Int. Agrophysics, 1994, 8, 475-483

APPLYING THE ACOUSTIC IMPULSE RESPONSE TECHNIQUE TO DETERMINE THE TIME FOR HARVEST AND STORAGE OF THE APPLE

F. Vervaeke, H. Chen, J. De Baerdemaeker

Department of Agricultural Engineering, Katholieke Universiteit Leuven, Kardinaal Mercierlaan 92, 3001 Heverlee, Belgium

A b s t r a c t. The acoustic impulse response technique is used as a non-destructive means to measure the apple firmness. Jonagold apples picked at different ripeness stages and stored for different periods of ULO and cold air storage are monitored for the change in the firmness and weight loss during shelf display. Suggestions are given for the picking time, length of storage and shelf display. This can guide the optimal control of the apple quality for a better market price.

K e y w o r d s: apple, acoustic impulse response, harvest time, storage

INTRODUCTION

The post-harvest changes that occur in apples are both chemical and physical. So far efforts have been made for developing criteria to monitor these changes as well as for improving storage conditions to slow down these changes.

To monitor the quality changes of apples in storage, Hardenburg *et al.* [3] suggested the titratable acidity of the apple juice, and Tijskens [9] suggested L-malate as the biochemical criteria. Tijskens [9] also found that the breaking force obtained by plate compression is the most useful to monitor the change in the apple texture. Holt and Schoorl [4] concluded that the ultimate tensile strength and fracture resistance provide a good measure of the deterioration of the apple. Unfortunately all the above criteria can only be measured in destructive ways. Firmness is a widely accepted criterion for the apple quality, and it is becoming possible to evaluate it in a non-destructive way in terms of the resonant frequency of intact apples. Hardenburg *et al.* [3] confirmed that the sonic firmness index f^2m, with f the second resonant frequency of an intact apple and m the mass of the apple, reflects a trend similar to the apple firmness obtained by the pressure test. Van Woensel and De Baerdemaeker [10] found that the stiffness factor $f^2m^{2/3}$ exhibits a sharp decline around the time when the maturity climacterium is reached. With a practical acoustic impulse response measurement system, relation of the acoustic stiffness factor versus the apple firmness, the surface colour and the damping was investigated [1].

The rate of change in the apple quality during storage is a function of the temperature, the relative humidity (RH) as well as the air composition. At present, three storage techniques, referred to as the cold air storage, the controlled atmosphere (CA) storage, and the ultra low oxygen (ULO) storage, are used in the EEC countries for different periods of storage of fruits. The cold air storage, which controls only the temperature and the relative humidity, is used for a maximum period of 3-4 months of storage in case of Jonagold apples [5]. The storage condition of -1 °C to 4.5 °C with 90 % RH was recommended for commercial storage of the apple [5]. The CA storage is realized by increasing the CO_2 content in the atmosphere to 3-4 % and meanwhile decreasing the O_2 content to 17 -18 %

under ventilation conditions, or CO_2 to 2-3 % and O_2 to 3-4 % without ventilation. Under this condition, Jonagold apples can be stored for 4-7 months. The ULO storage refers to controlling the CO_2 to 1.5-2 % and O_2 to 0.9-2.2 %, which allows Jonagold apples to be stored for 6-9 months [5]. It is the most efficient, but the most expensive method for storing the fruit.

The previous research has mainly been concentrated on Golden Delicious, Red Delicious and Jonathan apples. However, recently Jonagold apples have become the most appreciated in Belgium. It was reported by Odeurs [7] that the total yield of Jonagold apples in Belgium increased from 38.65 x 10^3 ton/year in 1985 up to 194.5 x 10^3 ton/year in 1992, and meanwhile the total yield of Golden Delicious apples decreased from 84.8 x 10^3 ton/year down to 52.4 x 10^3 ton/year.

In this research, Jonagold apples are measured for the acoustic resonant frequency and weight loss. The objective is to use the acoustic impulse response method to monitor and analyse the texture change of apples after harvest. It may give some advise on the reasonable time for harvest and the reasonable periods for storage.

