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FOOD SCIENCE AUSTRALIA

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INFLUENCE OF ELECTRICITY LOAD SHIFTING STRATEGIES ON CONTROLLED ATMOSPHERE STORED APPLES

Report for:

Horticultural Australia Limited

&

Batlow Fruit Co-op

HAL project number AP06063 (May 2008)

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The purpose of this work is to study the feasibility of reducing energy costs during controlled atmosphere storage of apples through the application of load shifting strategies with no significant influence on apple quality.

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INFLUENCE OF ELECTRICITY LOAD SHIFTING STRATEGIES ON CONTROLLED ATMOSPHERE STORED APPLES

1.0 MEDIA SUMMARY

This work investigates and proposes a cost energy saving scheme during controlled atmosphere (CA) storage of apples consisting of applying load shifting strategies. The proposed scheme consists of using electricity during periods of low tariffs (usually during the night), while avoiding electricity usage at periods of high tariffs (peak and shoulder hours). The application of such strategies will reduce energy costs but results in temperature oscillations within the store which could result in more rapid quality loss of the fruit. This study experimentally determined the influence of oscillating temperatures during controlled atmosphere storage on the quality of five apple cultivars: 'Braeburn', 'Fuji', 'Granny Smith', 'Pink Lady™' and 'Royal Gala'. The study shows that temperature oscillations of up to 4°C ± 2°C did not result in increased quality loss for, 'Royal Gala', 'Fuji' and 'Granny Smith' cultivars in comparison to fruit stored at 0.5°C ± 0.3°C and within the recommended shelf life. Oscillations greater than the control (0.5 ± 0.3°C) caused 'Granny Smith' to be significantly less firm at 330 days after harvest, but this could be attributed to an unexpected increase in the firmness of the control batch rather than a reduction of the actual firmness caused by higher temperature oscillations. 'Braeburn' and 'Pink Lady' can reach a maximum temperature of 2.75°C ± 1.25°C (T2) without resulting in reduced apple quality. Based on this, an energy saving scheme consisting of turning off the refrigeration power during peak hours was proposed for Batlow coolstores. This system can reduce the cost of energy during the months of operation after reaching the lowest storage temperature. The cost of energy could be reduced by about 45% during that period enhancing the profitability of horticultural industries. However, it is important to clarify that the proposed scheme is specific for Batlow Co-op therefore other industries should determine the specific details of the power interruptions (mainly time and duration of the power interruptions) that allow temperature oscillations on the range that do not affect the quality of the apples.

2.0 TECHNICAL SUMMARY

This work investigates the effect of temperature oscillations on the quality of apples stored in controlled atmosphere conditions aiming to reduce the cost of coolstorage by applying load shifting strategies. Load shifting entails the use of electricity during periods of low tariffs (usually during the night), while avoiding electricity usage at periods of high tariffs. It is expected that temperature oscillations produced as a consequence of load shifting strategies may result in more rapid quality loss of the fruit. However, recent developments indicate that the quality changes of fruit stored under controlled atmospheres may be negligible. This study has two main objectives: firstly, to experimentally determine the influence of oscillating temperatures during controlled atmosphere storage on the quality of five apple cultivars: 'Braeburn', 'Fuji', 'Granny Smith', 'Pink Lady™' and 'Royal Gala'; secondly, to monitor temperature and humidity oscillations in an industrial store room (at Batlow Fruit Co-op) subjected to power interruption. The aim was to determine temperature oscillations and temperature profiles after interrupting the refrigeration system. A mathematical model was also implemented as a tool to predict temperature changes and to define a load shifting strategy. Finally, energy consumptions characteristics at Batlow Co-op coolstores are monitored, and the collected data was used to predict the financial and energy consumptions benefits from the proposed load shifting strategy.

In the first part of the work, the effect of four different temperature oscillations (0.5 ± 0.3°C, 1.6°C ± 0.4°C, 2.75°C ± 1.25°C, 4°C ± 2°C) on the quality of five commercial apple cultivars was experimentally investigated. Apples stored in controlled atmosphere conditions (2 kPa O_2, 1 kPa CO_2). Changes in weight loss, firmness, external colour (hue angle) and incidence of decay, shrivel, scald, and internal browning were assessed on four removals from storage. The study shows that temperature oscillations of up to 4°C ± 2°C did not result in increased quality loss for 'Royal Gala', 'Fuji' and 'Granny Smith' cultivars in comparison to fruit stored at 0.5°C ± 0.3°C and within the recommended shelf life. Oscillations greater than the control (0.5 ± 0.3°C) caused 'Granny Smith' to be significantly less firm at 330 days after harvest, but this could be attributed to an unexpected increase in the firmness of the control batch rather than a reduction of the actual firmness caused by higher temperature oscillations. 'Braeburn' and 'Pink Lady' can reach a maximum temperature of 2.75°C ± 1.25°C (T2) without resulting in reduced apple quality. These results indicate that significant energy cost savings may be achievable in controlled atmosphere apple stores through the application of load shifting strategies with no significant influence on apple quality for most of the studied apple cultivars.

The temperature monitoring of the coolstore at Batlow during the power interruption showed a maximum temperature increase at the top of room while the average temperature changes on the middle and bottom of the room are insignificant. The average temperature of the top apples and the air in the headspace increased only 0.7°C and 1°C respectively after 19 hours of power interruption. The top of the coolstore is the place were apples warm up fastest given their proximity to the roof, which is exposed to direct solar radiation and where the warmer air inside the room moves by natural convection. The headspace between the top layer and the roof exhibits the highest air temperature increase. The temperature of buried apples under the top layer only increased 0.3°C during the power disruption.

A mathematical model that predicts the average temperature of the apples during storage was proposed. The model predicts that the temperature of the apples will increase only 0.4°C when turning off the refrigeration system during peak and shoulder hours. However, it must be taken into account that the model under-predicts the temperature of the apples at the top layer closer to the roof. The actual increase could be higher on a hot summer day. It is important to clarify that the model is specific to Batlow coolstores and that cool-stores should adjust the constants of the model or monitor temperature changes in their rooms under power-off conditions in order to accurately determine or predict temperature changes.

Finally, an energy saving scheme consisting of turning off the refrigeration power during peak hours was proposed for Batlow coolstores. This system can reduce the cost of energy during the months of operation after reaching the lowest storage temperature. The cost of energy could be reduced by about 45% during that period enhancing the profitability of horticultural industries.

3.0 INTRODUCTION

Apple quality attributes, such as firmness and colour, change during refrigerated storage as part of normal metabolism of the product. In the commercial environment it is common practice to apply controlled atmospheres (CA) to apples that are to be stored for extended periods of time. Rates of firmness change, and other quality attributes, slow down by storing the fruit in low oxygen (O_2) levels (Drake, 1993; Hertog et al., 2001; Johnston, 2001; Drake et al., 2002).

In recent times, energy use and costs have become a major global issue to all industries. One method of significantly reducing energy costs is load shifting. Load shifting entails the use of electricity during periods of low tariffs (usually during the night), while avoiding electricity usage at periods of high tariffs. A recently published Australian case study with controlled atmosphere apple cold stores indicated that up to 40% of refrigeration energy costs could be saved by strategies that induced a 0.3°C daily temperature swing within the store (Smale and East, 2007). These potential savings are counterbalanced by the requirement to maintain temperature within the store in order to provide the function of maintaining fruit quality.

Temperature is a major factor in maintaining quality in postharvest systems, and as such, it would be expected that oscillations in temperature, which expose fruit to period of higher then optimal temperature would result in more rapid quality loss. However, closer examination of the documented responses of fruit products to controlled atmospheres, suggests that in the controlled atmosphere environment, changes in quality of fruit may be negligible. Studies in which fruit stored at different but constant gas conditions show the ability of CA to at least partially negate the effects of temperature on fruit physiology for tomatoes, apples and pears (Andrich et al., 1998; de Wild et al., 2003; Jobling et al., 2003; Sanders and de Wild, 2003). These recent developments pave the way to explore opportunities to save energy costs through allowing temperature oscillations during the storage of apples in order to use less power during peak hours. Thus, the present work studies firstly the effect of temperature oscillations during CA storage on the quality of five apple cultivars: 'Royal Gala', 'Braeburn', 'Fuji', 'Granny Smith' and 'Pink Lady'; and secondly, the possibility of implementing an energy saving strategy by allowing temperature oscillations in industrial cold store rooms during the CA storage of apples.

4.0 METHODOLOGY

The project was divided into three complementary activities that allow firstly, quantifying the effect of oscillating temperature regimes on apple quality; secondly, monitoring temperature gradients during an interrupted refrigeration operation in an industrial cold room (Batlow Fruit Co-op); thirdly, developing a temperature and humidity mathematical model that allows predicting fruit temperature changes when turning on and off the refrigeration system; and finally, monitoring the energy consumption characteristics of the Batlow Co-op cool-store in order to estimate the possible financial and energy consumption benefits from the changes on the operating strategies of the refrigeration system.

The three main activities are:

- Measurement of temperature oscillation effects on the quality of apples
- Measurement and prediction of temperature and humidity gradients
- Proposal for energy saving at Batlow Fruit Co-op

Each one of these activities, its methodology and results will be discussed below

5.0 MEASUREMENT OF TEMPERATURE OSCILLATION EFFECTS ON THE QUALITY OF APPLES

5.1 Methodology

A set of apple storage experiments was conducted at Food Science Australia. Apples were supplied by Batlow Fruit Co-op and delivered via Flemington Markets to Food Science Australia, North Ryde where the experiments took place from 10th April 2007 to 20th February 2008. The experiments were set up to test the 5 following apple cultivars:

- 'Royal Gala'
- 'Fuji'
- Braeburn
- 'Granny Smith'
- 'Pink Lady'™

Table 1 shows the harvest date and pre storage treatments of the apples sourced from Batlow (NSW, Australia) in the 2007 harvest. All fruit from each variety were of mixed size and stored in a single 300kg wooden bin during prior storage and transport. Fungicide treatments (Carbendazine and Iprodione) were applied to some cultivars. Fruit were transported from Batlow to North Ryde, Sydney overnight on Wednesday 11th April 2007. On arrival at North Ryde on the 12th of April, fruit from each cultivar were sorted into 64 bags of 25 apples, with those apples of unusual size and shape, or observed damage to the skin discarded. Upon completion of sorting, each bag of apples was weighed prior to allocation into one of 16, 60L barrels (for each cultivar). Each barrel contained 4 bags (100 pieces) of fruit with 4 barrels being assigned to each temperature treatment. 100 remaining apples were stored at 20°C overnight for quality assessment on the 20th April 2007.

Cultivar	'Royal Gala'	'Braeburn'	'Fuji'	'Granny Smith'	'Pink Lady'
Harvest Date	20th February	10th April	11th April	27th March	11th April
Pre-storage treatments	None	DPA, Calcium, Fungicide	Fungicide	DPA, Fungicide	None
Storage at Batlow prior to FSA	0.5°C CA	None	None	0.5°C	None

Table 1. Harvest dates and pre-storage treatments of the apples sourced by Batlow.

All apple cultivars were stored under CA conditions of 2% oxygen (O_2) and 1% carbon dioxide (CO_2). Each cultivar was subjected to four treatments of temperature oscillations:

- T1: 4°C ± 2°C
- T2: 2.75°C ± 1.25°C
- T3: 1.6°C ± 0.4°C
- T4: 0.5°C ± 0.3°C (Control treatment)

Temperature treatments were established by creating four 1m wide x 2m high x 2m long rooms from 2" polystyrene, inside a 40' refrigerated container. Fruit temperatures were monitored on-line using type-T thermocouples and a Grant Squirrel data logger. Heaters were placed inside 3 of the rooms and controlled to turn on and off from measured fruit temperature inside the room. Cooling to all rooms was provided by the refrigerated container (set at 0.5°C). Each of the treatment rooms contained 20 barrels of apples, 4 for each cultivar. Figure 1 shows a typical temperature profile for each of the four temperature treatments. As seen in the figure, higher temperature oscillations exhibit longer times to complete a cycle because it takes longer to raise the temperature to higher values. However, this represents the real case in a cold room where it will take longer to warm up the room to higher temperatures after turning the refrigeration system off.

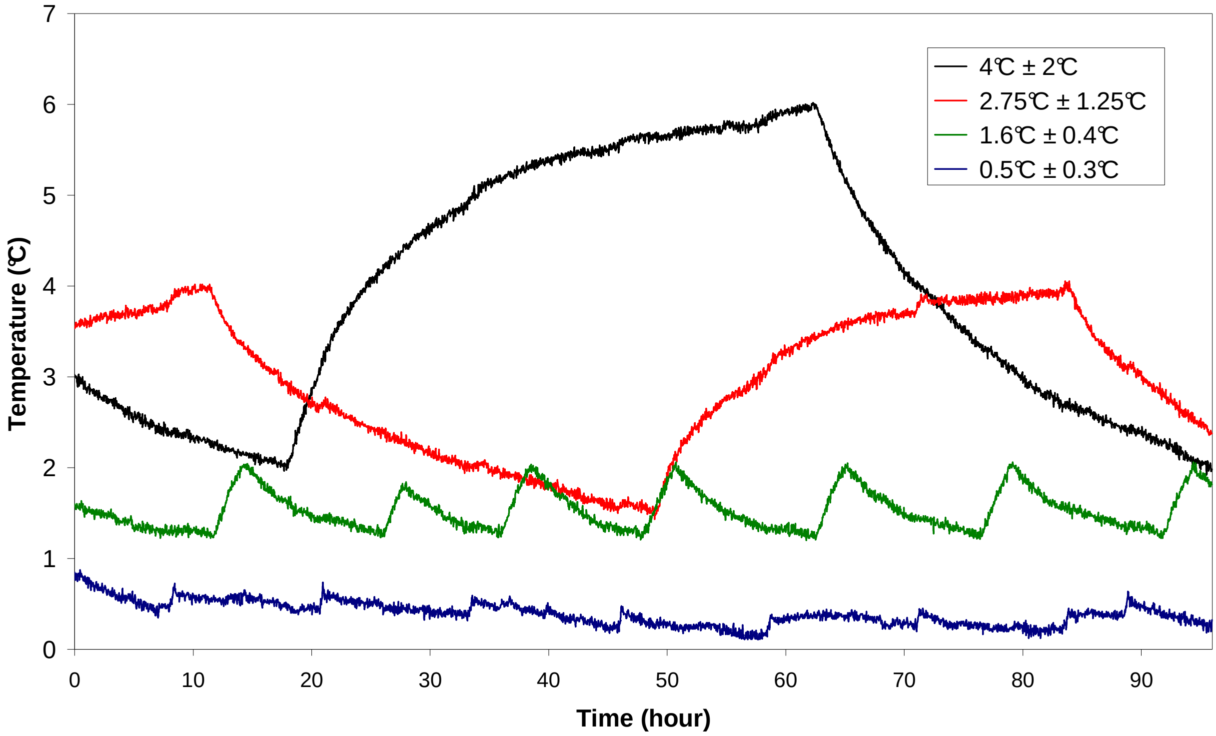


Figure 1. Typical temperature oscillation profile for each of the four temperature treatments.

CA atmospheres were established in every barrel with use of a centralised flow through system (Figure 2). Nitrogen (N_2) was supplied at 24L.min^{-1} as checked by the flow-rate from individual barrel tubes (300mL.min^{-1}). Air (as a source of oxygen) and CO_2 was mixed with this N_2 to a final atmosphere of 2% O_2 and 1% CO_2 (with the remainder being N_2) as measured when sampled at sample point A. A few barrels contain sample point B which provides an opportunity to sample in-barrel gas mixtures.

	'Royal Gala'		Braeburn		'Fuji'		'Granny Smith'		'Pink Lady'	
	Date	**Days**	**Date**	**Days**	**Date**	**Days**	**Date**	**Days**	**Date**	**Days**
Harvest	20/02/2007	0	10/04/2007	0	11/04/2007	0	27/03/2007	0	11/04/2007	0
Initial analysis	20/04/2007	59	20/04/2007	10	20/04/2007	9	20/04/2007	24	20/04/2007	9
1st Pull	21/06/2007	121	18/07/2007	99	25/09/2007	167	27/09/2007	184	26/09/2007	168
2nd Pull	**19/07/2007**	**149**	**21/09/2007**	**164**	23/10/2007	195	23/11/2007	241	22/11/2007	225
3th Pull	21/08/2007	182	19/10/2007	192	**21/11/2007**	**224**	**24/01/2008**	**303**	**25/01/2008**	**289**
4th Pull	20/09/2007	212	20/11/2007	224	19/12/2007	252	20/02/2008	330	21/02/2008	316

Table 2. Schedule and timing of the quality experiments.

Quality measurements were set up to conduct four sample withdrawals of each cultivar at each temperature treatment during the period of the storage. Each sample withdrawal consisted of 4 bags of apples containing approximately 25 apples each. Table 2 shows the measurement schedule for each cultivar. ‘Granny Smith’ and ‘Pink Lady’ were stored for significantly longer time than other cultivars due to their inherently longer storability. The second or third sample withdrawal of each cultivar corresponded to the suggested shelf life as advised by Batlow. These samples appear underlined in table 2.

