the amount of fresh air flowing around and through the box, heat removal causes a temperature decrease by ΔT_{Cool}.

$$\Delta T = \Delta T_{\mathrm{Re}\,sp} - \Delta T_{Cool} \tag{1}$$

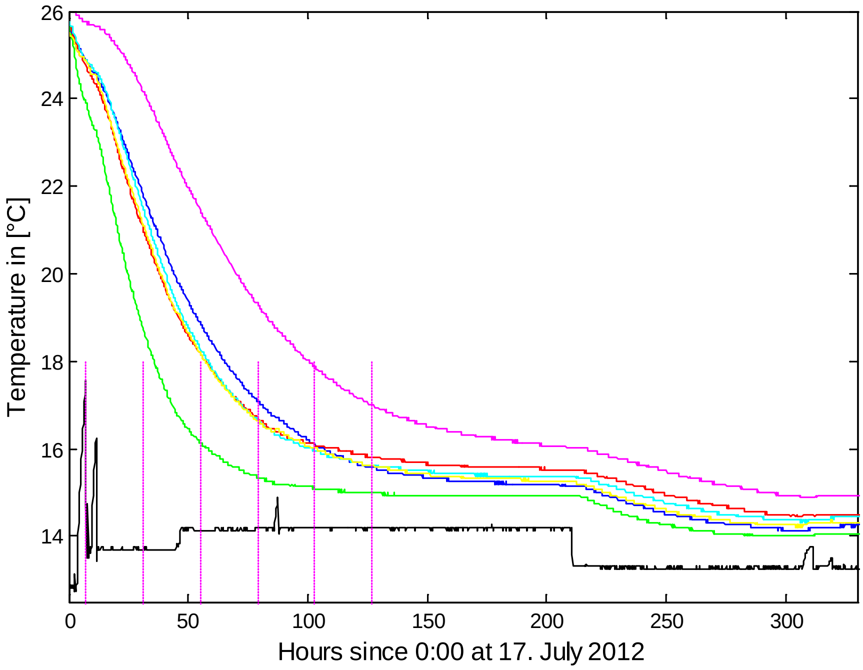

Fig. 1: Measured temperatures during 14 days of see transportation. Supply air (black) and 6 different positions in the center of the pallets (coloured). Test July 2012

Respiration heat increases exponentially with the temperature. The Q_{10} value indicates by which factor biological activity is accelerated as a consequence of increasing the temperature by 10°C. Eq. (2) also contains a proportional factor k_P summarizing further factors such as biological age of the bananas and concentration of CO_2 and other gases in the atmosphere.

$$\Delta T_{\mathrm{Re}\,sp} = k_P \cdot e^{\ln(Q_{10}) \cdot (T - 13°C)/10} \tag{2}$$

Temperature changes caused by the cooling unit depend on supply air temperature u_S and current box temperature T. For the dynamic case, where both $u_S(t)$ and $T(t)$ are changing over time, delays caused by the thermal mass of the bananas and of the box have to be considered. In a previous publication [Jed13] a model was described consisting of two delay elements, able to fit the model prediction with measured temperature curves very well by estimation of two parameters k_P and k_M (**Fig. 2**). The additional parameter k_M serves as an index value for the effectiveness of cooling in the modelled box. The time constants and Q_{10} were set to fixed values ($TC_3 = 4$ *hours*, $TC_4 = 15$ *hours*, $Q_{10} = 3$). For a detailed discussion of the parameters see [Jed13].