MATERIALS AND METHODS

Fruit sources

In October 1991, Jonagold apples, grown in an orchard of the Fruit Research Center of K.U.Leuven at Rillaar, Belgium, were picked for experiments. The apple trees with the rootstock M9 and the graft Cultivar Jonagold were selected. They were planted in 1982 in sandy-loam soil. In the orchard some apple trees of the variety Idared were also planted for pollination.

Four picking days were selected as October 3, October 10, October 17 and October 24, 1991. In the morning of each picking day, 400 apples were picked from an untouched tree. Different from the commercial picking procedure, all apples in a tree were randomly picked in obtaining each group of 400 apples so that human factors in deciding which apples should be picked and which should not could be avoided. Apples from the first picking day were referred to as group 1, apples from the second picking day were referred to as group 2, and so on. Each group of apples were randomly divided into four sub-groups, each having 100 apples.

Weather conditions during the picking season

The rain fall in the orchard recorded each day during September 26 and October 24, 1991 [11] is shown in Fig. 1. The corresponding average conditions including the maximum temperature T_{max} and the relative humidity RH of the air in each week during this period are shown in Fig. 2, where week 1 is the week right before the first picking

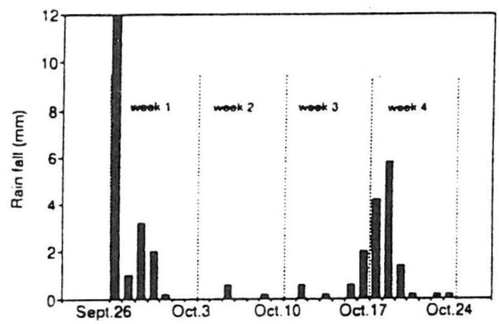

Fig. 1. Rain fall in the orchard during September 26 and October 24, 1991.

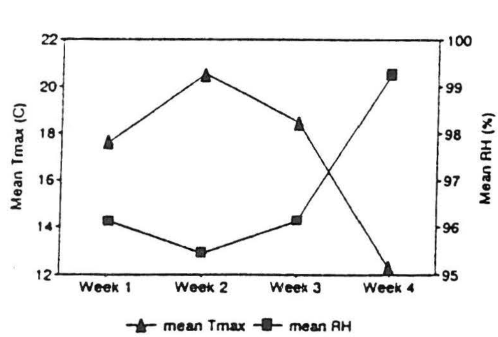

Fig. 2. Average relative humidity and maximum temperature in the orchard in each week before four picking days.

day, week 2 is the week right before the second picking day, and so on.

Conditions for storage and shelf display

After initial quality measurements at picking time, each sub-group of apples were packed in wooden boxes for storage. Four storage combinations listed in Table 1 were designed for all the apples. In storage 1, one sub-group of apples from each group were stored under ULO condition in a fruit auction market for one month and consecutively under the cold air condition in a climatic room in the laboratory for two weeks. In storage 2, another sub-group of apples from each group were stored under the ULO condition for three months and then under the cold air condition for four weeks, etc. At the end of each ULO storage the apples were kept in the ULO storage room for two days more under the same temperature and relative humidity for gradual equilibrium of the air composition to the fresh air. After different storage combinations, the apples were first measured for their quality and then stored under shelf display condition in the climatic room and monitored for quality changes. During shelf display the apples after storage 1 were measured for their firmness every seven days. This measurement interval seemed a little too long. Therefore in the following monitoring of the apples after storage 2 to 4, quality measurements were carried out every four days.

Table 1. Different storage combinations for apples during experiments in 1991-1992

Condition	Storage 1	Storage 2	Storage 3	Storage 4
ULO	1 month	3 months	5 months	7 months
Cold air	2 weeks	4 weeks	1 week	1 week

The ULO storage was in commercial long-term storage house at the auction market. During this ULO storage, the environment was controlled at set points of 2 °C and 90 % RH with O_2 content of 1.4 %, CO_2 content of 1.2 % as well as 20 ppm of C_2H_4. During the cold air storage, the environment was controlled at 2 °C and 90 % RH, while for the shelf display the environment was controlled at 18 °C and 65 % RH. It should be indicated that in the cold air storage and the shelf display, air composition in the climatic room was not controlled. Due to the life process of the apple, the air composition may differ to a certain extent from the fresh air even though ventilation was provided.