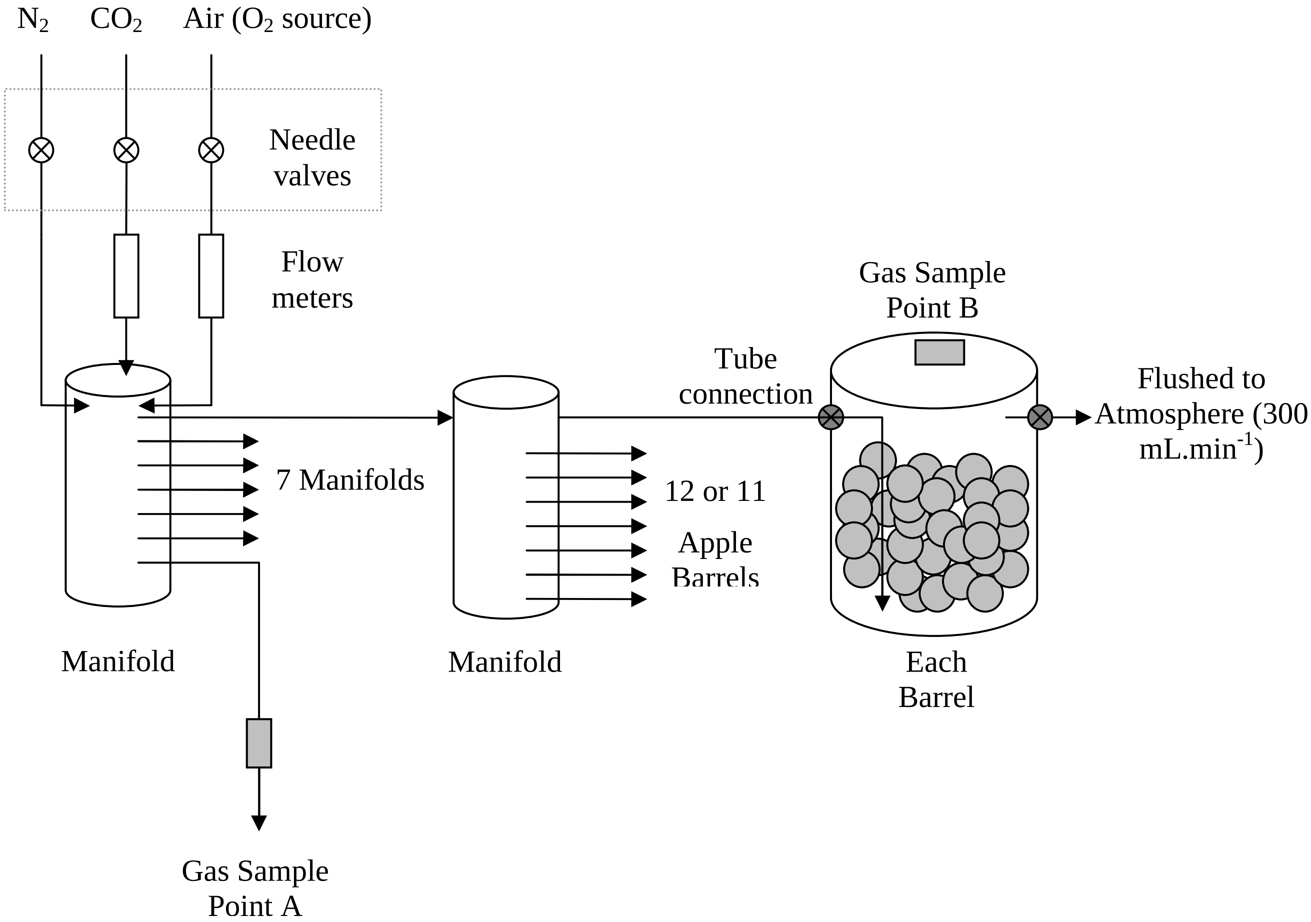


Figure 2. Centralized Control Atmosphere system.

The quality assessments consisted of the following steps:

1. Each of the bags of fruit was weighed before removing from the container (to avoid condensation).
2. The fruit was allowed to warm up to 20°C overnight in order to evaporate any condensation and to eliminate influence of temperature on colour and firmness measurement.
3. The fruit was given a visual assessment of shrivel, rots and scald, recording their presence.
4. Determination of the colour of the apple by taking a digital photograph of the “greenest side” of every apple - the data was then analysed by a Computer Vision System (CVS)
5. The firmness of each fruit was measured with a HortPlus penetrometer.
6. The fruit was cut in half and counts taken of the incidence of internal browning.

5.1.1 Weight measurement

Each bag of 25 apples was weighed prior to and after storage with a Precisa 30000D electronic scale (accuracy 0.1g). Average difference in weight of the 4 bags provides an estimate of the weight loss during the storage period.

5.1.2 Firmness measurement

The firmness was assessed with a HortPlus electronic penetrometer (HortPlus, New Zealand) which measures the peak force required to penetrate the peeled surface at the equator of an apple with an 11 mm circular (Effigi) probe to a distance of 8 mm. Before measuring the firmness, the apples were equilibrated to 20^{o}C in order to remove the influence of treatment temperature on measurement. On each measurement occasion, the flesh firmness was measured at two locations, and the average of the resulting 100 measurements per temperature treatment was used for analysis. Force measured by the load cell within the penetrometer was calibrated against calibrated scales by applying a force between the two devices. Settings for the penetrometer were:

- Minimum firmness threshold: 4
- Calibration offset: -6.15
- Calibration multiplier: 0.0524
- Yield point: -0.1

5.1.3 Colour determination

Our team at FSA has recently developed a method to capture the external colour of fruits with a computer vision system (CVS). The CVS provides an accurate method to measure hue angle and chroma from solid objects with smooth surfaces, and has been tested to measure the colour changes of ‘B74’ mangoes as a function of storage temperature (Kang et al., 2008). In these experiments the colour of each apple was measured with the CVS on the “greenest” side of the fruit. The CVS consists of a standard illuminant, a camera for image acquisition and software to process the image. The computer vision system used in this study consisted of two fluorescent lamps (TL-D Delux, 18W/965, Philips) that were mounted at the top corners of a light box, parallel to each other, placed to illuminate the product at an angle of 45° (Figure 3). These lamps were chosen to set the colour temperature to D65 (6500K), a common light source used in food engineering. A colour digital camera (Olympus SP-500 UZ) captured images through a hole on the top surface of the light box. Colour measurements are reported in the CIE $L^*a^*b^*$ colour scale or as hue angles. The images were processed on a PC to give hue angle data for each pixel of each fruit.

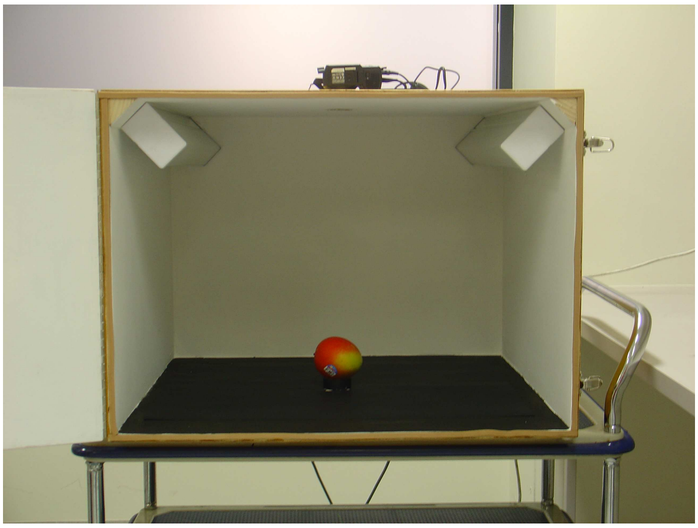


Figure 3. Computer vision system equipment used for external colour measurements.

5.1.4 Shrivel, decay and internal disorders

Apples are prone to skin shrivel during prolonged storage in air. This skin disorder is usually associated with dehydrated fruit which tend to be tough and rubbery compared with turgid fruit [4]. This skin disorder is more severe during storage in dry atmospheres. Figure 4 shows two examples of shrivel on ‘Pink Lady’ apples.

Figure 4. Shrivel on ‘Pink Lady’ apples.

Incidents of decay observed on the apples were caused by the fungi *Penicillium spp.* They are characterised as a soft watery brown spot which will rapidly enlarge when exposed to temperatures above 20°C. Eventually blue green fruiting bodies will appear on the lesion. Figure 5 shows two examples of decay in ‘Royal Gala’ apples.

Figure 5. Decay in ‘Royal Gala’ apples.

Storage scald is a diffuse browning of the skin of apples that only affects the skin. The discoloration is usually irregular in shape varying from light brown to dark brown [5]. The specific mechanism of scald development is unknown although it is believed to be induced by autoxidation products of α-farnesene and formation of free radicals [6]. This disorder is usually prevented or reduced with DPA and 1-MCP. Figure 6 shows two examples of scald in 'Granny Smith' apples.

Figure 6. Scald in 'Granny Smith' apples.

Internal browning of apples can appear as radial, diffuse or CO_2 browning and as also been known as Core flush in Australia. This disorder is exacerbated by high CO_2 concentrations in air or CA storage [7]. The causal mechanism for each type of browning is not fully understood. However, CO_2 and O_2 levels during prolonged storage are known to have an effect on the incidents of internal browning as are the growing conditions. Cultivars such as 'Cox's Orange Pippin', 'McIntosh', 'Granny Smith' and 'Pink Lady' apple are all prone to internal browning [8]. Figure 7 shows examples of internal browning, comparing two levels of severity (mild and severe browning) with an unaffected apple on the left hand side.

Figure 7. Internal Browning.

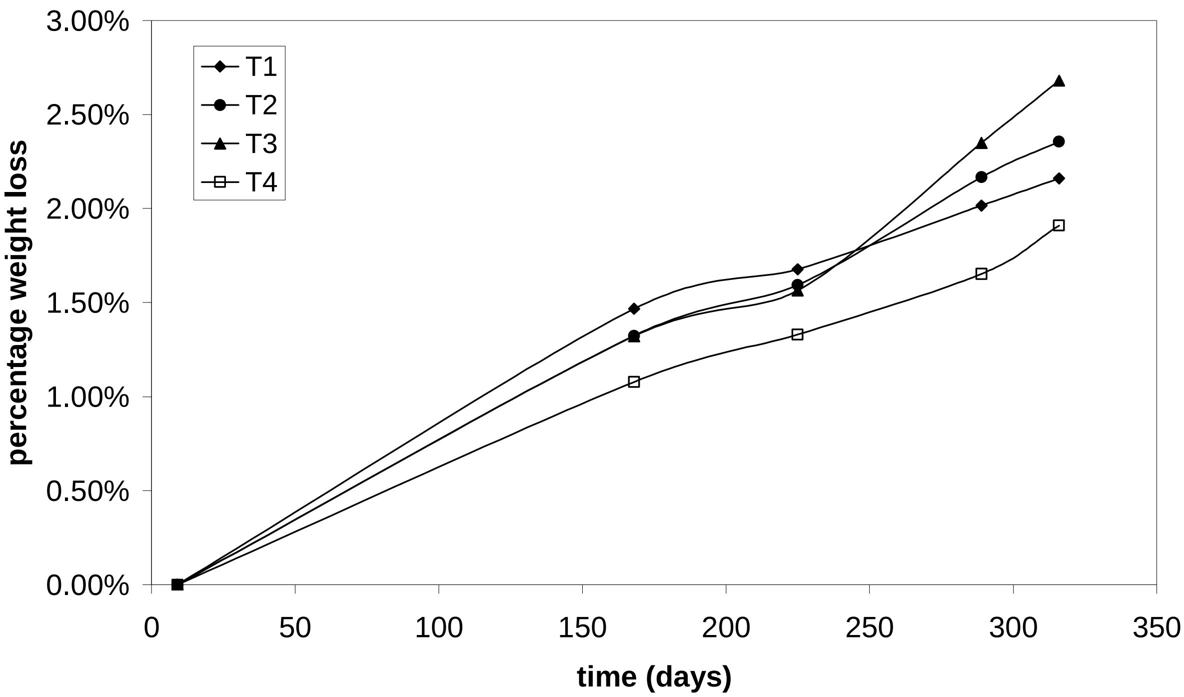
Incidence of internal disorders were counted in this work by visually inspecting the fruit subsequent to a single cut through the equator of the fruit. The internal browning was recorded as absence, mild browning and severe browning.

5.2 Results

5.2.1 Weight loss

Figure 8 shows the percentage of weight loss of 'Pink Lady' apples from the initial weight measurement on April 20, 2007. Looking at the figure it seems that the temperature treatments T1, T2 and T3 lost more weight than the control treatment T4. To verify this, the data was analysed via a one way analysis of variance (ANOVA) using a Dunnett's family error of 5%. This test allows comparing the average weight loss over time of each one of the temperature treatments with the control T4 without taking into account differences between all the other treatments for the four cultivars. Thus, Dunnett's analysis is more appropriate than Tukey's test. The statistical analysis was conducted with the software package MINITAB. Table 3 shows that of the 5 apple cultivars studied, three of the cultivars ('Braeburn', Granny Smith' and 'Pink Lady') were observed to lose weight at a significantly faster rate than the control (0.5 ± 0.3°C) at 4°C ± 0.3°C. Furthermore the 'Pink Lady' cultivar was found to particularly sensitive with all three oscillation treatments resulting in increased weight loss in comparison to storage at 0.5°C ± 0.3°C.

It would seem that weight loss may be the most likely reduction in quality from apple exposed to oscillating temperature conditions during CA storage, although the results generated for weight loss in this study are difficult to transfer to commercial scenarios due to the differences in which the CA was established in this study (a flow through system) to those in commercial practice (a closed system). Further studies of the movement of moisture in a commercial coolstore during load shifting strategies may elucidate the more likely commercial results.



- Figure 8. Percentage weight loss of 'Pink Lady' apples. T1: 4°C ± 2°C; T2: 2.75°C ± 1.25°C; T3: 1.6°C ± 0.4°C; T4: 0.5°C ± 0.3°C

Treatment	Weight Loss (%/day)				
	'Braeburn'	**'Fuji'**	**'Granny Smith'**	**'Pink Lady™'**	**'Royal Gala'**
T1: 4 ± 2°C	**0.0062***	0.0036	**0.0039***	**0.0065***	0.0068
T2: 2.75 ± 1.25°C	0.0056	0.0030	**0.0045***	**0.0046***	0.0061
T3: 1.6 ± 0.4°C	0.0058	0.0041	0.0036	**0.0044***	0.0072
T4: 0.5 ± 0.3°C	*0.0048*	*0.0044*	*0.0028*	*0.0034*	*0.0070*
$LSD_{0.05}$	0.0013	0.0017	0.0011	0.0009	0.0015

Table 3. One way analysis of variance (ANOVA) of the average weight loss over time using a Dunnett's family error = 5%. Values presented are average rates of up to 16 individual bags measured on four occasions during storage. Values for the control treatment are presented in italics while those values that are significantly different to the control are indicated with an * and are presented in bold.

5.2.2 Firmness

Figure 9 shows the firmness of 'Royal Gala' apples in the four temperature treatments. The firmness does not show a clear trend as a function of time. A one way ANOVA using a Dunnett's family error of 5% was also chosen to analyse the data, thus allowing comparison of each of the temperature treatments with the control T4 at each one of the four sample withdrawals. An example MINITAB analysis for 'Royal Gala' at time = 1 is shown below:

Results for: Firmness(time = 1)

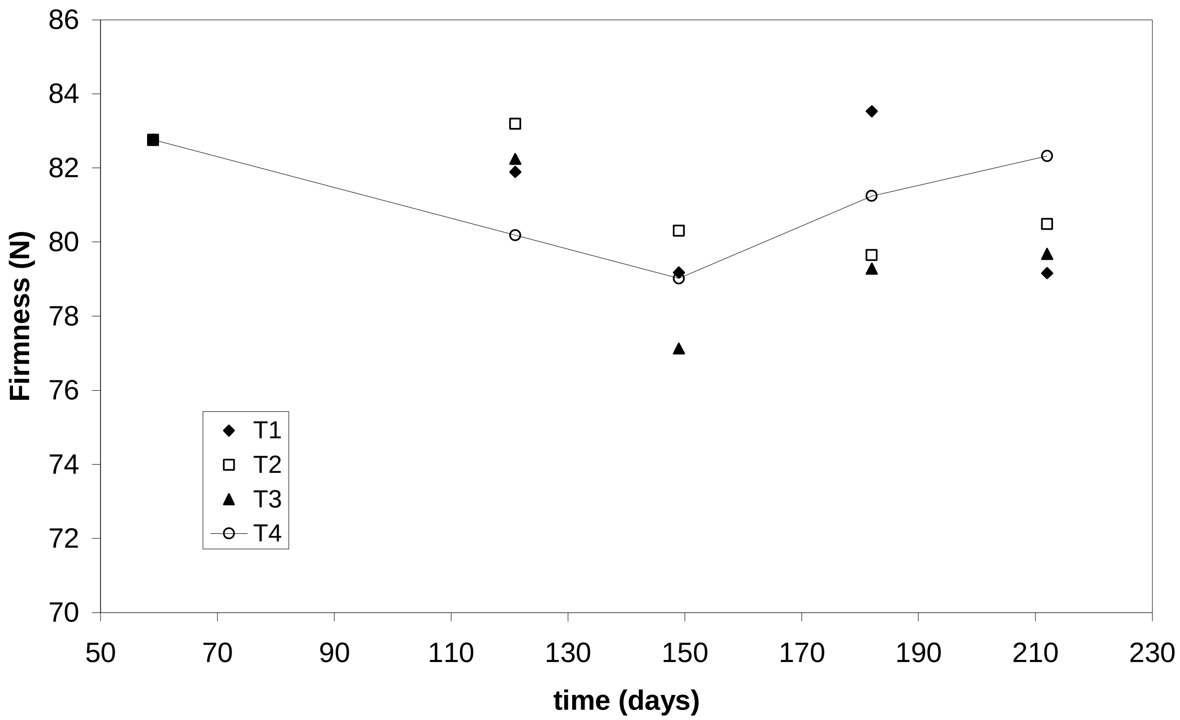
One-way ANOVA: Firmness versus Temperature

```
Analysis of Variance for Firmness
Source     DF        SS        MS        F        P
Temperat    3       981       327     2.57    0.053
Error     815    103845       127
Total     818    104826
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
1         202     81.89     11.05           (------*-------)
2         203     83.19     10.84                 (-------*-------)
3         205     82.25     11.56             (------*-------)
4         209     80.18     11.67  (-------*-------)
                                   -------+---------+---------+---------
Pooled StDev =    11.29                80.0      82.0      84.0

Dunnett's comparisons with a control

    Family error rate = 0.0500
Individual error rate = 0.0190

Critical value = 2.35

Control = level (4) of Temperat

Intervals for treatment mean minus control mean
```

```
Level         Lower     Center      Upper -----+---------+---------+---------+--
1             -0.91       1.71       4.33 (-------------*------------)
2              0.40       3.01       5.63        (------------*------------)
3             -0.54       2.07       4.67   (------------*------------)
                                          -----+---------+---------+---------+--
                                               0.0       2.0       4.0       6.0
```

$LSD_{0.05} = 2.62$

The change in signs between the lower and upper of the intervals above indicates that it is not possible to distinguish between any of the treatments and T4. The $LSD_{0.05}$ (least significant difference) indicates the minimum average difference to be able to see statistically significant differences on the test. Table 4 shows the results of the statistical analysis for each cultivar at each time. The first column shows the average firmness. The second (Differences), shows the result of the one way analysis of variance, when asking whether there are differences in firmness between each of the temperature treatments compared with the control. The third column (reduction), answers the question whether there is a reduction in firmness compared with the control T4. The table shows that there were no differences for most of the cases, and when there were differences, there was not a reduction in firmness, which indicates that the apples under temperature oscillations did not degrade faster than the control treatment. The only significant reduction in firmness of 'Royal Gala' appears at T1 and time = 4, which is after the recommended shelf life for that cultivar and only under the highest temperature oscillation treatment. 'Granny Smith' showed a significant firmness decrease for all the temperature treatments at time = 4 but this reduction only happened after the recommended shelf life for that cultivar (time = 3). Besides, the average firmness of T4 for both cultivar ('Royal Gala' and 'Granny Smith') at time = 4 is higher than at previous times suggesting that the result of the test can be explained by an unexpected increase in the firmness of the control batch rather than a reduction of the actual firmness caused by higher temperature oscillations, which could be attributed to normal physiological variability . The $LSD_{0.05}$ is reported at bottom of each test.