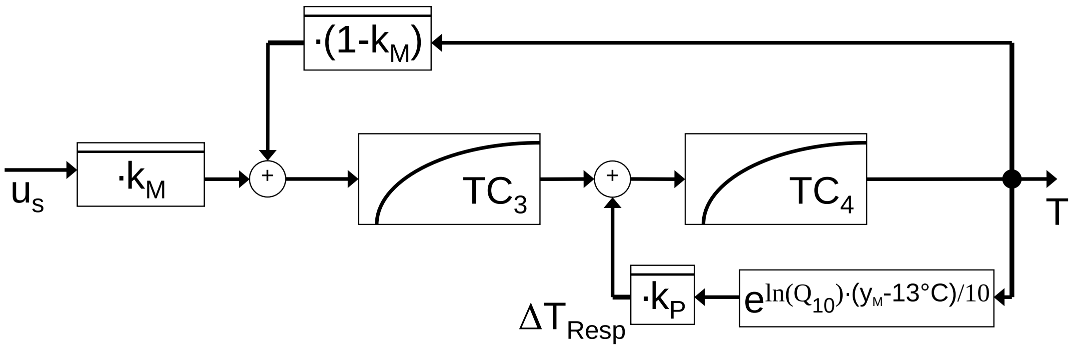

Fig. 2: Dynamic temperature model for temperature in the box center.

Fig. 3 shows a typical temperature curve, measured in a test ashore for a change of the cooling unit set point from 16°C to 13°C together with the estimated model.

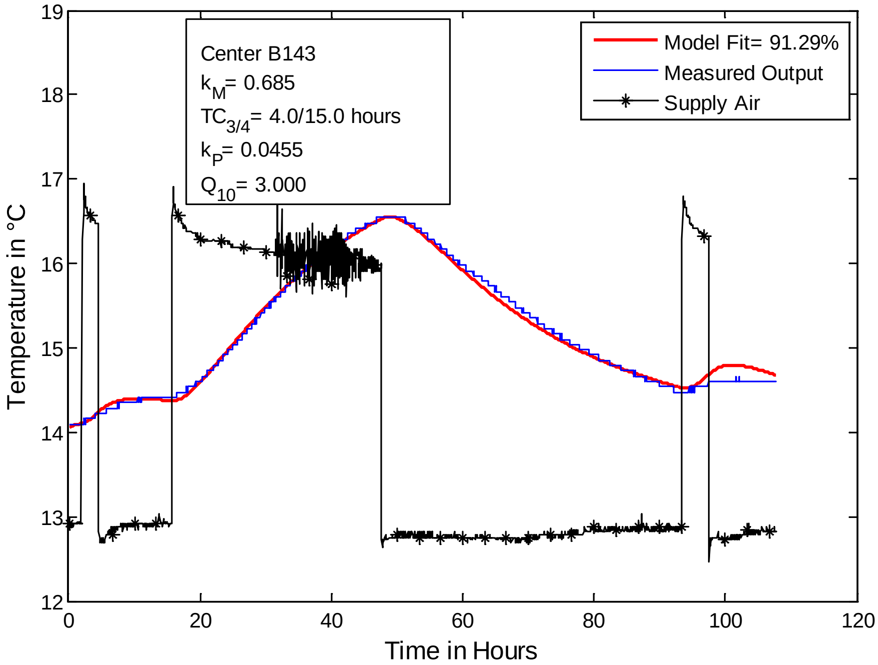

Fig. 3: Measured temperature in a test ashore and model fit. Test January 2012

As an example application of the model we consider the speed of temperature changes at *T*=15°C. The effect of respiration heat can be calculated by Eq. (2) to:

$$\Delta T_{Resp}(15°C) = 1.246 \cdot k_P \qquad \left[\frac{K}{hour}\right] \tag{3}$$

The effect of cooling cannot be calculated by the model directly, it can only be approximated for a constant supply air temperature of u_S = 13°C, $TC_3 << TC_4$ and small changes of *T*:

$$\Delta T_{Cool}(15°C) \approx 0.1333 \cdot k_M \qquad \left[\frac{K}{hour}\right] \tag{4}$$

Although Eq. (4) is only a rough approximation with an error of about 5%, it shows the effect of the model parameter k_M on temperature changes. Multiplying Eq. (1) with the thermal capacity of one ton of bananas of 3350 kJ/K [Wil05 p. 80] converts the equation to a description of the rate of heat flow, measured in Watt with ΔU_{Therm} as the change of thermal energy, $P_{Resp}=C_P \cdot \Delta T_{Resp}$ as generated power by respiration and $P_{cool}= C_P \cdot \Delta T_{Cool}$ as transferred power by cooling. The constant C_P=930.5 [Ws/K] also includes a conversion from hours to seconds.

$$\Delta U_{Therm} = P_{Resp} - P_{Cool} \tag{5}$$

In the example in **Fig. 3** the bananas generate 52 Watt of heat per ton. The cooling unit is able to remove 85 Watt per ton, therefore, temperature decreases.