Quality measurements

The quality measurements include measuring the acoustic resonant frequency and the weight of the apples.

The acoustic resonant frequency f was measured by using the acoustic impulse response system described by Chen *et al.* [1]. The stiffness factor S in the form of $f^2m^{2/3}$ was adopted as a non-destructive index for the evaluation of the apple firmness. The average of the resonant frequencies measured at three random positions around the equator of each apple was used in calculating the stiffness factor.

The weight was measured by individual weighing of each apple to the accuracy of 0.01 g. The weight loss is then calculated according to:

$$\text{weight loss} = \frac{(m_0-m)}{m_0} \cdot 100\ \%$$

where m_0 is the initial weight of an apple weighed soon after being picked from the tree, m is the weight of the apple after storage and during shelf display.

RESULTS AND DISCUSSION

Picking time

During the growth in the tree, the apple relies on the photosynthesis of leaves by which energy derived from the sun is stored continuously in the apple in the form of chemical energy, mainly in carbohydrates. As a result, the apple enlarges its size due to cell division and water uptake, and changes its chlorophyll, flesh, pH, etc. The season for commercial harvest of Jonagold apples in Belgium is normally in September and October. In the first week of the commercial picking period, some ripe apples, which amount to 5 to 10 % of the total apples in the tree, are picked. In the second week, 40 to 50 % of the total apples are picked, and in the third week about 20 to 40 % of the total apples are picked. For 1991 most of the apples are harvested during the second and third week of October.

Figure 3 shows the average stiffness factor S and weight m_0 at the picking time for the four groups of the apples. The later picked apples have a higher firmness than the earlier picked apples. The apples picked during the later two weeks kept their firmness higher in most cases of this experiment during different storage combinations as well as the consecutive display on shelf, as exhibited in Fig. 4. It verifies the conclusion obtained by Finney [2] and Van Woensel *et al.* [10] that the later picked fruit maintains its firmness better during storage than the earlier picked fruit. There is no similarity between the curves in Fig. 2 and the curve of the firmness change in Fig. 3, which implies that the influence of the weather conditions during the picking season on the

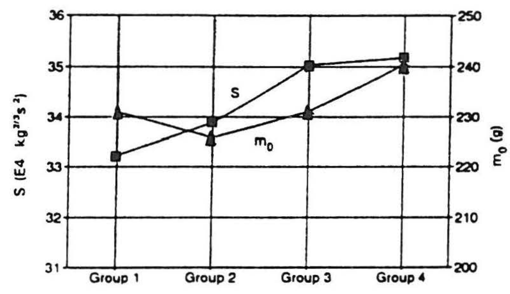

Fig. 3. Average stiffness factor and weight of apples at four picking days (group 1 to 4) in October 1991.