- Figure 9. Firmness of 'Royal Gala' apples. T1: 4°C ± 2°C; T2: 2.75°C ± 1.25°C; T3: 1.6°C ± 0.4°C; T4: 0.5°C ± 0.3°C.

'Royal Gala'												
	Time 1 = 121 days			Time 2 = 149 days			Time 3 = 182 days			Time 4 = 212 days		
Tem. T.	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction
T1	81.89	No	**No**	79.178	No	**No**	83.53	No	**No**	79.16	Yes	**Yes**
T2	83.19	Yes	**No**	80.307	No	**No**	79.65	No	**No**	80.48	No	**No**
T3	82.25	No	**No**	77.129	No	**No**	79.28	No	**No**	79.68	No	**No**
T4	80.18			79.018			81.25			82.33		
$LSD_{0.05}$			2.62			2.053			2.49			2.64
Braeburn												
	Time 1 = 99 days			Time 2 = 164 days			Time 3 = 192 days			Time 4 = 224 days		
Tem. T.	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction
T1	76.342	Yes	**No**	73.135	No	**No**	72.56	No	**No**	70.204	No	**No**
T2	75.625	No	**No**	75.797	Yes	**No**	75.077	Yes	**No**	73.017	No	**No**
T3	74.226	No	**No**	75.735	Tes	**No**	74.462	Yes	**No**	74.368	No	**No**
T4	73.899			73.236			72.089			72.216		
$LSD_{0.05}$			1.922			1.943			2.339			2.316
'Fuji'												
	Time 1 = 184 days			Time 2 = 241 days			Time 3 = 303 days			Time 4 = 330 days		
Tem. T.	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction
T1	64.78	No	**No**	67.18	No	**No**	65.26	No	**No**	67.95	No	**No**
T2	67.43	No	**No**	70.03	No	**No**	65.24	No	**No**	66.11	No	**No**
T3	66.98	No	**No**	69.02	No	**No**	65.34	No	**No**	68.67	No	**No**
T4	66.2			68.62			65.28			70.77		
$LSD_{0.05}$			2.51			2.63			2.47			2.8
'Granny Smith'												
	Time 1 = 184 days			Time 2 = 241 days			Time 3 = 303 days			Time 4 = 330 days		
Tem. T.	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction
T1	79.43	No	**No**	81.592	No	**No**	79.262	No	**No**	78.01	Yes	**Yes**
T2	81.566	Yes	**No**	79.616	No	**No**	79.551	No	**No**	80.04	Yes	**Yes**
T3	81.889	Yes	**No**	81.19	No	**No**	79.527	No	**No**	78.77	Yes	**Yes**
T4	79.423			80.452			80.118			82.6		
$LSD_{0.05}$			2.029			2.265			2.322			2.42
'Pink Lady'												
	Time 1 = 168 days			Time 2 = 225 Days			Time 3 = 289 days			Time 4 = 316 days		
Tem. T.	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction	Firmness	Differences	Reduction
T1	80.132	No	**No**	80.218	Yes	**No**	77.9	No	**No**	83.516	Yes	**No**
T2	80.239	No	**No**	78.786	No	**No**	77.193	No	**No**	81.247	Yes	**No**
T3	78.27	No	**No**	80.389	Yes	**No**	78.603	No	**No**	81.387	Yes	**No**
T4	78.413			76.711			77.053			78.255		
$LSD_{0.05}$			1.879			2.083			2.293			2.129

Table 3. One way ANOVA analysis of the firmness using a Dunnett's family error = 5% . T1: 4°C ± 2°C; T2: 2.75°C ± 1.25°C; T3: 1.6°C ± 0.4°C; T4: 0.5°C ± 0.3°C.

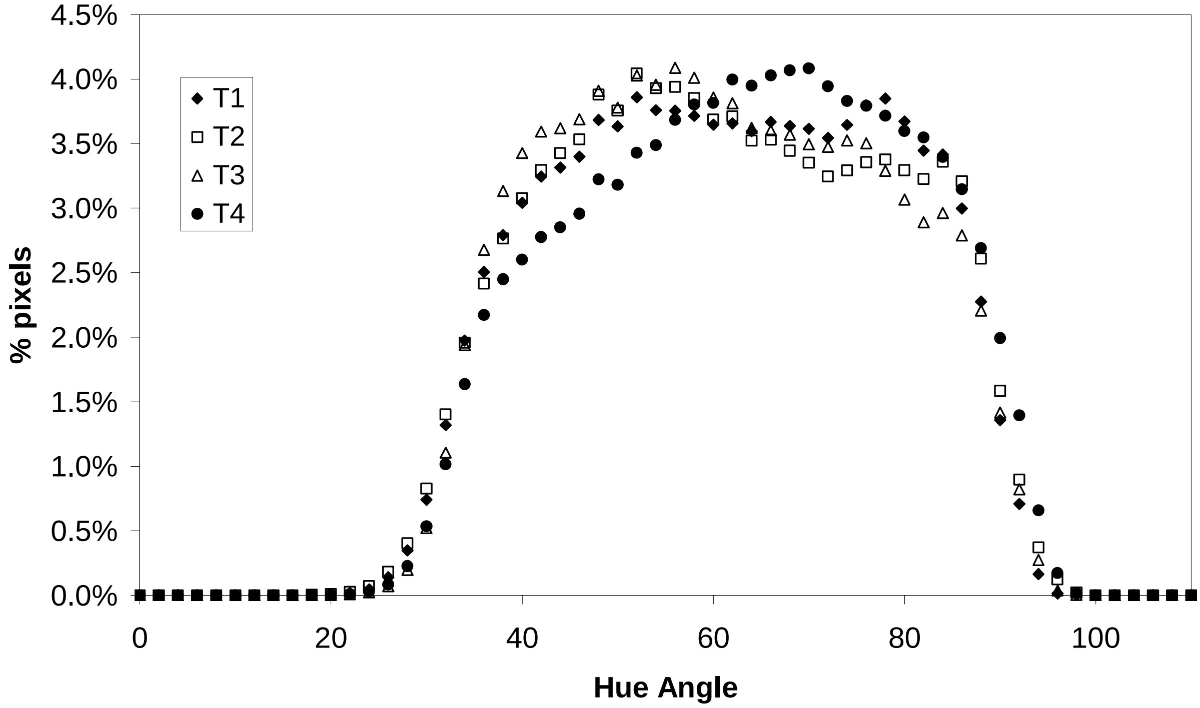


Figure 10. Hue angle pixel distribution of ‘Fuji’ apples at time =3. T1: 4°C ± 2°C; T2: 2.75°C ± 1.25°C; T3: 1.6°C ± 0.4°C; T4: 0.5°C ± 0.3°C.

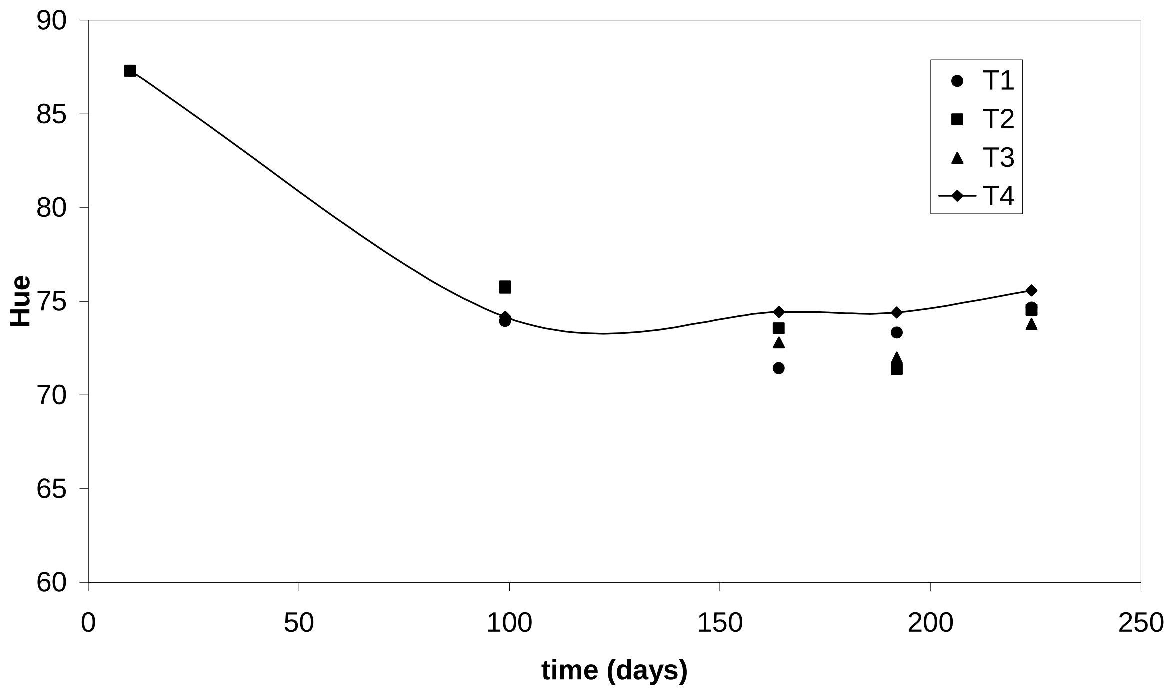


Figure 11. Hue angle vs. time for Braeburn apples. T1: 4°C ± 2°C; T2: 2.75°C ± 1.25°C; T3: 1.6°C ± 0.4°C; T4: 0.5°C ± 0.3°C.

'Royal Gala'												
	Time 1 = 121 days			**Time 2 = 149 days**			**Time 3 = 182 days**			**Time 4 = 212 days**		
Tem. T.	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**
T1	73.01	No	**No**	60.8	No	**No**	62.85	No	**No**	67.39	No	**No**
T2	75.9	No	**No**	62.79	Yes	**No**	64.2	No	**No**	65.51	No	**No**
T3	75.03	No	**No**	60.53	No	**No**	64.68	No	**No**	64.54	No	**No**
T4	76.48			57.15			66.24			63.96		
LSD0.05			3.77			4.21			3.89			3.77
Braeburn												
	Time 1 = 99 days			**Time 2 = 164 days**			**Time 3 = 192 days**			**Time 4 = 224 days**		
Tem. T.	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**
T1	73.917	No	**No**	71.33	No	**No**	73.36	No	**No**	74.536	No	**No**
T2	75.902	No	**No**	73.528	No	**No**	71.58	No	**No**	74.882	No	**No**
T3	75.934	No	**No**	72.713	No	**No**	71.78	No	**No**	73.544	No	**No**
T4	74.361			74.441			74.51			75.871		
LSD0.05			3.241			3.293			3.46			3.011
'Fuji'												
	Time 1 = 184 days			**Time 2 = 241 days**			**Time 3 = 303 days**			**Time 4 = 330 days**		
Tem. T.	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**
T1	59.61	No	**No**	58.913	No	**No**	61.466	No	**No**	60.744	No	**No**
T2	64.9	Yes	**No**	61.746	Yes	**No**	61.911	No	**No**	61.611	No	**No**
T3	62.33	No	**No**	58.444	No	**No**	61.053	No	**No**	61.542	No	**No**
T4	60.27			56.886			63.836			60.984		
LSD0.05			3.39			3.281			3.217			3.211
'Granny Smith'												
	Time 1 = 184 days			**Time 2 = 241 days**			**Time 3 = 303 days**			**Time 4 = 330 days**		
Tem. T.	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**
T1	97.682	No	**No**	97.739	No	**No**	96.859	No	**No**	96.686	No	**No**
T2	97.396	No	**No**	98.09	No	**No**	97.15	No	**No**	96.696	No	**No**
T3	97.44	No	**No**	97.795	No	**No**	96.477	No	**No**	96.934	No	**No**
T4	97.638			97.761			96.643			97.208		
LSD0.05			0.621			0.606			0.605			0.568
'Pink Lady'												
	Time 1 = 168 days			**Time 2 = 225 Days**			**Time 3 = 289 days**			**Time 4 = 316 days**		
Tem. T.	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**	**Colour**	**Differences**	**Reduction**
T1	74.1	No	**No**	68.61	No	**No**	72.69	No	**No**	68.91	No	**No**
T2	72.94	No	**No**	68.6	No	**No**	71.37	No	**No**	72.52	No	**No**
T3	67.7	No	**No**	71.18	No	**No**	68.27	No	**No**	69.11	No	**No**
T4	71.63			69.46			70.73			70		
LSD0.05			4			4.06			3.72			4.01

Table 4. One way ANOVA analysis of the colour (hue angle) using a Dunnett's family error = 5% . T1: 4°C ± 2°C; T2: 2.75°C ± 1.25°C; T3: 1.6°C ± 0.4°C; T4: 0.5°C ± 0.3°C.

5.2.3 Colour

The CVS provides information on the distribution of pixels as a function of the hue angle. Figure 10 shows 'Fuji' apples at time = 3 as an example. Hue angle was chosen to represent the colour of the apples given that it is the simplest single number that can describe the perceived change in colour of the fruit during ripening. Figure 10 accounts for the pixel distribution of the lot of 100 apples at each temperature treatment. This figure shows that distributions of hue angles for the four treatments are very similar. The average hue angle can be calculated from the figure as the pixel weighted average. Figure 11 shows the changes of the average hue angles with time showing an apparent reduction in hue angle for temperature treatments T1-T3 when compared with T4. However, this must be statistically tested via a one way ANOVA using a Dunnett's family error of 5% as done to the firmness before.

Table 4 shows the results of the statistical analysis when comparing treatments T1 to T3 with the control T4. The table shows that there are no significant changes in colour comparing treatments T1, T2 and T3 with the control T4 at any time for the five cultivars except for the second pull treatment T1 for 'Royal Gala'.

5.2.4 Shrivel, decay, scald and internal browning

The presence or absence of shrivel, decay and scald was recorded for each of the 100 apples at each sample withdrawal time and temperature treatment. The internal browning was recorded as absence, mild browning and severe browning. It is important to note that the worse-looking bags of apples, in terms of development of rots, where taken for analysis in each pull. This was in order to reduce infection of healthy apples. However, this procedure creates skewness on the data. Therefore, in order to reduce the skewness, the disorder data was summed over time. The final categorical data (total counts for scald, non scald, non browning, mild browning etc) was analysed by a Chi Square test, which is the appropriate statistical analysis to investigate the relationship between two or more classes or categories of variables.

	'Royal Gala'			Braeburn			'Fuji'			'Granny Smith'			'Pink Lady'		
	P-value	T. Treat.	Differences	P-value	T. Treat.	Differences	P-value	T. Treat.	Differences	P-value	T. Treat.	Differences	P-value	T. Treat.	Differences
BP Decay	0.626	T1-T4	**No**	0.969	**T2-T4**	**No**	0.189	T1-T4	**No**	0.565	T1-T4	**No**	0.526	**T2-T4**	**No**
Shrivel	0.421	T1-T4	**No**	NA	T1-T4	**NA**	0.169	T1-T4	**No**	NA	T1-T4	**NA**	0.000	T1-T4	**Yes**
Browning	0.597	T1-T4	**No**	NA	T1-T4	**NA**	NA	T1-T4	**NA**	0.936	T1-T4	**No**	0.172	T2-T4	**No**
Scald	Na	T1-T4	**NA**	0.282	T1-T4	**No**	NA	T1-T4	**NA**	0.801	T1-T4	**No**	0.567	T1-T4	**No**

Table 5. Chi Square analysis of the decay data. T1: 4°C ± 2°C; T2: 2.75°C ± 1.25°C; T3: 1.6°C ± 0.4°C; T4: 0.5°C ± 0.3°C.