3. Effects on Greenlife

The above described k_{MP}-model can be applied in various ways: It can be used to detect conditions for hotspots with $\Delta T_{Cool} < \Delta T_{Resp}$, to evaluate whether cooling is sufficient for container ripening, and for evaluating effects of modified packing. In this section we will show, how changes in the k_M and k_P parameters are related to the green life at the end of transport. The green life gives the number of days, for which the bananas can be stored until an unwanted self-induced ripening process starts. We rely on the model of Praeger et. al. [Pra13] that will be presented separately on the same conference. The green life GL_{const} for constant temperature *T* can be estimated according to Eq. (6):

$$GL_{const}(T) = 159.86 \cdot e^{-0.124 \cdot T} \tag{6}$$

Eq. (6) provides only an average value for the expected green life, since its duration depends on biological variance and various factors such as pre-harvest conditions and age at harvest.

For T=13°C, the green life arrives at a maximum of GL_{max} = 31.89 days. For dynamic temperature conditions the loss-per-day LPD can be calculated as a function of current temperature by Eq. (7) and be step-wise subtracted from the initial value GL_{max}.

$$LPD(T) = \frac{GL_{\max}}{GL_{const}(T)}$$
$$GL_{dyn} = GL_{\max} - \int LPD(T(t)) \cdot \partial t \tag{7}$$

This model can be applied to the measured temperature curves. However, for evaluation of the effects of changes in k_M and k_P, it is better to run the green life model on temperature curves related to identical start conditions ($T(0)$=25°C) and supply air temperature (u_S = 13.3°C). Therefore, the input temperature curves for the green life model were generated by simulation of the k_{MP}-model. By using this approach it is also possible to extrapolate the effects of cooling parameters estimated ashore to a simulated setup for sea transportation. The remaining green life at the end of a simulated transport over 14 days is given by the black contour lines in **Fig. 4**. For the example above with k_M=0.685 and k_P=0.0455 the green life calculation results to 11.5 days. The red and blue triangles mark all k_M/k_P pairs in this container in boxes at the right/left wall side. Details about this test with different gaps widths will be discussed in the next section. The green life for some boxes with blocked gaps would be zero, if these conditions were maintained over the full transport duration of 14 days. The blue stars mark the k_M/k_P pairs of a final test with improved packing, which resulted in an extension of the remaining green life to values between 13 and 15 days.