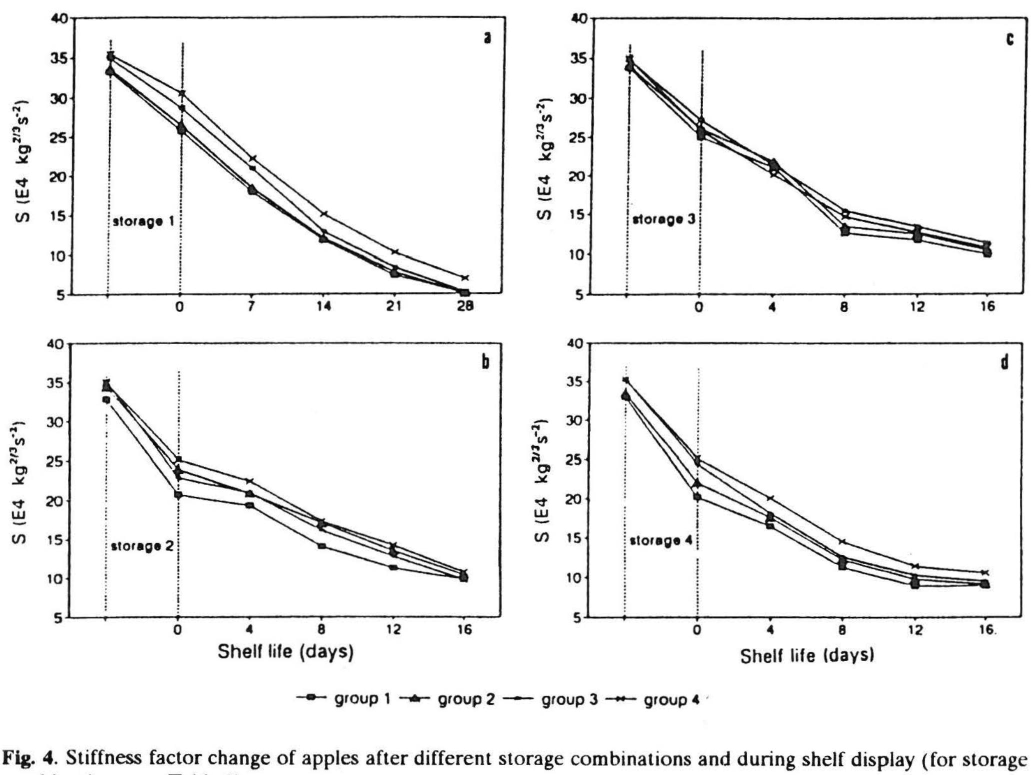

Fig. 4. Stiffness factor change of apples after different storage combinations and during shelf display (for storage combinations, see Table 1).

firmness of the apple in the picking time is not obvious. For the purpose of having an apple with a higher firmness, or keeping an apple for a longer period above a certain firmness level, it seems better to pick most of the apples in the third and fourth week under the condition of 1991. The picking time can be flexible to a certain extent, depending on the weather conditions during the whole growing season.

It is noticeable that the apples from different picking days have different average weight. In harvest season, the apple ceases to increase its size. One of the reasons causing the change of the weight may be the weather conditions during the harvest season. Comparing Fig. 3 with Fig. 2, we may note that the change in the weight of the apple is similar to the evolution of the mean RH of the air and opposite to the change in the mean T_{max}. Compared with week 2, there was more rain fall during week 4, the maximum temperature was lower and the relative humidity was higher. Under these weather conditions, the apple took up more water, therefore had more weight. It is desirable to harvest when the maximum possible water content is present as this results in a crisp texture [2]. From this consideration, the apples are suggested to be picked after several rainy days.

Figure 5 shows for the four groups of the apples the percentage of the apples rotten at the end of 16 days on the shelf after the different storage combinations. The apples having a brown spot of more than 2 cm in diameter on their surface were supposed to be rotten. It is found that more of the apples picked in the later weeks were rotten than of those picked in the earlier weeks. More of the later picked apples either had probably more spoils or were already overripe at the picking time, therefore could not sustain a long-term of storage. To avoid such a loss, these early ripe apples are suggested to be picked in the earlier weeks of October. The current commercial picking procedure with several picking steps is reasonable and necessary, but it appears that changes in the picking time and the percentage of the total apples picked each time are possible. The firmness and the weight of an apple in the picking time may also possibly influence the susceptibility of the apple to damage during handling. Further research concerning this topic remains to be done.

ULO and cold air storage

During ULO storage and cold air storage, the apple simultaneously loses its firmness and weight. As shown in Figs 6 and 7, after being stored for one month in ULO and two weeks in cold air (storage 1), the apple loses 19 % of its firmness and 2 % of its weight; after three months in ULO and one month in cold air (storage 2), the apple loses 33 % of its firmness and 2.8 % of its weight; after five months in ULO and one week in cold air (storage 3), the apple loses 24 % of its firmness and 3.1 % of its weight; and after seven months in ULO and one

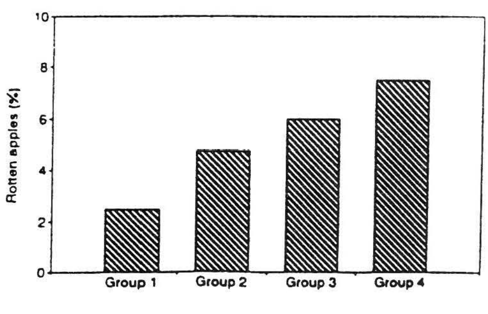

Fig. 5. Rotten apples after shelf display for 16 days.