Table 5 shows the results of the decay data. P-values higher than 0.05 indicates that there are no significant differences between the treatments. NA means that the test failed because the count was too small. This can be interpreted as no significant difference (very small or null count). The "T2-T4" term, highlighted in the table, shows that there is no significant difference between temperature treatments T2 to T4 but there are differences when incorporating T1 into the analysis. Thus T1, the highest temperature oscillation of up to 6°C, exhibits a faster decay in Braeburn and 'Pink Lady' cultivars than the other treatments. 'Pink Lady' also shows significant differences in shrivel but a close inspection of the data reveals that those differences only appear in the first of the series of four barrels for each temperature treatment. The shrivel of the 'Pink Lady' apples in these barrels can be explained by the low humidity of the CA gas entering the series of barrels. Subsequent barrels do not exhibit shrivel probably due to the increase in the humidity of the gas after absorbing the vapour produced by the respiration of the apples in the first barrel. Thus, the differences in shrivel can be attributed to the low humidity in the first barrels instead of temperature treatments.

5.3 Conclusion

- Based on the statistical analysis of firmness, colour, weight loss, and decay, it can be concluded that temperature oscillations of 4°C ± 2°C (T1) do not increase the rate of loss of quality during the tested storage times for 'Royal Gala', 'Fuji' and 'Granny Smith' within the recommended shelf life. 'Braeburn' and 'Pink Lady' can reach a maximum temperature of 2.75°C ± 1.25°C (T2) without increasing the loss of quality during storage. These temperature limits correspond to the temperature of the air around the apples during storage.
- It would seem that weight loss may be the most likely reduction in quality from apples exposed to oscillating temperature conditions during CA storage, although the results generated for weight loss in this study are difficult to transfer to commercial scenarios due to the differences in which the CA was established in this study (a flow through system) to those in commercial practice (a closed system).

6.0 MEASUREMENT AND PREDICTION OF TEMPERATURE AND HUMIDITY GRADIENTS

6.1 Methodology

Air temperature and humidity data were collected by placing sensors at the top of the bins while fruit temperatures were assessed by placing sensors inside apples at the top of the bins and under the top superficial layer. Special attention was paid to the top layer of bins because these fruit are subjected to both the highest temperature and lowest relative humidity during periods of no refrigeration. Temperature data was collected with TinyTag temperature loggers, while humidity data was collected with Hy-Cal Survivor II sensors (Honeywell, USA) logged with Eltek Squirrel dataloggers (Eltek, Ltd, Cambridge, UK).

Apples were stored in bins of 1.2 x 1.2 x 1 m in the cold room in figure 12. The numbers around the cold room represent the Tinytag dataloggers that recorded the external temperatures. The bins were arranged in the cold room following the pattern in figure 13. The bins were stacked 8 high except at the door way where they were stacked 4 bins high. The changes of orientation of the bins are indicated in the figure by change of direction of the numbers. Fruit and air temperatures and air humidity were collected in the CA room in a 3 dimensional grid pattern. Figures 14 to 18 show the locations of the sensors in the head space between the roof of the room and the bins, and the top of the horizontal layers 8, 6, 4 and 1 respectively.

The apples ('Pink Lady' cultivar) were stored in the room on the 24 April 2007. The refrigeration system was activated following a stepwise pull-down process as shown in figure 19. The temperature set-point of the room was initially reduced to 4°C, then to 2°C and finally to 1°C. The refrigeration system was turned off during 6-7 June 2007 in order to determine the impact of turning off the refrigeration system on the temperature profiles inside the cold room. The intervention was conducted as follows:

- At 11:05 am on 6 June 2007, the set point of the refrigeration system was changed from 0.9°C to -1°C, which meant that the refrigeration plant was always on after that change.
- At 2:05 pm on 6 June 2007 the power to the room was turned off.
- The power was turned back on at 9:05 am on 7 June 2007 (set point remained at -1°C)
- Finally the set point was changed back to 0.9°C at 2:05 pm on 7 June 2007.

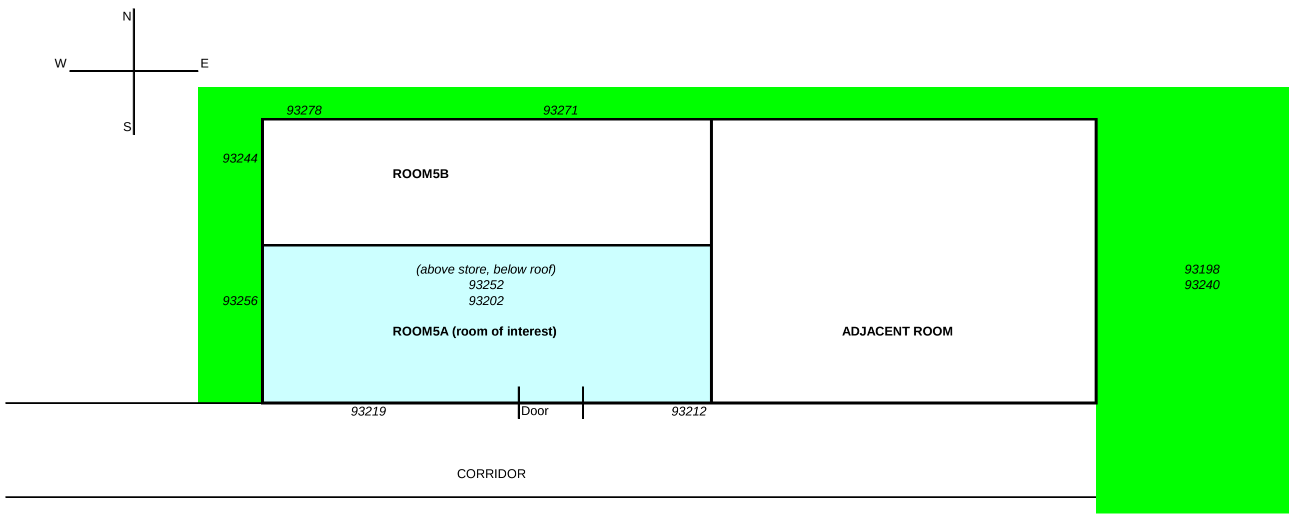


Figure 12. Map of the cold store room and position of the external temperature sensors.

6.2 Results

Figure 20 shows the temperature profiles of the apples at the top of the 8th layer. This is the level where apples warm up the fastest, given its proximity to the roof, which is exposed to direct solar radiation and where the warmer air inside the room moves by natural convection. The average temperature of these apples dropped from 1.5°C to 0.9°C after changing the set point of the refrigeration system from 0.9°C to -1°C. Then, after turning off the refrigeration, the temperature of the apples increased until it reached a maximum of 1.6°C (average temperature increase of only 0.7°C). After turning the refrigeration system back on, the temperature dropped to 0.8°C. Finally, fruit temperature slowly increased after changing the set-point back from -1°C to 0.9°C.

Figures 21 and 22 show the temperature profiles in the head space of the coolroom (between the top of the fruit and the roof), and in the air around the top layer of fruit, respectively. As expected, the temperature in that region exhibits the highest temperature oscillations cause by direct solar radiation on the roof and the movement of warmer air by natural convection as described above. The highest temperature increase registered by the sensor TC1 was 1.7°C but the average temperature increase in the headspace was only 1°C. Figures 23 and 24 show the temperature profiles in the fruit buried in the top layer and in the air besides the buried fruit respectively. Interestingly, the temperature of the apples only increased 0.3°C during the power disruption. Figures 25 to 27 show the temperature profiles in the air at the top of the bins in layers 6, 4 and 1 showing that temperature remains almost constant during the power disruption. Thus, the biggest temperature changes occurred only in the headspace region and in the top layer of fruit. However, during the intervention the average temperature increase at the top was only 1°C for the headspace and 0.7°C for the apples at the top, which will not affect the quality of the apples. Figure 26 shows that the average relative humidity on the headspace, top, 6th and 4th layers remains almost constant and is not affected by the power intervention.

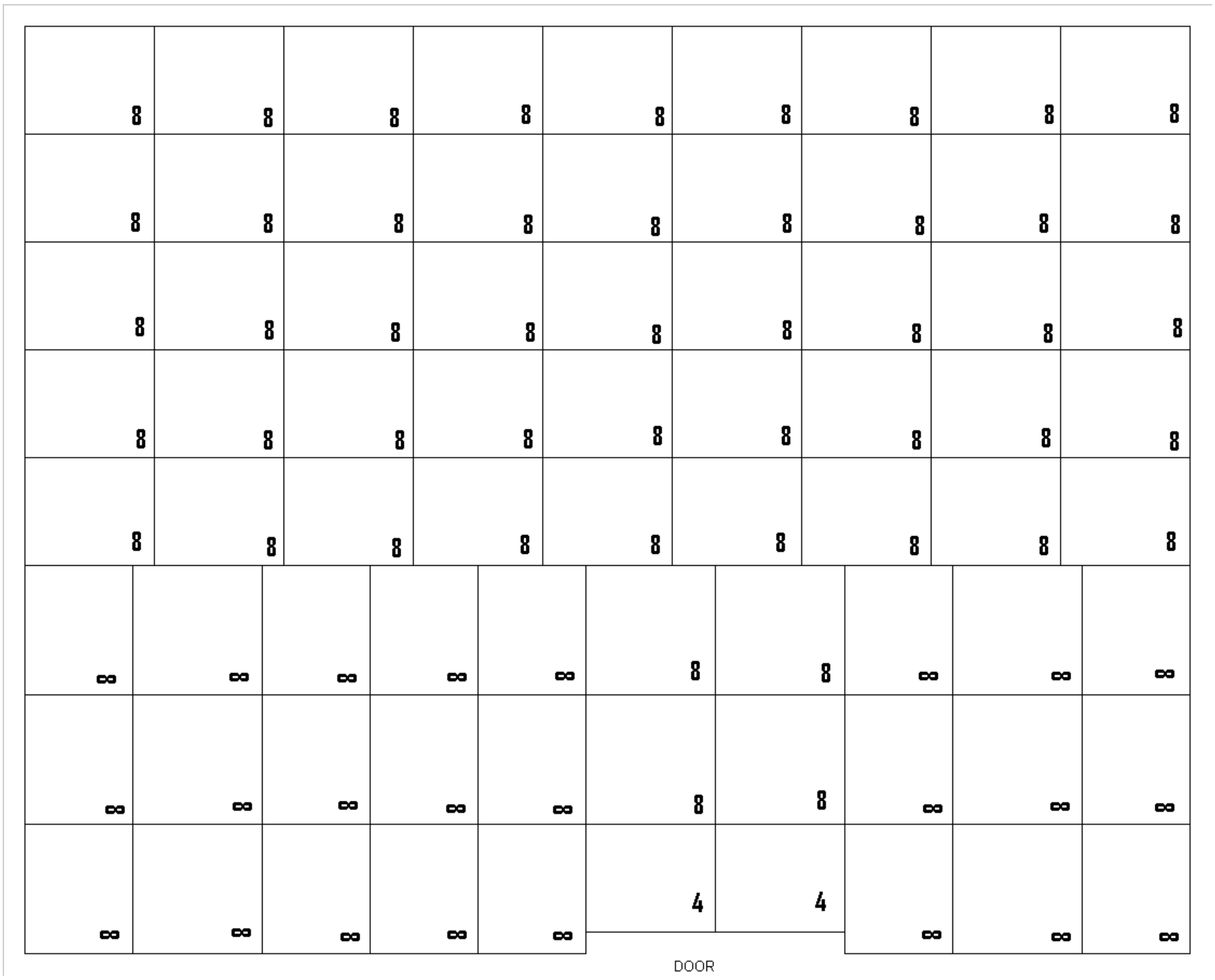


Figure 13. Floor plan of the arrangement of bins at the cold store in Batlow.

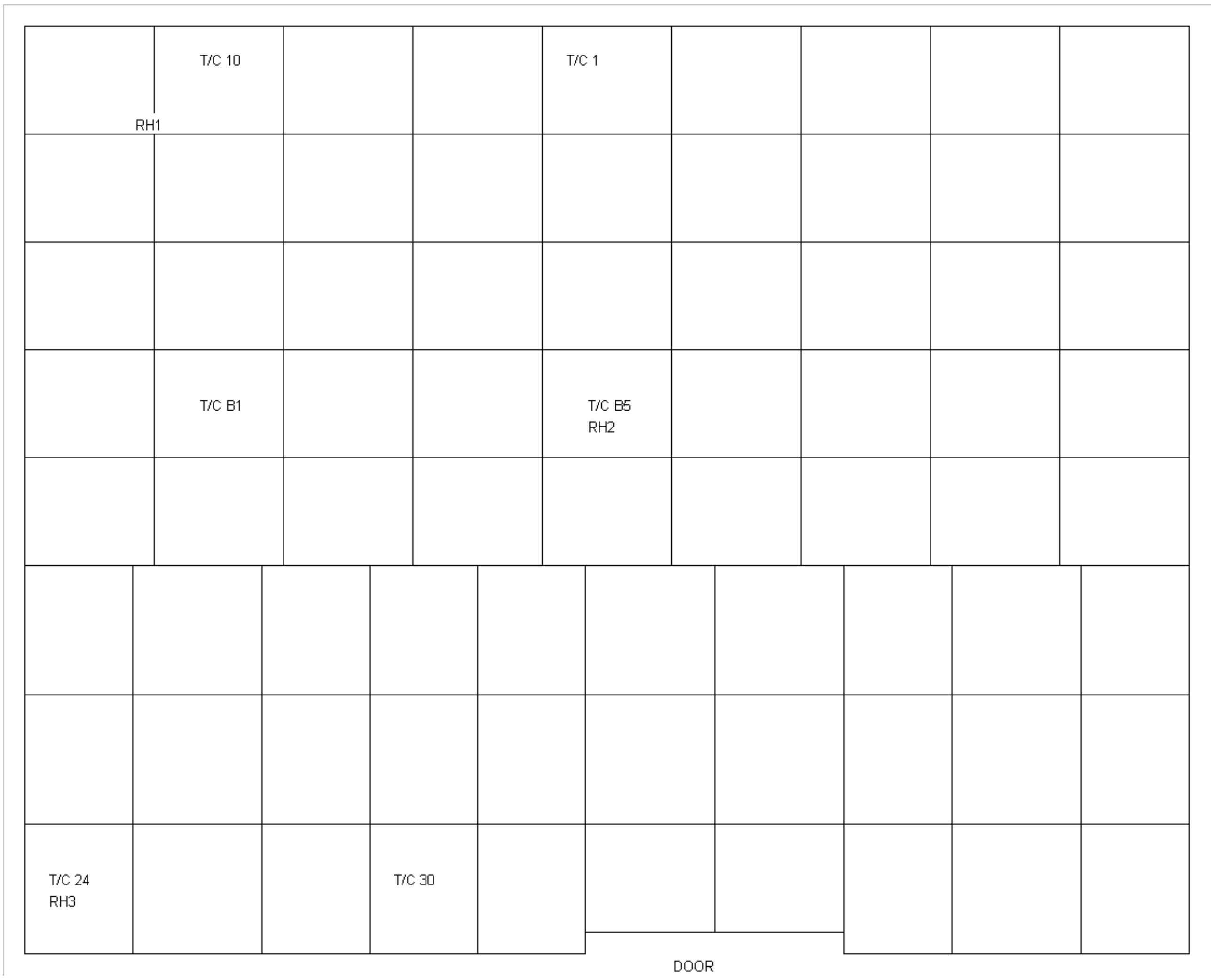


Figure 14. Arrangement of the sensors in the head space.

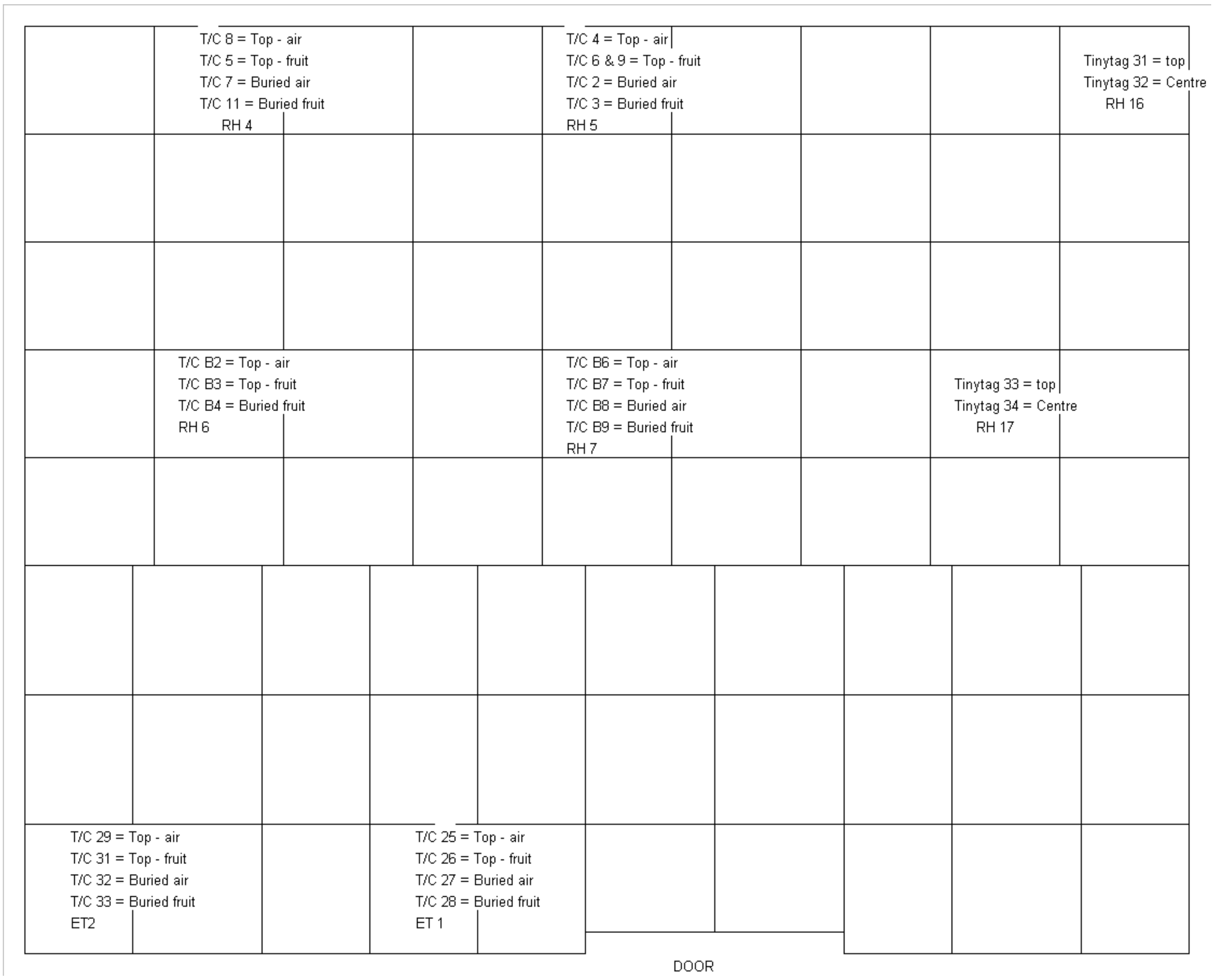


Figure 15. Arrangement of the sensors in the top layer.