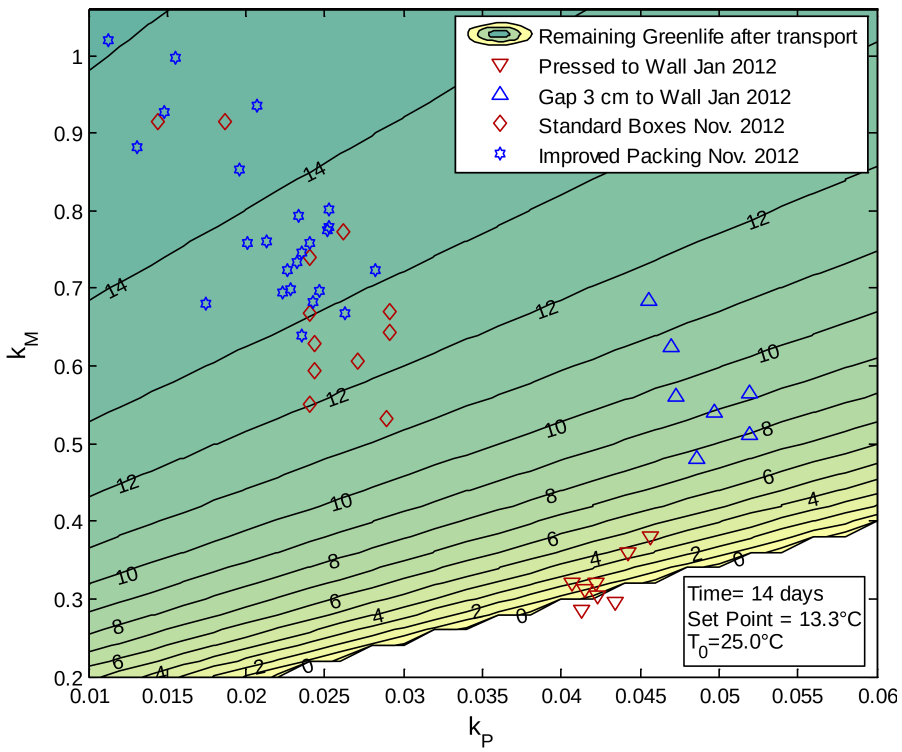

Fig. 4: Calculated green life at end of transport for the k_M / k_P parameters estimated during two field tests.

4. Improving the effectiveness of cooling

During an offshore test in 2011 with a 3 year old container under controlled atmosphere conditions, averaging of the estimated model parameters for 16 sensors in different boxes resulted in k_M = 0.524, equivalent to the heat removal of 81 W/ton at 15°C, or 1.4 kW for a full container load of 17.6 tons of bananas. According to the manufacturer data sheet, the Carrier Primeline unit provides a cooling capacity of more than 12 kW at 15°C. This clearly indicates that air flow conditions with the current loading scheme are anything but optimal. The airflow outside as well as inside the pallets has to be improved. A further indicator for suboptimal airflow is the high variation of the observed k_M values. In the test from 2011 k_M ranges from 0.295 to 0.872. Some boxes are poorly cooled, others very well.

We found that these deviations are mostly caused by different gaps between pallets and between pallets and walls. If no special measures are taken to ensure equal distances between pallets, some gaps are completely closed, whereas others can extend to 4 cm or more. In a further test ashore in 2012, the pallets were pressed to one side of the container, leaving a gap of approximately 3 cm on the opposite side. **Fig. 5** compares the measured temperature curves for the center of boxes close to either the right or left wall.

The average of the estimated k_M values shows also a large difference with $k_M = 0.322 \pm 0.032$ for the right wall without gap and $k_M = 0.567 \pm 0.069$ for the left wall with a 3 cm wide gap. Since the bananas were harvested 2 weeks before the test and no measures were taken to modify or control the atmospheric conditions, the respiration heat increased to 50.3 W/ton with k_P = 0.0434. At the left wall, cooling could remove 87.6 W/ton, while on the right wall only 49.8 W/ton could be removed. The container failed to maintain a temperature of 15°C on the side with the closed gaps. After increasing the set point to 16°C for 32 hours, the container was not able to cool down the respective boxes as can be seen from **Fig. 5**. In order to avoid the negative effect of closed gaps, we installed spacers between pallets and wall in the subsequent tests.