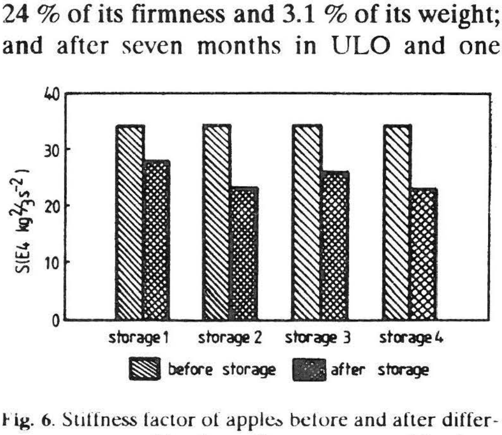

Fig. 6. Stiffness factor of apples before and after different storage combinations (for storage combinations, see Table 1).

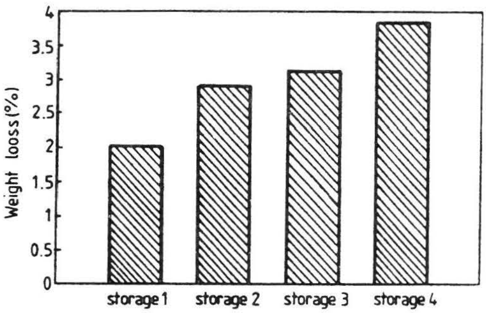

Fig. 7. Weight loss of apples after different storage combinations (for storage combinations, see Table 1).

week in cold air (storage 4), the apple loses 33 % of its firmness and 3.7 % of its weight. The loss in the firmness and the weight can be attributed to the ripening process of the apple after harvest.

Respiration is a major metabolic process taking place in the apple during storage. It can be described as the oxidative breakdown of the more complex materials normally present in cells such as starch, sugars and organic acids, into simpler molecules, such as carbon dioxide and water, with the concurrent production of energy and other molecules which can be used by the cell for synthetic reactions. The breakdown of the pectin by which cells are bound together results in the firmness loss in the apple. The respiration process can be expressed in a general equation as [12]:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

The continued respiration uses up the O_2 in the storage atmosphere, and meanwhile gives off the CO_2 into the storage atmosphere. It suggests that respiration rate could be slowed down by limiting the O_2 or by raising the CO_2 concentration in the storage atmosphere. It can be seen from Fig. 6 that the firmness loss after storage 4 is about as much as the firmness loss after storage 2. In this case, four months in ULO has the same effect on the firmness of the apple as three weeks in cold air. ULO storage can considerably extend the life of the apple after harvest in comparison with the cold air storage, therefore it has become a preferred technology for fruit storage these years.

The continued transpiration of the apple evaporates the internal water, which is held by osmotic forces within the cells mostly as free water. It is a major factor causing the weight loss or water loss. The rate of water loss can mainly be reduced by controlling the relative humidity of the storage atmosphere towards the equilibrium relative humidity of the apple. Comparing the weight loss of the apple after the above four storage combinations reveals that controlling the atmosphere composition does not make obvious differences in weight loss. Weight loss increases with storage time. Although the apples have approximately the same firmness after storage 4 and 2, the weight loss after storage 4 is much larger than that after storage 2. It can be concluded that under the same temperature and relative humidity, controlling the air composition may slow down the ripening of the apple, but does not influence its weight loss. ULO storage cannot obviously reduce the weight loss.

For all sub-groups of the apples, the standard deviations (SD) of the stiffness factor before storage are calculated between 1.78×10^4 to 2.49×10^4 $kg^{2/3}s^{-2}$, and increased to 1.99×10^4 to 4.06×10^4 $kg^{2/3}s^{-2}$ after storage. The increase in SD during storage implies that each apple loses its firmness at a different rate. However, comparing the SD values of all the sub-groups of the apples does not reveal that the originally firmer apples decrease relatively less in firmness than the softer apples .