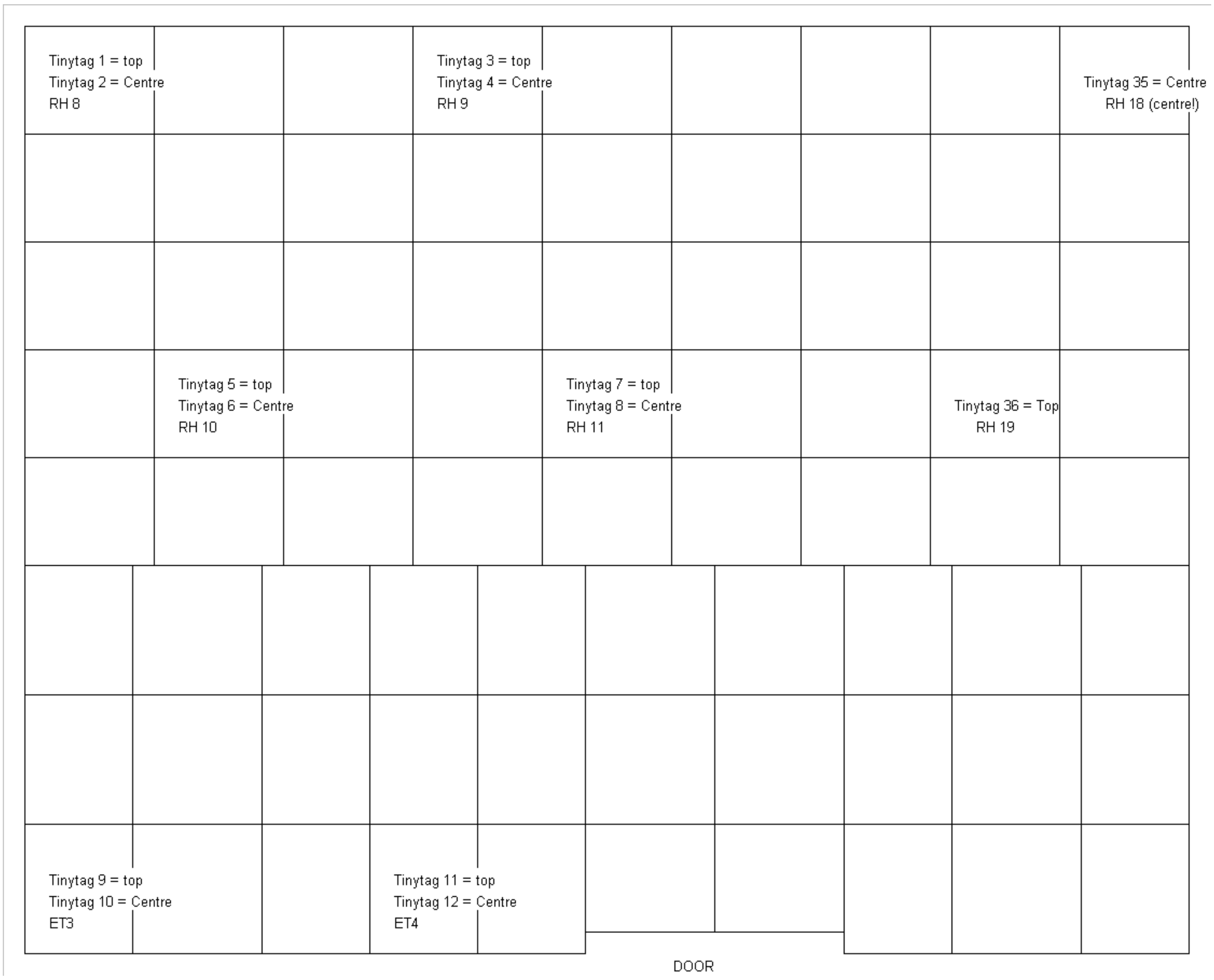


Figure 16. Arrangement of the sensors in layer 6.

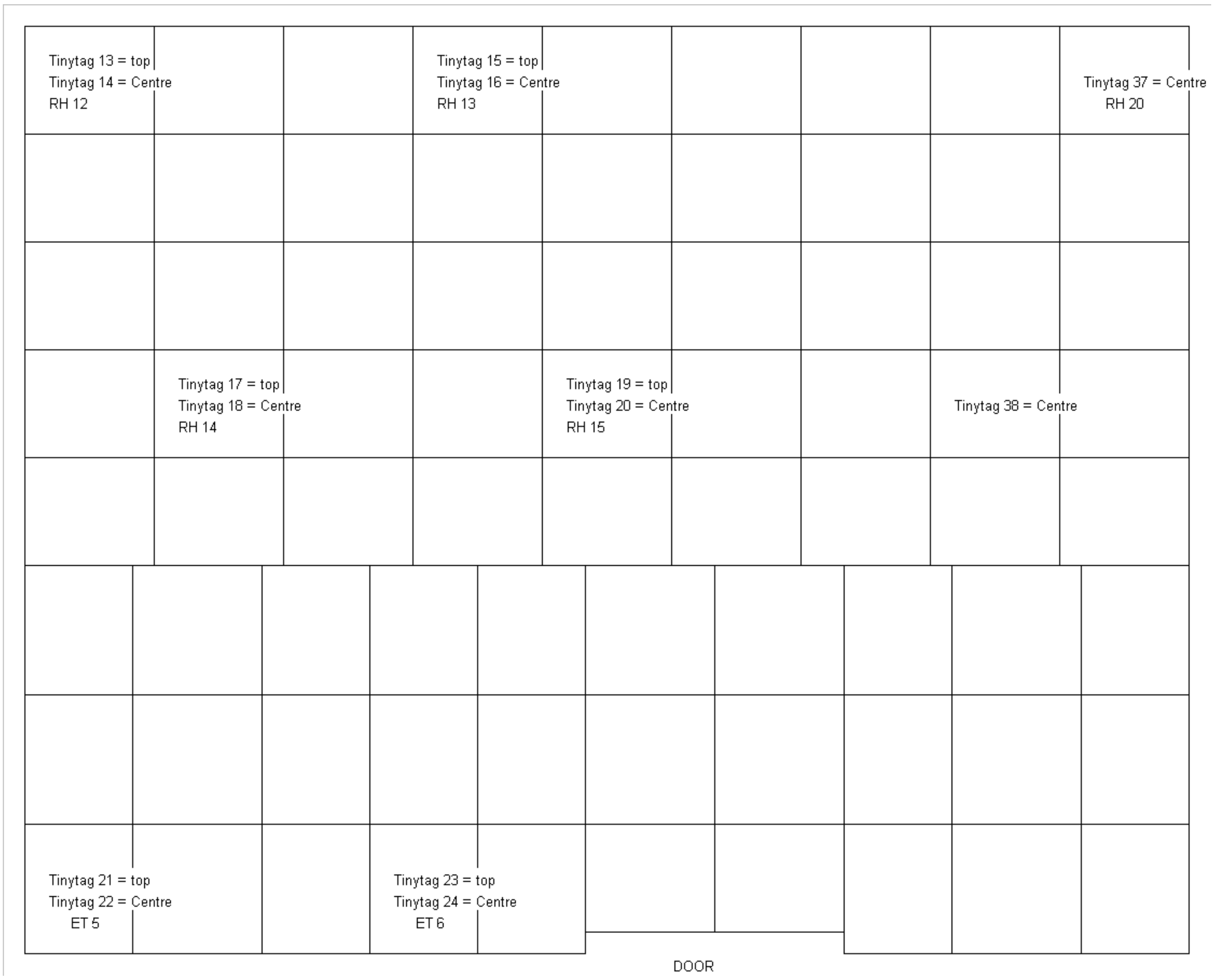


Figure 17. Arrangement of the sensors in layer 4.

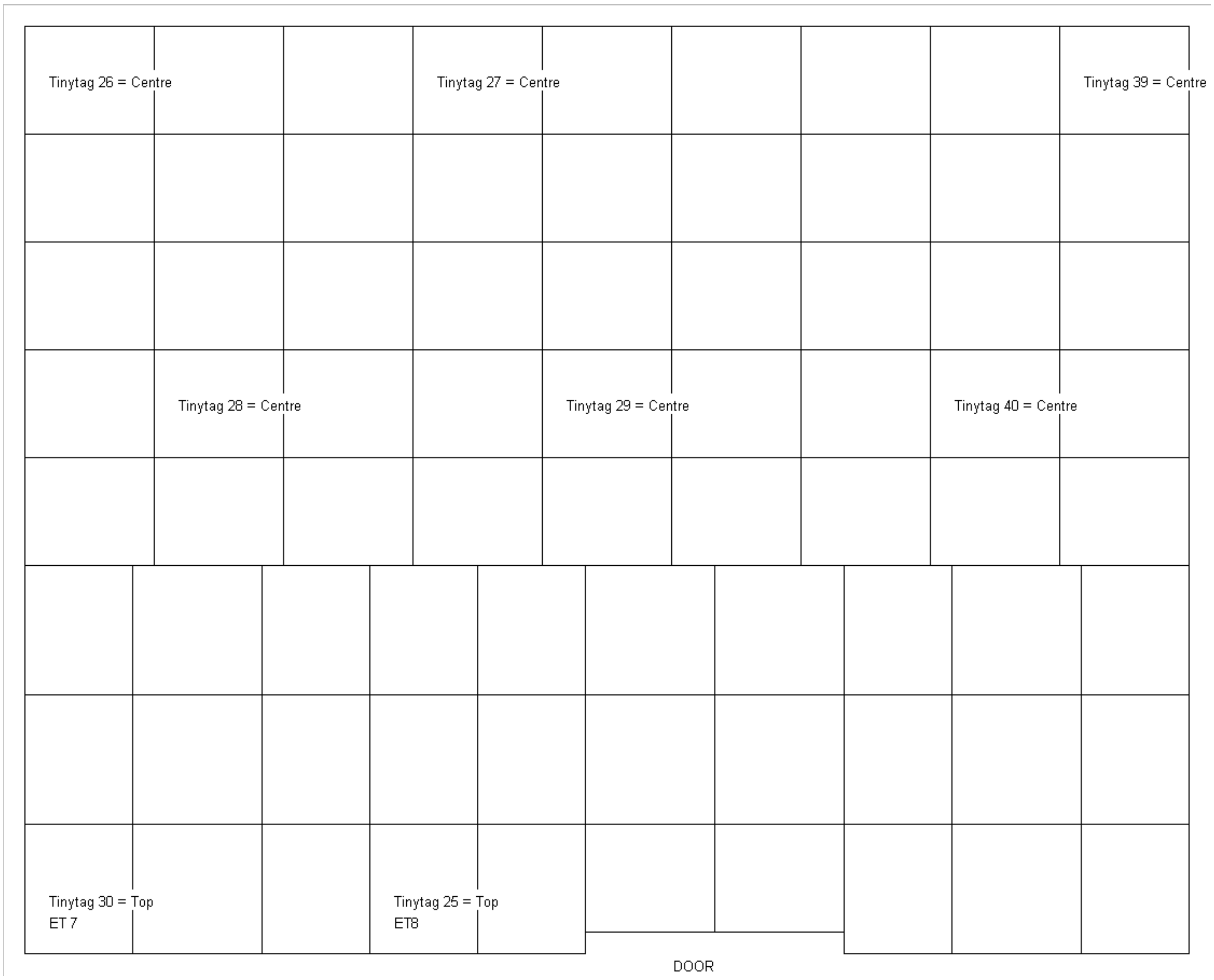


Figure 18. Arrangement of the sensors in layer 1.

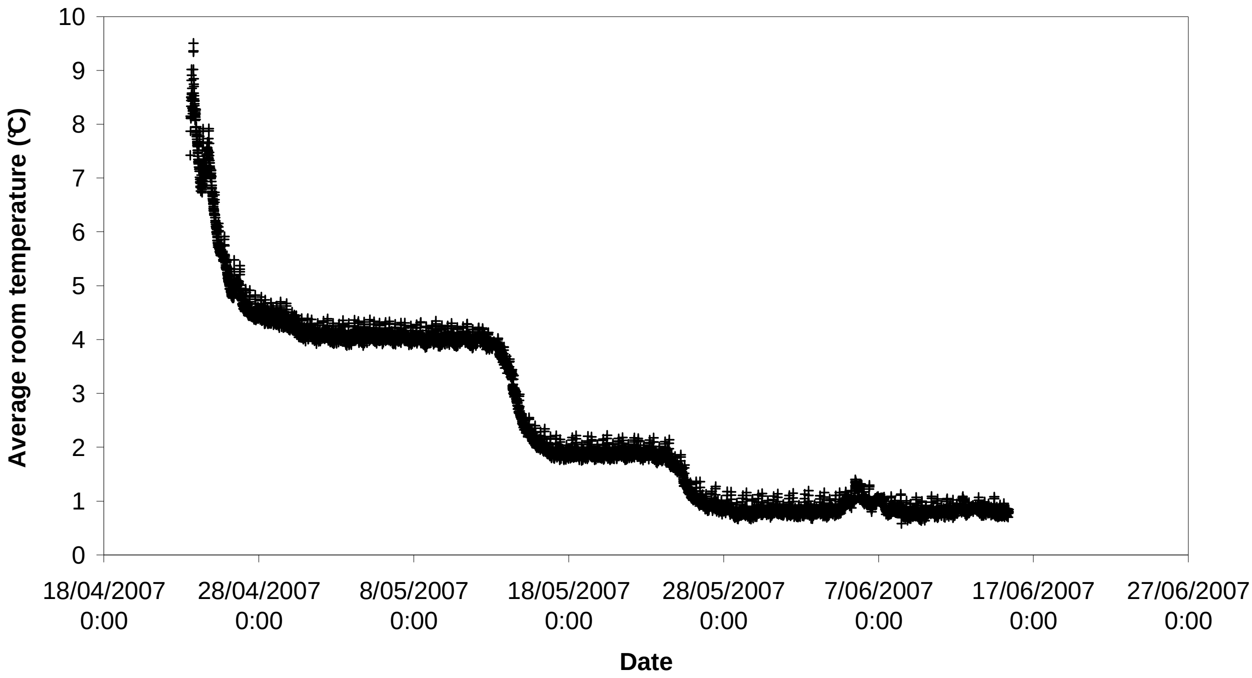


Figure 19. Average room temperature from initial loading of the room.

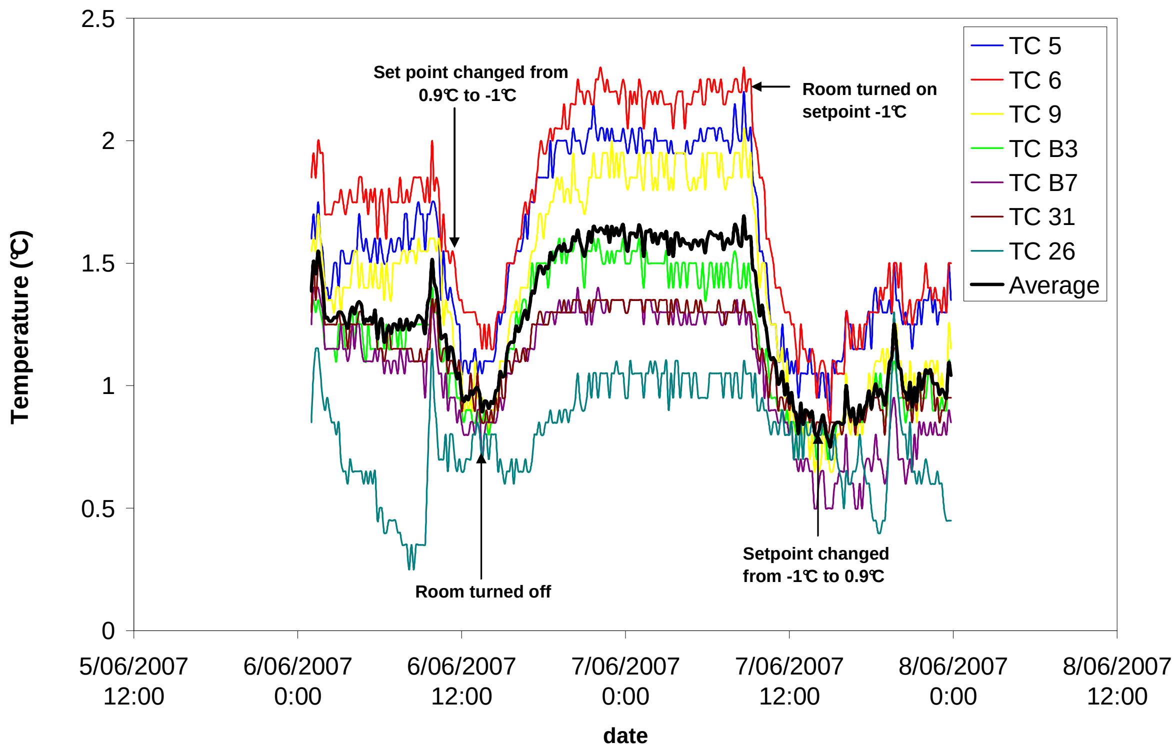


Figure 20. Fruit temperature in the top layer. See positions of the sensors in figure 15.