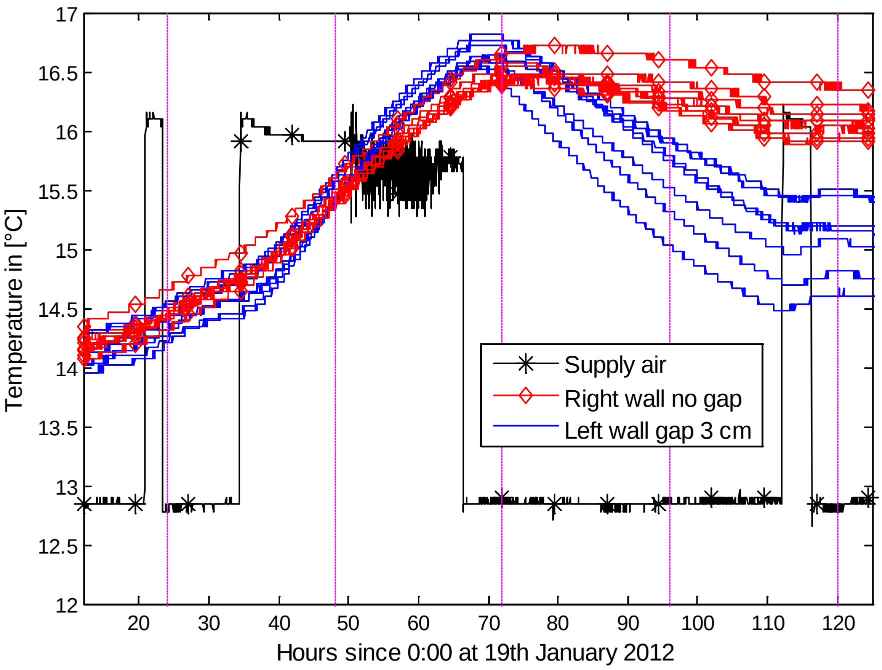

Fig. 5: Measured temperature in boxes at walls (no gap, 3 cm gap). Test January 2012.

4.1. Improving air flow through the boxes

The second approach to improve the cooling of the bananas is to enable better air flow through the boxes. Since the middle of 2012 Dole uses boxes with 8 additional holes at 4 edges of the box with 3.5 cm diameter, the so called Score Vents (**Fig. 6**). Unfortunately we had only one test during which both types of boxes had been in the same container. The k_M values were compared in pairs for boxes in similar positions, e.g. towards wall or toward mid container. The boxes with Score Vents showed a 14.8% ± 9.2% higher k_M value. The test data clearly verify the advantage of the Score Vents, but could not be used for an exact quantification due to the high standard deviations and the limited data size of only 5 pairs of boxes equipped with sensors.

Fig. 6: Score Vent boxes

During the last sea transportation test in November 2012 we modified the packing of the bananas inside the boxes in order to enable a higher air flow through the boxes. The boxes with standard packing had an average k_M value of 0.687±0.127. For the improved packing the k_M value increased by 13.7% to 0.780±0.104. The advantage of better cooling has to be balanced with the loss of packing volume per box by 4%. Details about the new packing scheme will be published soon.

Compared to the first sea transportation test from 2011, the k_M value could be increased by almost 50% from k_M =0.524 to k_M =0.780. The advantage can be attributed to different measures such as spacers between pallets, Score Vents and improved packing, although it is hardly possible to quantify the effect of single measures.

5. Container ripening

Bananas are transported ‘green’ from Central America to Europe. Ripening is triggered ashore in the destination countries by gassing with ethylene in special ripening rooms. The ripening process requires between 5 and 7 days in addition to the transport duration of 14 days.

Ripening ‘offshore’ during transport in the container would not only save time, but also reduce costs for warehouses ashore. The requested volumes for ‘ripe’ bananas by retailers are evenly distributed over all days of the week, whereas deliveries from Central America arrive only once per week. If the ripening process is split into a period offshore and a period ashore, the containers on a ship can be assigned to groups, in which the ripening process is initiated at different days to exactly meet the market requirements.

We carried out two tests for container ripening at the Dole branch in Stelle, Germany in August and December 2012, subsequent to a transport test from Costa Rica. Because of the lower mains voltage (405 Volt versus 440 Volt) and frequency (50 Hz versus 60 Hz) the air flow generated by the cooling unit was slightly lower than during sea transportation. This was compensated by reducing the number of pallets left in the container for the ripening test to 8 pallets.