Shelf display

After different periods in the ULO and the cold air storage, the apples show different trends in the loss of firmness on the shelf. It can be seen in Fig. 4 that after storage 1 the apples lose their firmness during shelf display at a gradually reduced rate. After storage 2 to 4, the apples show a quicker decline in firmness in the period from 4 to 8 days on the shelf. For the latter apples, no more than four days on shelf are recommended in order to prevent their quick loss in firmness. It is not clear if it is commercially feasible.

So far there is no quantified level of the stiffness factor which is related to the sensory acceptance of the apple quality for the consumers. However, it was found by Chen *et al.* [1] that keeping the apple firmness above the critical level of the stiffness factor of 18×10^4 $kg^{2/3}s^{-2}$ can prevent the apple from suffering a quicker loss in its yield shear stress which was proved to be a good measure of deterioration of the apple by Tijskens [9] and Holt *et al.* [6]. Keeping the apple stiffness above a lower level of 12×10^4 $kg^{2/3}s^{-2}$ can prevent the apple from suffering a quicker increase in its damping. Taking the value of 18×10^4 $kg^{2/3}s^{-2}$ as a critical level, allowable shelf life of the apple after different storage combinations is calculated from Fig. 4 and listed in Table 2. After storage 1, the apple can be displayed on shelf for 7 to 9 days. After storage 2, the apple can be displayed for 5 to 7 days. After storage 3, the apple can be displayed for 5 to 6 days. After storage 4, the apple can be displayed for 2 to 5 days. It is obvious that the shelf-life of the apple decreases with its length in ULO and cold air. The shelf-life after storage 4 is obviously shorter in comparison with that after storage 1 to 3. It is suggested that ULO storage do not exceed five months. Otherwise the market price for these apples may not be guaranteed. This suggested time period is shorter than that reported by Herregods [5].

Table 2. Proposed shelf-life of apples derived on the basis of the critical stiffness factor and weight loss. Unit: day

Group	Storage			
	1	2	3	4
	for critical stiffness factor			
1	7.0	5.0	5.3	2.0
2	7.1	7.0	5.7	3.7
3	8.3	6.5	5.3	4.0
4	9.1	7.4	6.1	5.5
	for critical weight loss			
1	11.5	9.5	12.5	6.5
2	9.5	8.0	7.0	2.5
3	10.0	6.7	4.5	4.5
4	10.5	7.0	4.0	3.5

It is also noticeable from Table 2 that the initial ripeness of the apple at picking time may cause difference in the shelf-life. In this experiment, the later picked apples have a higher firmness at the picking time, during ULO and cold air storage as well as shelf display than the earlier picked apples. The former apples have about 1 to 3 days more in shelf-life.

It was said above that the apples after storage 2 and storage 4 have approximately the same firmness. Nevertheless the apples after storage 2 show a longer shelf-life. Comparing Fig. 4b and 4d reveals that the apples after storage 2 show a slower trend in decreasing the firmness during the first four days on shelf than the apples after storage 4. It seems for the apples of the same firmness at the beginning of the shelf display that those after a long-term of storage in ULO lose their firmness faster during shelf display than those after a short-term of cold air storage. Further verification remains to be done.

In shelf display the apples also continuously lose their weight. It was reported by Peleg [8] that a loss over 5 to 10 % of weight would usually cause significant wilting, reduction of firmness, shrivelling and poor taste. Taking 5 % as a critical value for weight loss, the shelf-life can then be calculated and listed in Table 2. The table reveals the same trends as that concluded according to the critical value of the stiffness factor: the shelf-life of the apple decreases with the length of time during which they were stored in ULO and/or cold air. When considering its weight loss, five months are also a reasonable limitation for ULO storage of the apples used here. However, the table also shows that the later picked apples have a shorter shelf-life than the earlier picked apples, which is against the conclusions obtained according to the critical value of the stiffness factor. Checking the weight loss of the different group of the apples, we may note that in most cases in this experiment the later picked apples lose more water during storage and shelf display than the earlier picked apples.