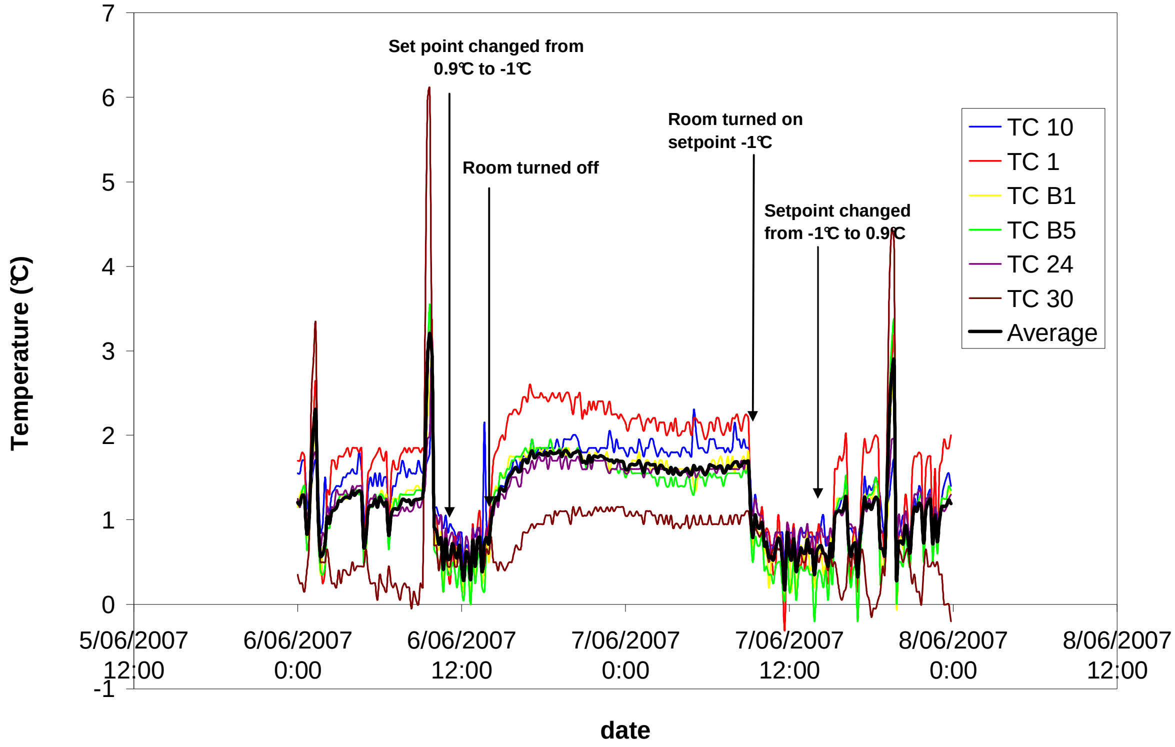


Figure 21. Air temperature in the head space. See positions of the sensors in figure 14.

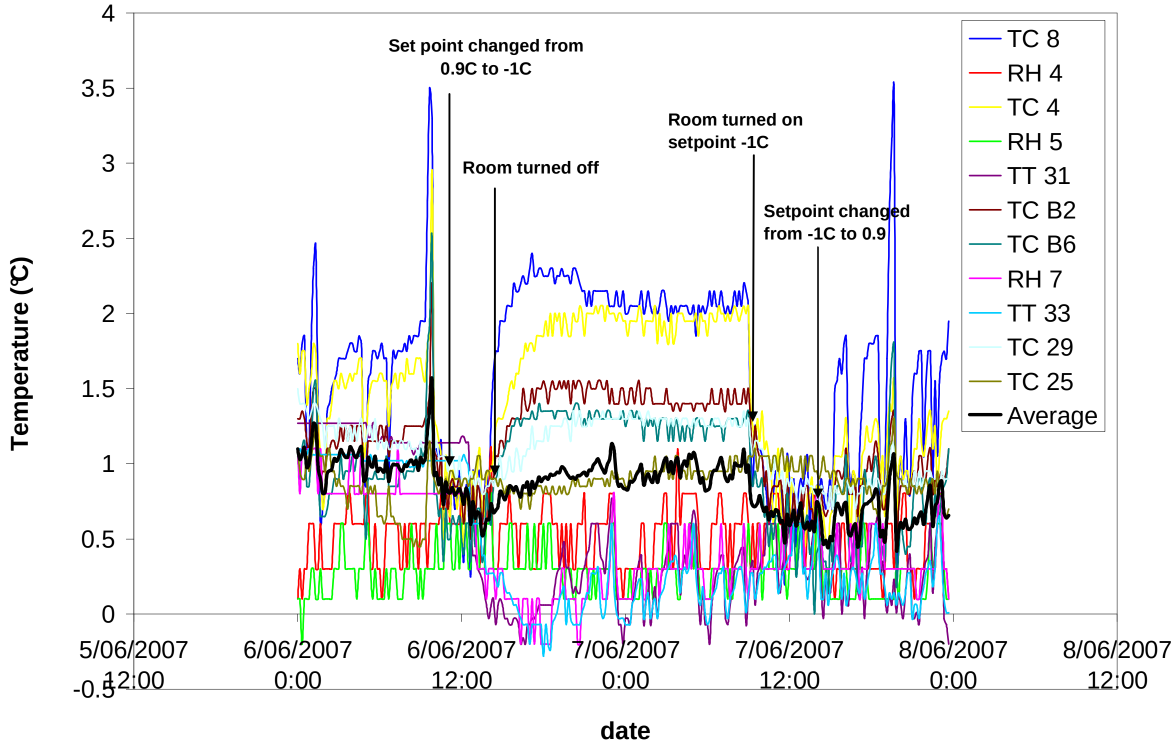


Figure 22. Air temperature in the top layer of bins. See positions of the sensors in figure 15.

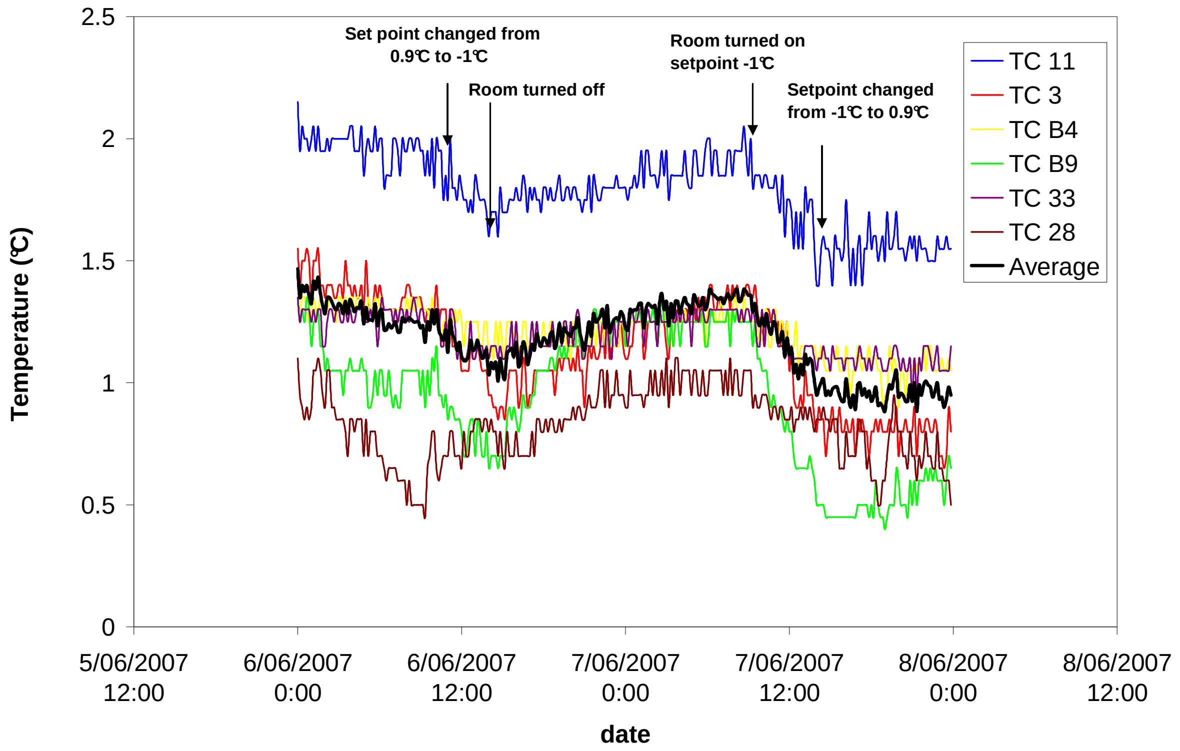


Figure 23. Fruit temperature in the top layer of buried fruit. See positions of the sensors in figure 15.

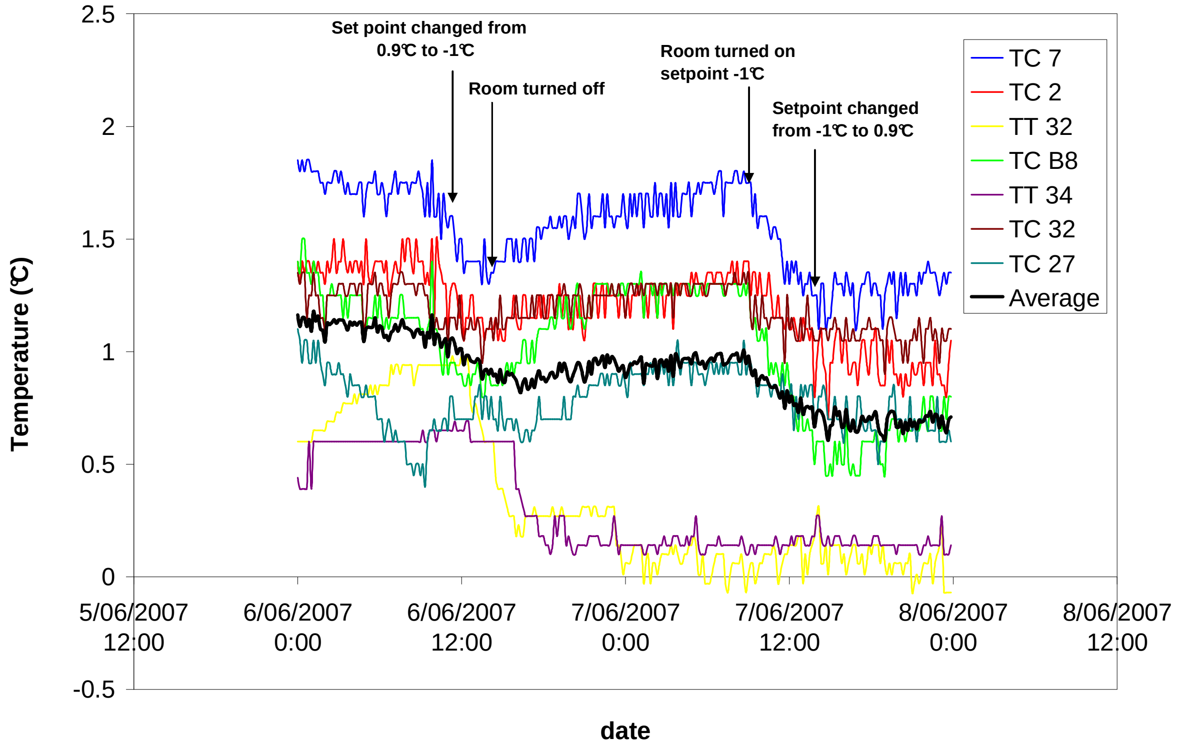


Figure 24. Air temperature beside buried fruit underneath top layer. See positions of the sensors in figure 15.

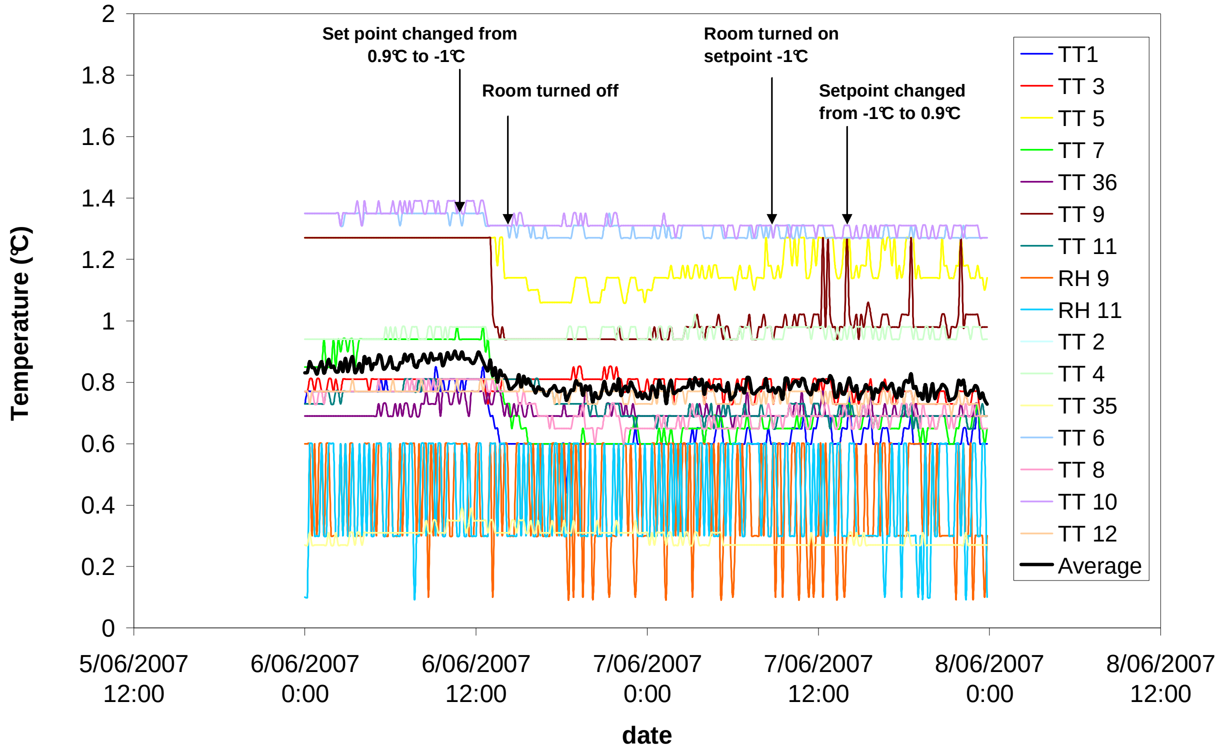


Figure 25. Air temperature in layer 6. See positions of the sensors in figure 16.

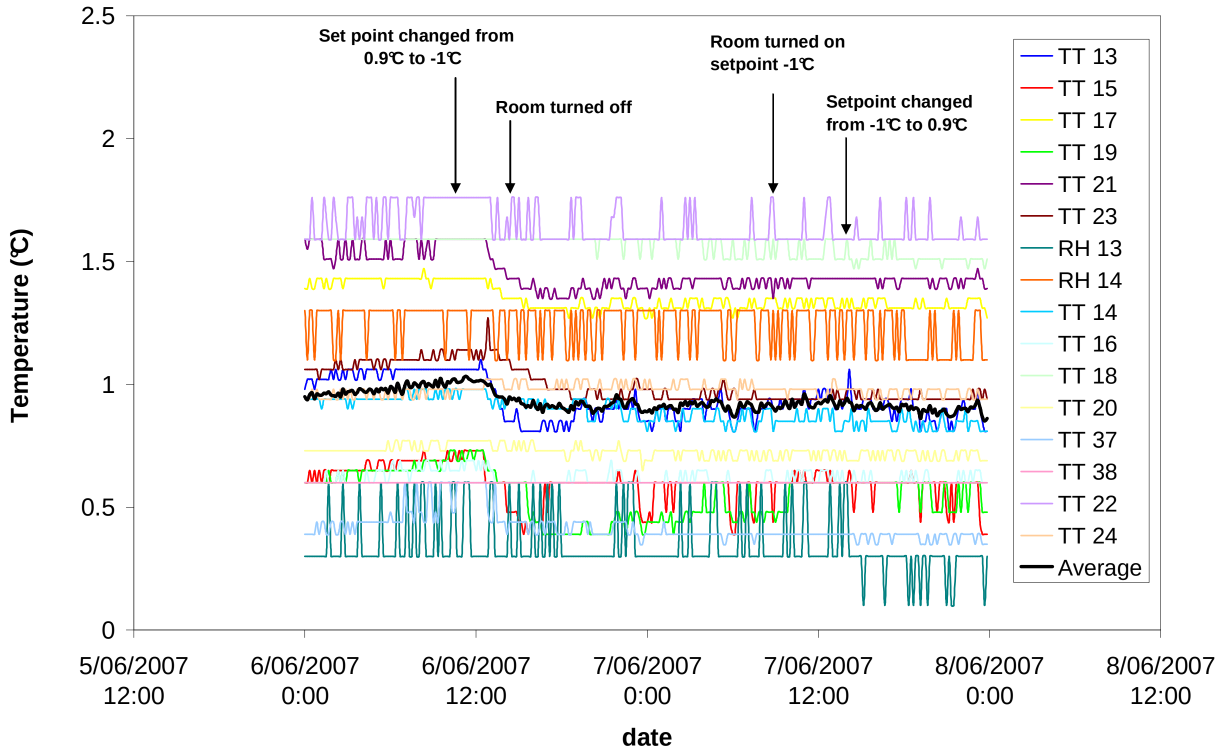


Figure 26. Air temperature in layer 4. See positions of the sensors in figure 17.