During the first test in August we used boxes with Score Vents plus spacers at the pallet corners. The set point was reduced to 13.3 °C after the ethylene treatment. The test had to be stopped after 5 days because the unit was no longer capable of controlling the increase of temperature (**Fig. 7** top left) and a critical threshold of 18°C was almost reached. The generated ripening heat P_{Resp} was obviously larger than the amount of heat removed by cooling. For a detailed analysis we recalculated P_{Resp} from the measured temperature curves.

During transport, the respiration heat depends exponentially on temperature and a proportional factor k_P as in Eq. (2). After ethylene treatment, respiration heat increases with the time according to the progress of the ripening process and can therefore not be calculated by Eq. (2). But Eq. (5) provides another way to calculate the amount of generated heat. ΔU_{Therm} can be calculated by the differential of the temperature over time function. If k_M was already estimated during the preceding transport, P_{Cool} can be calculated according to Eq. (4). Instead of numerical differentiation and use of the approximation in Eq. (4), we applied a Kalman filter to the full model in **Fig. 2** to achieve higher accuracy. The respiration heat in the lower part of **Fig. 7** was calculated by this approach. Owed to limited space the details of the Kalman filter cannot be described here.

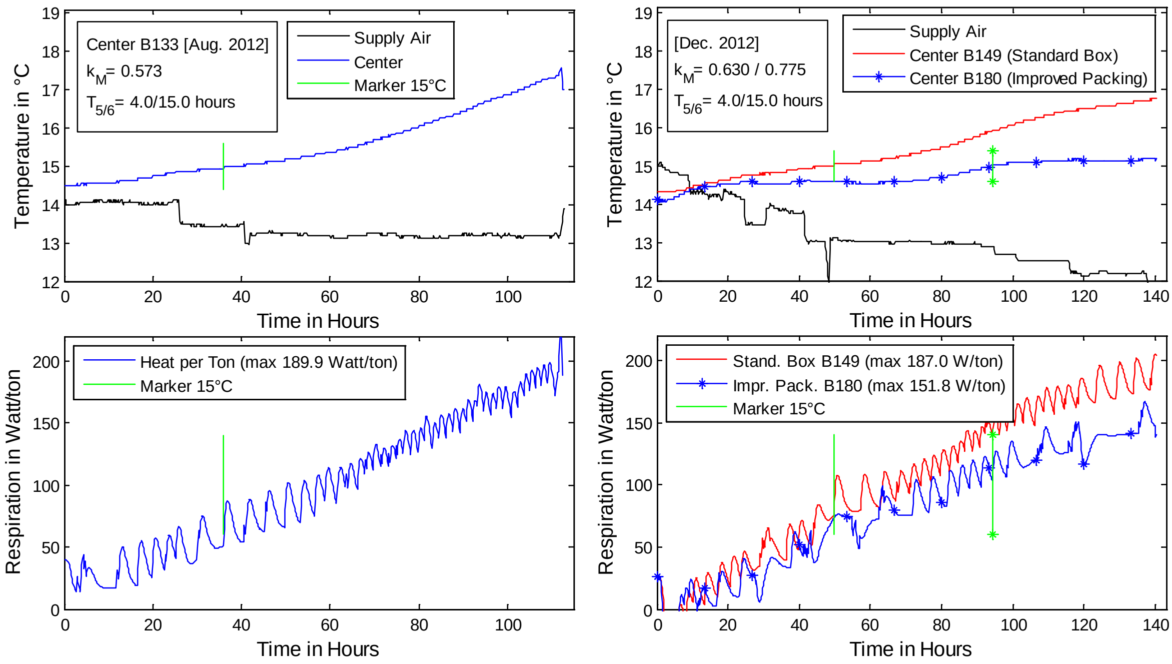

Fig. 7: Temperature during ripening (top), first test with unstable temperature development (left) and repeated test with lower set point and improved packing (right). The lower diagrams show the respiration heat calculated by the Kalman filter.