In general, the shelf-life determined from the critical value of the stiffness factor 18×10^4 $kg^{2/3}s^{-2}$ is shorter than that determined from the critical value of the weight loss of 5 %. This firmness criterion can therefore guarantee the apple to suffer a weight loss less than 5%. The critical stiffness factor of 18×10^4 $kg^{2/3}s^{-2}$ is an adequate and reliable index in evaluating the deterioration of the apples during either ULO, cold air storage or shelf display.

CONCLUSIONS

Jonagold apples were commercially harvested in October 1991 on several picking days. The research here reveals that the later picked apples have a higher firmness than the earlier picked apples. The weight of the apples in the picking time depends on the weather conditions. Several days of rain fall before the picking time are appreciated in order to obtain apples with the maximum possible water content.

During ULO or cold air storage, the apple continues to ripen and meanwhile to lose its water content, causing a loss in firmness. ULO conditions can considerably slow down the ripening of the apple, but does not make an obvious difference in the weight loss in comparison with the cold air condition. Under certain temperature and relative humidity, the weight loss increases with storage time. The same group of apples tend to diverge more and more in firmness during the storage due to the different rate of each apple in the decrease of the firmness.

A critical stiffness factor of 18×10^4 $kg^{2/3}s^{-2}$ can be used to determine the allowable shelf-life of the apple after different periods of ULO and cold air storage. The shelf-life decreases with the length of ULO and cold air storage, and no more than five months in ULO would be suggested for apples used in this experiment. The shelf-life depends to a certain extent on the initial firmness and the storage conditions. The later picked apples, which are harder in firmness, have in general one to three days more in their shelf-life. With the same firmness at the beginning of the shelf display, the apples after a long-term of ULO storage have a shorter shelf-life than the apples after a short-term of cold air storage. Further verification remains.

The shelf-life determined from the critical stiffness factor is compared with the shelf-life determined from the critical weight loss of 5 %. In general the critical stiffness factor of 18×10^4 $kg^{2/3}s^{-2}$ can guarantee that the apple has less than 5 % of the weight loss.

ACKNOWLEDGEMENT

The authors are grateful to EUROFRU for the financial support for this research.

REFERENCE

1. **Chen H., De Baerdemaeker J., Vervaeke F.**: Acoustic impulse response of apples for monitoring texture change after harvest. Proc. Int. Conf. Agric. Eng., Beijing, China, 30-38, 1992.
2. **Finney E.E., Jr.**: Mechanical resonance within red delicious apples and its relation to fruit texture. Trans. ASAE, 23(1), 177-180, 1970.
3. **Hardenburg R.E., Anderson R.E., Finney E.E., Jr.**: Quality and condition of 'Delicious' apples after storage at 0 °C and display at warmer temperatures. J. Amer. Soc. Hort. Sci., 102(2), 210-214, 1977.
4. **Hardenburg R.E., Watada A.E., Wang C.Y.**: The Commercial Storage of Fruits, Vegetables and Florist and Nursery Stocks. USDA Agric. Handbook No. 66, U.S. Gov. Printing Office, Washington, 1990.
5. **Herregods M.**: Wanneer Jonagold Plukken en hoe Bewaren. Fruitteelt-Berichten, 5(16), 7-10, 1992.
6. **Holt J.E., Schoorl D.**: Mechanical properties and texture of stored apples. J. Texture Studies, 15, 337-394, 1984.
7. **Odeurs J.**: International Congress Prognosfruit. Belgische Fruitrevue, 44(8), 395-397, 1992.
8. **Peleg K.**: Produce Handling, Packaging and Distribution. The AVI Publ. Co., Inc., Westport, Connecticut, 1985.

9. **Tijskens L.M.M.**: Texture of Golden Delicious apples during storage. Lebensm. Wiss. Technol., 12, 138-142, 1979.
10. **Van Woensel G., De Baerdemaeker J.**: Mechanical properties of apples during storage. Lebensm. Wiss. Technol., 16, 367-376, 1983.
11. **Verheyen J.**: Weather Data Acquisition. Unpublished data, 1991.
12. **Wills R.H.H., Lee T.H., Graham D., Mcglasson W.B., Hall E.G.**: Postharvest: An Introduction to the Physiology and Handling of Fruit and Vegetables. The AVI Publ. Co., Inc., Westport, Connecticut, 1981.