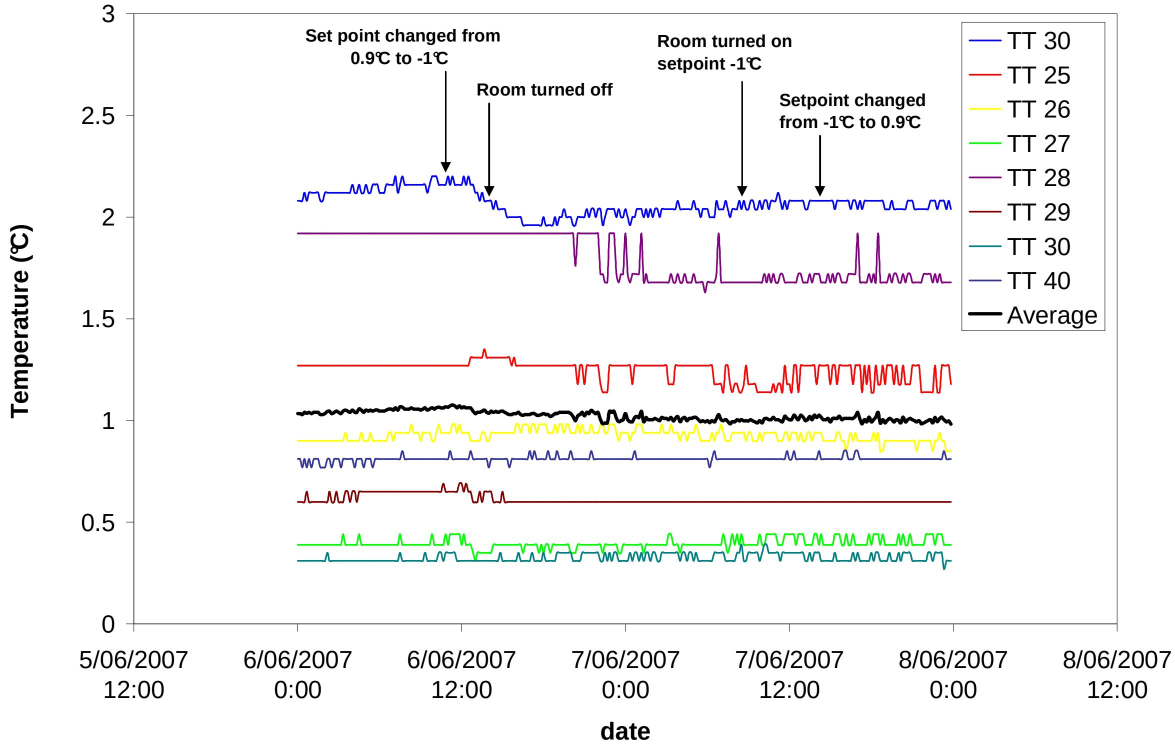


Figure 27. Air temperature in layer 1. See positions of the sensors in figure 18.

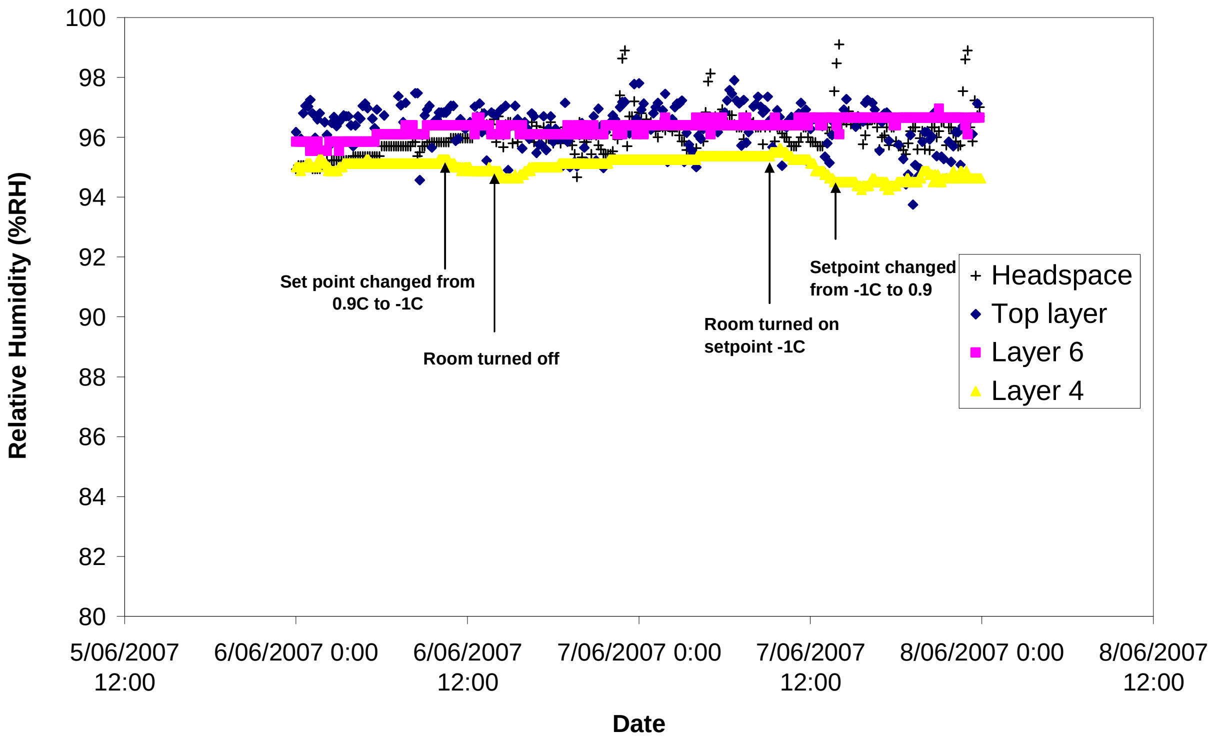


Figure 28. Relative Humidity in each layer.

6.3 Mathematical model

Mathematical modelling is a tool that can be used to investigate the effect of load shifting strategies on temperature profile inside coolstores. It allows the prediction of temperature changes based on factors such as external temperature, geometrical characteristics of the room, refrigeration system and power interruptions without the need for further experimentation, yet the model needs to be experimentally validated to be reliable. Mathematical models can exhibit different levels of complexity that can vary from simple lump parametric to highly complex Computational Fluid Dynamics (CFD) models. The choice of a particular type of model is usually based on the balance between simplicity of the model and its accuracy. For instance, a CFD model can predict temperature gradients all around the coolstore but the computational processing time and the cost of implementing it can be high. This type of model can be justified for situations where there are important temperature differences around the room affected by complex geometrical scenarios, flow velocity, buoyancy effects etc. On the other hand, a simple lump parameter model is easy to implement, fast and inexpensive but it could only be applied for situations where the temperature gradients are zero or negligible.

In this work two simplified models are proposed and compared with the experimental data of the studied coolstore room at Batlow. Both models attempt to predict the fruit temperature changes during a daily, cyclical, on/off refrigeration scheme. Changes on humidity were not modelled given that humidity did not change during the power disruption as seen on figure 28. The models will be compared and a choice will be made based on the balance between accuracy and simplicity.

Model 1 is a simple lumped approach which can be justified given the very small temperature increases during the intervention. Figure 29 shows a schematic representation of the cold room. The model assumes that the cold room, including the stored apples, behaves as a single thermal mass where there are no internal temperature gradients. The temperature inside the room changes via the following interactions:

- Heat transfer with the external environment, which consist of the infiltration of heat through the walls, roof and floor.
- Heat produced by the respiration of the apples.
- Heat incorporated into the room by the fans when running.
- Heat withdrawn from the room by the refrigeration system.

The equation representing the model is:

$$\frac{d\left(m \cdot C_p \cdot T_a\right)}{dt} = A_r h_r \left(T_o - T_a\right) + A_w h_w \left(T_o - T_a\right) + A_f h_f \left(T_g - T_a\right) + \mathrm{Re}\,sp + Fans - REF \quad (1)$$

Where *m* represents the mass of the stored apples, C_p is the heat capacity of the apples, T_o, T_a and T_g are the temperatures of the external ambient, stored apples and ground respectively. *Resp* and *Fans* stand for the heat produced by respiration of the apples and by the fans when they are turned on, *A* is area, *h* is the heat transfer coefficient, and the subscripts *r, w and f* stand for roof, wall and floor respectively. The heat transfer coefficients are usually calculated by adding the resistances to the heat transfer. However, given that the roof, walls and floor are very well insulated, only the resistance to the conduction of heat through those walls (including roof and floor) was accounted for, neglecting the external and internal convective heat transfer resistances (the inverse of the external and internal heat transfer coefficients). This was achieved by adding the resistances of the insulation material of the walls. The heat produced by the fans and the heat withdrawn by the refrigeration system are incorporated into the calculation only when the refrigeration system is turned on. The constants of the model can be seen in table 6.

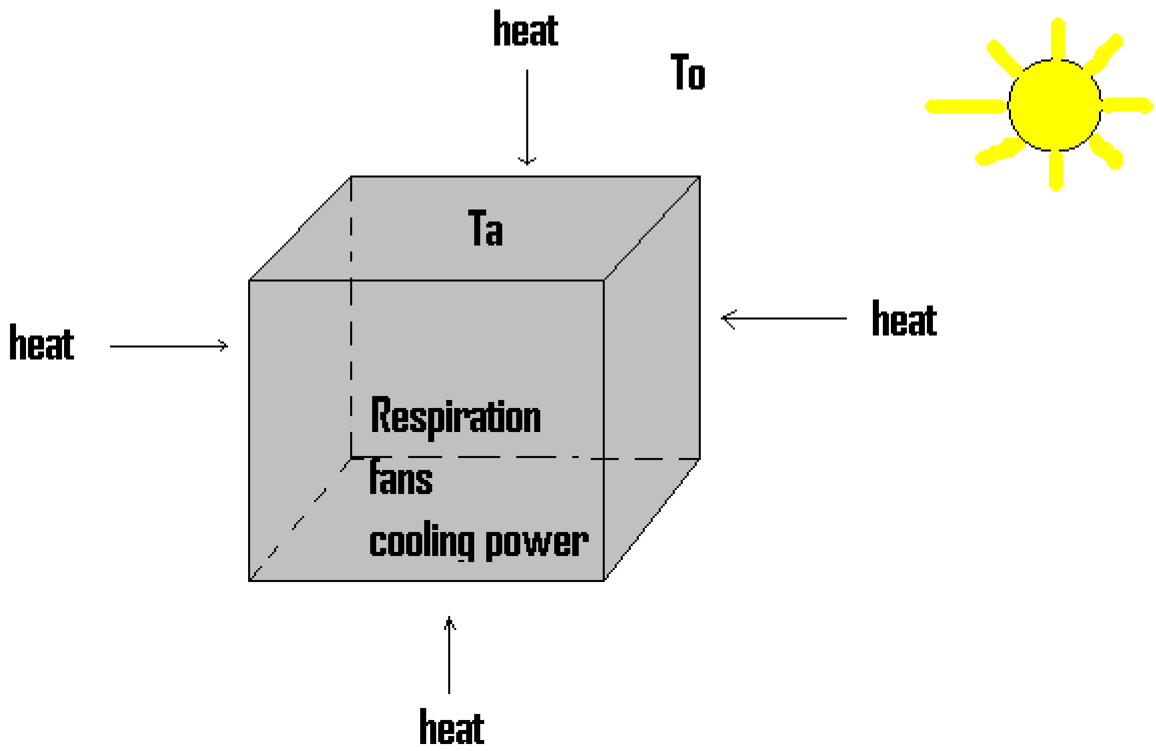


Figure 29. Schematic simplification of the cold store rooms.

The refrigeration system works continuously at the beginning of the storage period until reaching the final desired set point, but it cycles on and off once it reaches the set point. It was estimated that during the current operation the refrigeration system works for 4.1 hours/day totalling 62 compressor starts per day. Table 7 summarizes the characteristics of the system, during the current operation, which are used to calculate and incorporate the *Fan* and *REF* terms into equation (1).

C_p	4180	$J.Kg^{-1}.K^{-1}$
h_r	0.48	$W.M^{-2}.K^{-1}$
h_w	0.48	$W.M^{-2}.K^{-1}$
h_f	1.1613	$W.M^{-2}.K^{-1}$
Fan	13.2	kW
Resp	12.15	$W.Ton^{-1}$
REF	120	kW
m	620000	Kg

Table 6. Constants used in the model.

Current operation		
Deadband	0.3	oC
Starts	62	per day
Run time	4.1	h per day
Between starts	23	minutes
Each start	4	minutes

Table 7. Characteristics of the refrigeration system during the current operation.

Model 2 is an improvement of model 1 consisting of estimating gradients of temperature inside the room, which are higher at the top and lower at the bottom of the room as seen on figures 21 to 27. The model assumes the infiltration of heat from the environment is one-dimensional from the roof to the bottom. Even though this is not true, because there is also infiltration of heat through the walls and floor, it has been demonstrated that the temperatures at the top layer and on the headspace are always higher. The equation representing model 2 is:

$$\frac{\partial\left(\rho\cdot C_p\cdot T_a\right)}{\partial t}=\nabla\left(k_{eff}\frac{\partial T_a}{\partial x}\right)+\rho\cdot \mathrm{Re}\,sp+\frac{Fans}{V}-\frac{REF}{V} \tag{2}$$

Where ρ is the apparent density of the room (weight of apples divided by the volume of room). k_{eff} is the effective thermal conductivity on the room (this simplification takes into account the combined effect of conduction throughout the apple's bed and convection of the air that moves throughout the spaces between the apples). V is the total volume of the room.

The boundary condition at the top of the room is:

$$k_{eff}\left.\frac{\partial T_a}{\partial x}\right|_{roof}=h_c\left(T_o-T_a\right) \tag{3}$$

Where h_c is the heat transfer coefficient taking into account the area-weighted average infiltration of heat thought all the walls. Model 2 was solved using the finite volume method which was programmed in Visual Basic. Model 1 which is mathematically very simple was solved in an Excel spreadsheet. Both models were used to predict the average fruit top layer temperature during 6-7 June 2007 when the intervention was conducted. The external temperature was measured with Tinytag sensors placed outside the cold room as seen in figure 12. Figure 30 shows the average measured external temperature profile.

Figure 31 compares the prediction obtained with both models. Model 2 shows a better representation of actual shape of the curves. It also tends to over-predict the actual temperature. On the other hand, model 1 does not follow exactly the actual shape of the curve and under-predicts the fruit temperature at the end of the off-power period, but by only 0.2°C. It is expected that model 1 will normally under-predict the highest fruit temperature but given the small temperature differences, the model can still be used to estimate energy-saving strategies.

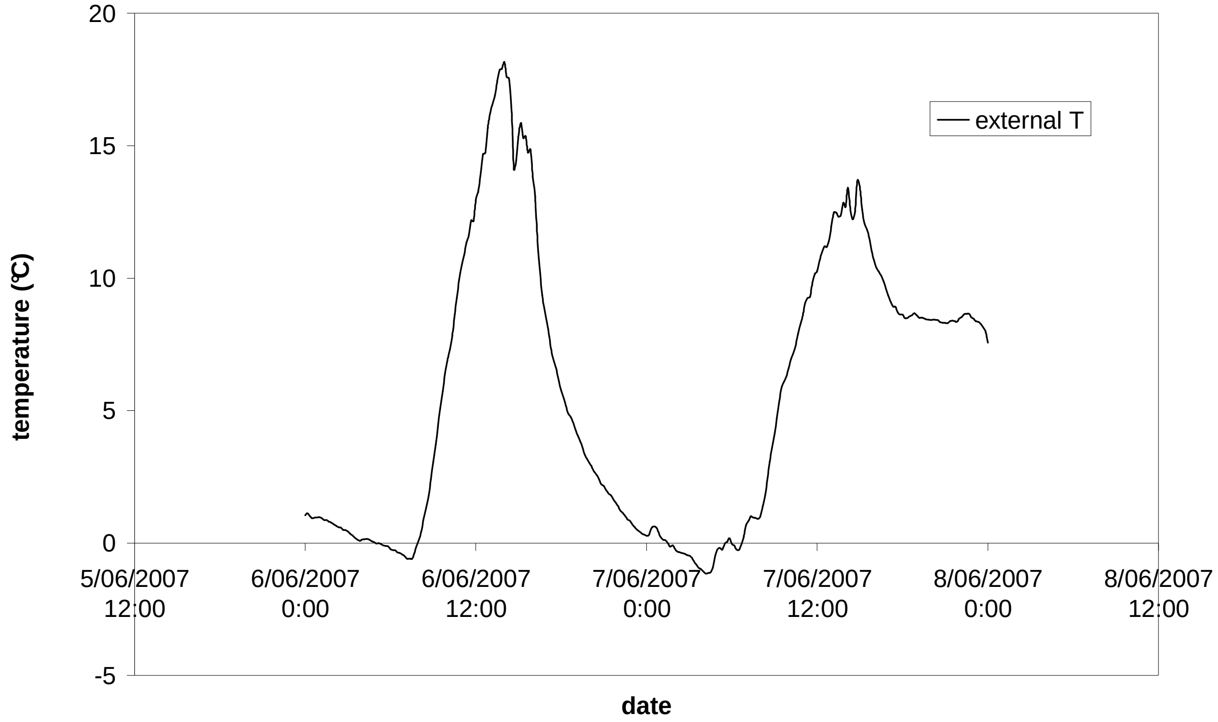


Figure 30. External temperature profile.