Fig. 7 demonstrates the crucial problem of container ripening. The bananas can achieve a state within a few days, at which the cooling unit is no longer capable to remove the generated heat. During normal 'green' transport conditions, between 16 and 50 W/ton are generated by biological activity. **Table 1** gives example values based on the estimated k_P parameters during 3 experiments. The heat generation during ripening was estimated by the Kalman filter as shown by the green markers in **Fig. 7**. At 15°C, between 70 and 115 W/ton are generated during ripening, which is between 2.2 and 3.6 times higher than under typical transport conditions with modified atmosphere. If the temperature increases by 2°C, the generated heat almost doubles to a value between 185 and 210 W/ton.

Table 1: Respiration heat under different atmospheric conditions and during ripening

Condition	**Test**	$\mathbf{k_P}$	$\mathbf{P_{Resp}(15°C)}$
Controlled atmosphere CO_2 = 4.5%, O_2 = 3%	Mar. 2011, Offshore	0.0139	16 W/ton
Modified atmosphere CO_2 = 2%, O_2 = 19%	Jul. 2012, Offshore	0.0280	32 W/ton
No atmosphere control	Jan. 2012, Ashore	0.0434	50 W/ton

Condition	**Test**	***T***	$\mathbf{P_{Resp}(\mathit{T})}$
Ripening after gassing with ethylene	Aug. 2012, Ashore	15°C	70 … 115 W/ton
		17°C	185 …210 W/ton

CO_2-production of ripening bananas rises up to 280 mg/(kg·h) at T=20°C which is equivalent to 830 W/ton [Gro04 and Ker04]. Own laboratory tests resulted in a similar maximum value of 250 mg /(kg·h) at T=20°C equivalent to 740 W/ton.

During the test in August, cooling could only remove 70 W/ton for k_M = 0.573, which is too low to compensate for the ripening heat. After this test we started to search for further improvements of the air flow through the boxes, which resulted in modified packing of the bananas in the boxes. For a repetition of the test in December 2012, the boxes of two pallets were packed accordingly. Additionally, the set point was adjusted to lower values between 12.8°C and 12.2°C during the last 3 days of ripening. A further decrease of the set point over prolonged periods is not possible because of the risk of chilling injuries of the fruit.

In the boxes with improved packing the temperature hardly increased above 15°C (15.2°C±0.8°C, **Fig. 7** right). The process resulted in an even quality of the bananas with a level 3 degree of ripeness (more green than yellow), similar to the quality that is achieved in special ripening rooms. According to Eq. (4) cooling can remove 97 W/ton at 15°C with a set point of 13°C for the average k_M value of 0.780. For a set point of 12.5°C this value increases to 121 W/ton.

Due to the lower set point, the temperature increase in the pallets with standard boxes was also lower than in the previous test. However, at the end of ripening the temperature was with 16.9°C ±1.3°C far above the optimal value of 15°C. The bananas also showed a larger variation in the degree of ripeness between level 3 and 4.

6. Conclusions

The improvement of air flow conditions inside and outside the pallets is a crucial factor to improve the transport conditions of green bananas. The suggested measures can lead to an extension of green life from 11.5 to 14 days on average remaining when the ship arrives in Europe. The difference becomes even more significant, if time spans for harbour handling and road transports within Europe are taken into consideration. For example, if we consider total transport duration to the retailer's facilities of 20 days instead of only two weeks of ocean transport, the remaining shelf life shrinks to 5.5 or 8 days, respectively, which is equivalent to an improvement of 45%. If the remaining shelf life is known at arrival in Europe, containers with low shelf life can be assigned to priority handling and nearby customers.

Furthermore, improved cooling is a precondition for container ripening. Although, we proved by the test in December 2012 that ripening in the container is feasible, the process involves high risks. Slight losses of cooling performance or increases in biological activity can lead to an uncontrollable temperature rise. Therefore, it is necessary to monitor all containers during transport and exclude those from automated ripening, which have suboptimal cooling conditions. However, even if only 50% of a ship load is suited for container ripening, it can lead to large economical benefits. Shifting only part of the ripening process to the container offshore results in more flexibility to meet market requirements and reduces the risk of uncontrollable temperature increase.

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