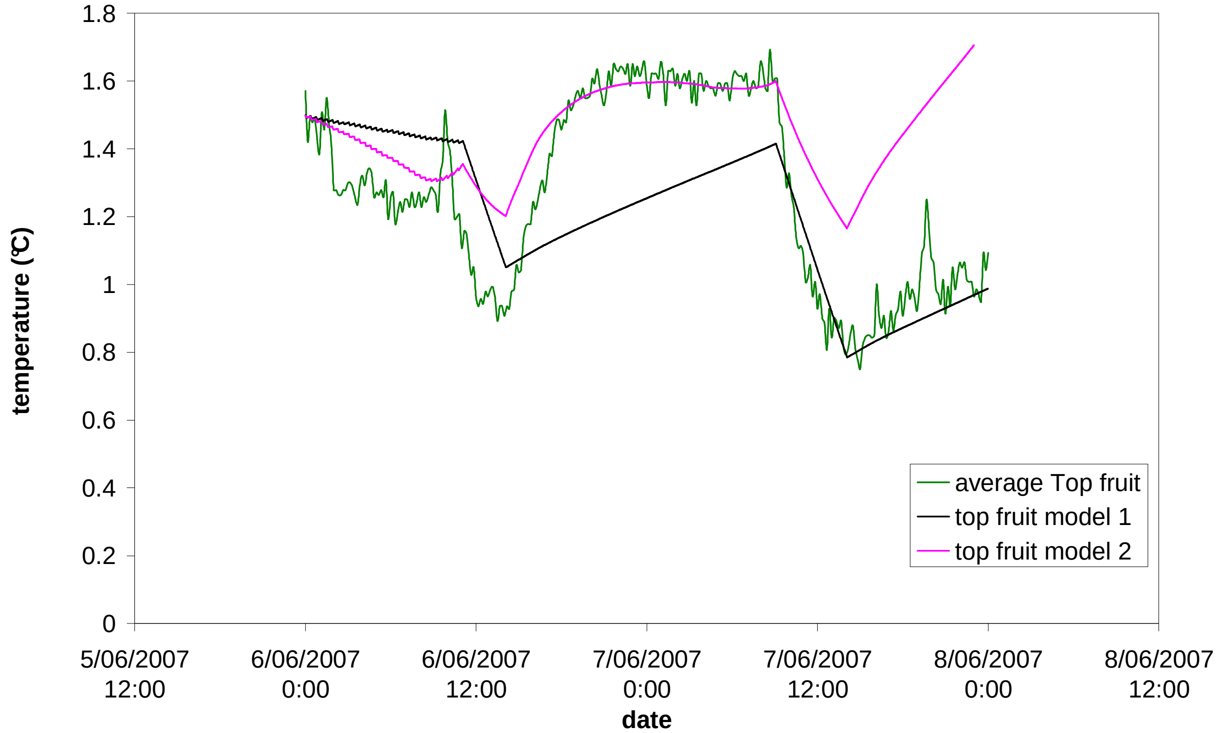


Figure 31. Comparison of models 1 and 2 predicting the average top fruit temperature.

7.0 PROPOSAL FOR ENERGY SAVING AT BATLOW FRUIT CO-OP

A cost analysis was added to model 1 in order to estimate the cost of energy consumption during the standard operation at Batlow. This cost is compared with a proposed operational scheme consisting of turning off the refrigeration system during the peak/shoulder hours. The model is used to estimate the energy and cost savings by implementing an energy saving strategy that allows reducing or eliminating the energy consumption during peak and shoulder hours. The power consumed when the refrigeration system is turned on is estimated by adding the energy consumed by the fans and compressors and the capacity of the refrigeration system (*REF*) divided by *COP* (the refrigeration system's coefficient of performance):

$$Power\left(kW\right) = Fan + \frac{REF}{COP} \tag{4}$$

The energy consumed is equal to the power consumed multiplied by the hours of operation:

$$Energy\left(kWh\right) = Power(kW) * t(h) \tag{5}$$

where t is the time in hours. The cost of energy can be estimated by taking into account the consumed energy and the average power demand during the peak/shoulder and off-peak hours. The estimation is conducted for a single large room at Batlow with a storage capacity of approximately 1700 bins. The total cost of the operation at Batlow is estimated by assuming that all the rooms (33) are operating at the same time. The current analysis does not take into account the Market Participation charges. The cost per kWh of energy consumed takes into account the energy cost and the network/metering cost:

$$\begin{aligned} &Peak / shoulder\_\cos t = 0.056263 + 0.018630 = \$0.074893 / KWh \\ &off - peak\_\cos t = 0.025717 + 0.01524 = \$0.040957 / KWh \end{aligned} \tag{6}$$

The cost of power demand is:

$$\begin{aligned} &Peak / shoulder\_demand\_\cos t = \$5.2020 / KVA \\ &off - peak\_demand\_\cos t = \$1.478 / KVA \end{aligned} \tag{7}$$

The cost of a normal operation at Batlow, meaning the cost of operating the refrigeration system for 24 hours under on/off temperature control, was estimated assuming that the initial temperature of the apples is 1°C, and that the refrigeration system follows the characteristics in table 7. The external temperature profile (c.f. fig. 32) was estimated as the average temperature profile at Albury on the financial year 2002-2003 excluding the period from the 1 January to 31 March, when usually there is no stored fruit. Figure 33 shows the predicted apple temperature profile under normal operating conditions, when running the refrigeration system under the operational characteristic in table 7. Under these operating conditions, the temperature of the apples remains between 0.9°C - 1°C.

It is important to say that this operation scheme CAN ONLY BE APPLIED when the apples reach the lowest storage temperature (between 0.5°C - 1°C). This scheme SHOULD NOT BE IMPLEMENTED during the initial temperature pull down given that the cooling down process will take much longer than it currently does. Figure 33 shows that it takes almost four times longer to cool down the room from 10°C to 4°C by turning off the refrigeration system during peak/shoulder hours than operating the system under the current operation (system continuously on). In the case of

'Pink Lady' apples, which follows a stepwise cooling down process, we CANNOT recommend applying this scheme on the intermediate steps (4°C and 2°C) given that the conducted study did not follow the stepwise cooling down process.

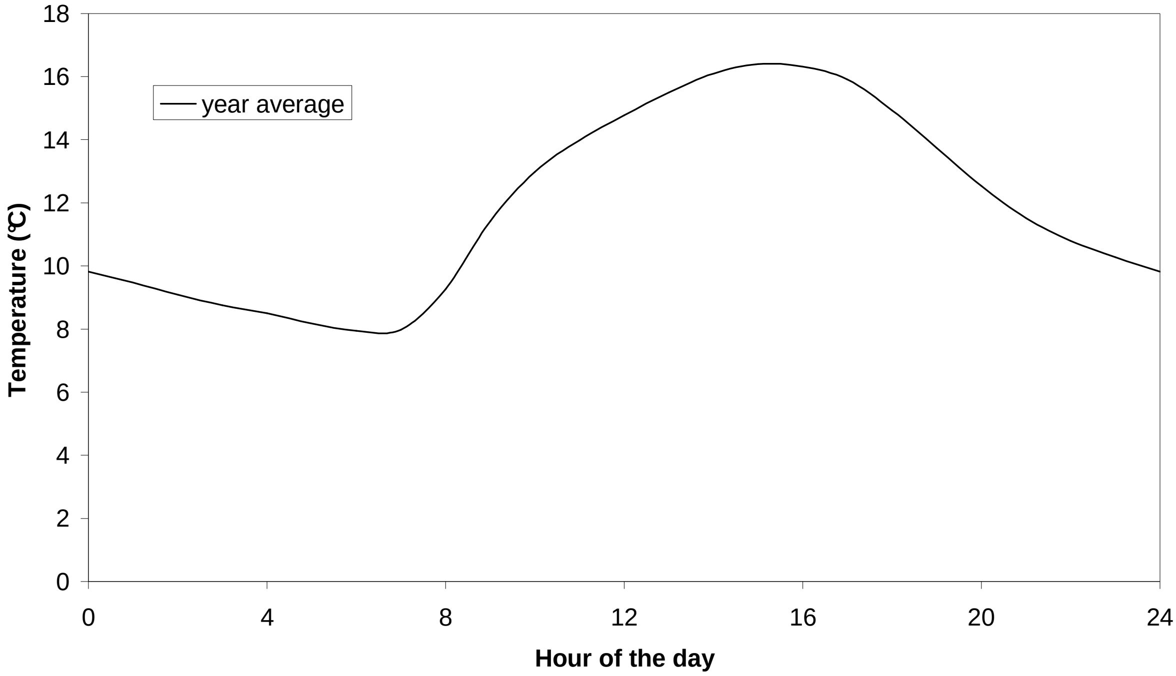


Figure 32. Average temperature profile at Albury from 1/06/2002 to 31/05/2003 excluding the period from 1/01/2003 to 31/03/2003.

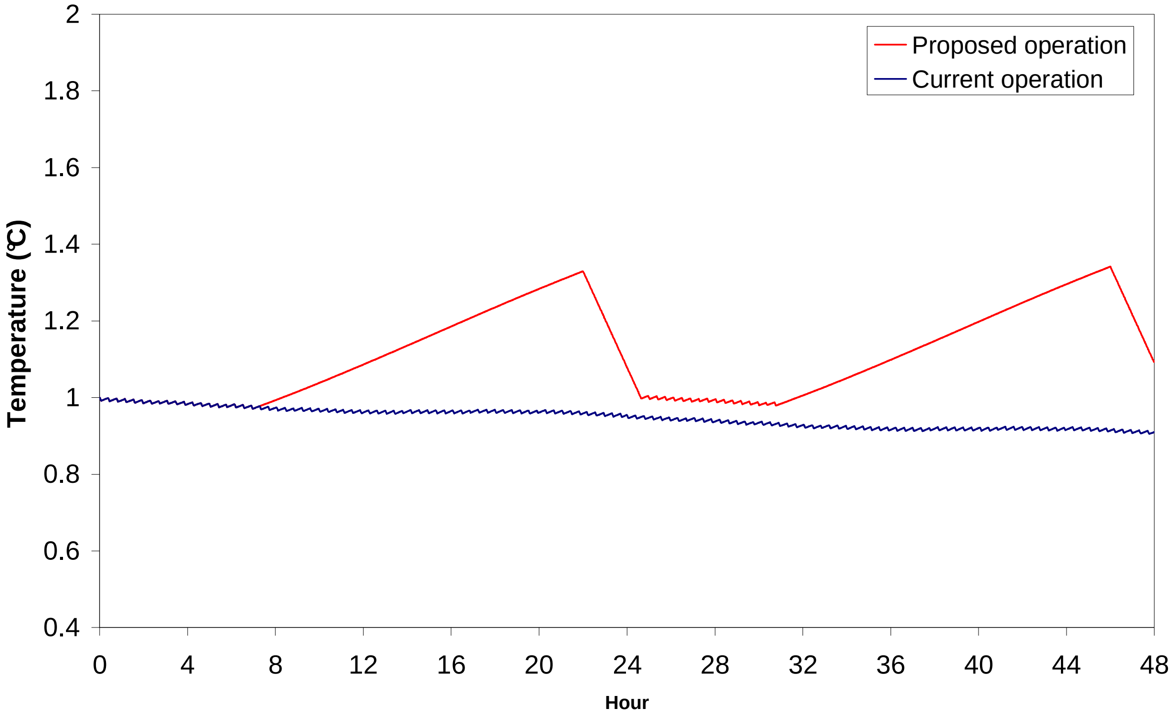


Figure 33. Predicted temperature of the warmest apples under normal and proposed operating conditions.

Figure 33 displays the fruit temperature when turning off the refrigeration system during the peak and shoulder hours from 7 am to 10 pm (proposed operation). The average fruit temperature only increases 0.4 C during the peak/shoulder hours under the proposed operation. However, it must be taken into account that the model under-predicts the temperature at the top layer and that a higher temperature increase is expected on hot summer days. A monthly cost of the operation at Batlow was estimated assuming full capacity operation under the current and proposed operating scheme (turning off the system on peak/shoulder hours) respectively. It was found that there are cost savings on both the energy consumption and the power demand even though the power demand during off peak hours increases more than two fold under the proposed scheme (the savings come from the lower price of energy at non-peak hours). The details of the cost analysis remain confidential but overall, the cost of energy can be reduced by 45%.

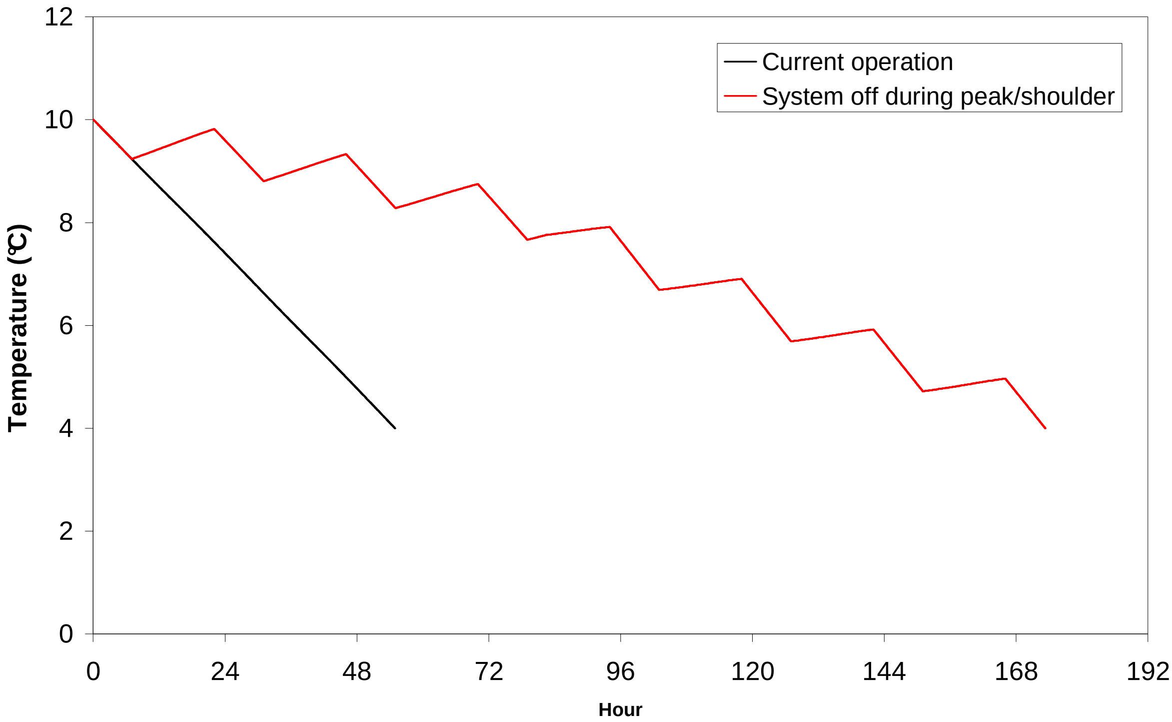


Figure 33. Comparison of the current temperature pull-down process, with a system where the refrigeration is turned off during the peak and shoulder hours.

8.0 CONCLUSIONS

- Based on the statistical analysis of firmness, colour, weight loss, and decay, it can be concluded that temperature oscillations of 4°C ± 2°C (T1) do not increase the rate of loss of quality during the tested storage times for 'Royal Gala', 'Fuji' and 'Granny Smith' within the recommended shelf life. 'Braeburn' and 'Pink Lady' can reach a maximum temperature of 2.75°C ± 1.25°C (T2) without increasing the loss of quality during storage.

- It would seem that weight loss may be the most likely reduction in quality from apples exposed to oscillating temperature conditions during CA storage, although the results generated for weight loss in this study are difficult to transfer to commercial scenarios due to the differences in which the CA was established in this study (a flow through system) to those in commercial practice (a closed system).

- During the refrigeration intervention at Batlow, the average temperature of the top apples and the air in the headspace increased only 0.7°C and 1°C respectively. This is the place were apples warm up fastest given their proximity to the roof, which is exposed to direct solar radiation and where the warmer air inside the room moves by natural convection. The headspace between the top layer and the roof exhibits the highest air temperature increase.

- The temperature of buried apples under the top layer only increased 0.3°C during the power disruption.

- A mathematical model that predicts the average temperature of the apples during storage was proposed. The model predicts that the temperature of the apples will increase only 0.4°C when turning off the refrigeration system during peak and shoulder hours. However, it must be taken into account that the model under-predicts the temperature of the apples at the top layer closer to the roof. The actual increase could be higher on a hot summer day. The mathematical model has been validated for Batlow coolstore rooms hence it is the responsibility of other packhouse industries to determine whether the model can be extended for their particular conditions.

- The average relative humidity remained constant during the power intervention at Batlow. Thus, its effect was not quantified in the model.

- The energy saving scheme that we proposed consists of turning off the refrigeration power during peak hours. However, it is recommended that the temperature of the air on the top layer must be monitored when implementing this scheme to ensure the preservation of quality of the apples at the top. This system can reduce the cost of energy during the months of operation after reaching the lowest storage temperature. The cost of energy could be reduced by about 45% during that period.

- The proposed operation scheme CAN ONLY BE APPLIED when the apples reach the desired long-term storage temperature (between 0.5°C - 1°C) and under controlled atmosphere conditions. This scheme SHOULD NOT BE IMPLEMENTED during the initial temperature pull-down given that the cooling down process will take much longer than the current operation, possibly affecting the quality of the apples during storage.

- We CANNOT recommend applying this scheme for 'Pink Lady' apples on the intermediate steps (4°C and 2°C) given that the study conducted at FSA did not follow the stepwise cooling down process normally implemented at Batlow.

- The proposed energy-saving operating scheme only applies to the storage rooms at Batlow. Other cool-stores should monitor temperature changes in their cold rooms under power-off conditions in order to determine the scheme's viability before attempting to implement it.

9.0 TECHNOLOGY TRANSFER

Batlow Fruit Co-op is taking up these finds. The results of the study can be used by other packhouse industries but the proposed energy-saving operating scheme only applies to the storage rooms at Batlow. Other cool-stores should monitor temperature changes in their cold rooms under power-off conditions in order to determine the scheme's viability before attempting to implement it.

10.0 ACKNOWLEDGMENTS

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