MULTI-OBJECTIVE OPTIMIZATION OF STORAGE TEMPERATURE OF APPLE TO MINIMISE ENERGY USE

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ABSTRACT

The use of refrigeration accounts for up to 15% of the global use of electricity. For example, low temperature storage is widely employed to prolong the storage life of apples. Increasing the storage temperature by 1°C can significantly reduce the total cost of electricity during apple storage. In this study, a multi-objective optimization approach is used to suggest new storage temperatures of apple, taking into consideration the cost of electricity and the quality of the apple at the end of storage. Energy use was calculated using vapor pressure compression cycle models. Apple firmness was selected as the most important quality indicator for apple grading. The quality of the apple at the end of storage was converted to money value in €, based on the current grading system of apples in Belgium. Firmness was calculated using the firmness model developed by Gwanpua et al. (2012).The objective was to optimize storage temperature by minimizing the electricity usage, while minimizing quality losses (i.e. by maximizing the money value of the apple at the end of storage). This was done for different storage durations, and also for cool rooms with different storage capacity. New storage temperatures of apple, that will reduce the use of energy, were suggested.

1. INTRODUCTION

Over the last decades, several storage experiments have been carried out in order to optimize the storage conditions, namely temperature, relative humidity and gas compositions. For example, Kupferman (1997) reported that most apple cultivars can be stored for several months at temperatures between 0 and 3°C, and under controlled atmosphere (CA) conditions. However, most of these studies were done with the objective of only limiting quality losses, but not considering the aspect of energy use and environmental impact of the refrigeration technology. The objectives of reducing quality losses in apples during storage, the energy use and environment impact (via emission of CO_2 to the environment) are conflicting objectives, since improving on the quality retention at the end of storage (by storing at lower temperatures) will lead to more energy usage and greater environmental impact by the refrigeration technologies. In tackling such problem, a multi-objective optimization approach can be used. In this approach, a set of solutions that presents the best alternatives, the pareto optimal, is obtained (Deb, 2001; Ehrgott and Gandibleux, 2002).

The objective of this work is to present a multi-objective approach that can be used in selecting new optimal storage temperatures, such that quality loss is minimized, while at the same time minimizing the energy used and environmental impact of the particular refrigeration technology.

2. MAIN ALGORITHM

Step 1: Identify objective functions

The objective functions are the functions that define the objectives that need to be optimized in an optimization problem. They can either be algebraic or differential equations, and must be a function of the decision variable (i.e. in this case, they must be a function of temperature). In the current optimization problem, the main objective functions are the models for calculating (or predicting) energy use, CO_2 emission and quality loss during apple storage.

Step 2: Define constraints

Most often, during an optimization process, there may be optimal solutions that are not practically feasible. For example, apples cannot be stored at a temperature below its freezing point to prevent chilling injury (Watkins and Jackie Nock, 2004). Also, at certain high temperatures, the fruit may become susceptible to physiological disorders, such as internal browning (Lau et al., 1998) and loss in tritratable acids. This information, which is based on literature information about the particular apple cultivar, is used to define temperature bounds.

Step 3: Solve the multi-objective optimization problem

The multi-objective optimization problem is then solved using the multi-objective evolutionary algorithms (MOEAs). The optimization problem was implemented in Matlab (Matlab R2012a, The Mathworks Inc., Natick, USA) and solved using the Global Optimization Toolbox of Matlab (Matlab R2012a, The Mathworks Inc., Natick, USA). The output is a set of optimal solutions, the Pareto front. By defining a weighted multi-objective cost function, a single optimal storage temperature can be selected.

3. CASE STUDY: OPTIMIZING COLD STORAGE OF JONAGOLD APPLES

3.1. Objective functions

The three main objectives to be minimize are quality losses, energy use and CO_2 emission.

Objective 1: Minimize Quality loss

The goal of this first objective is to minimize quality loss in the fruit during storage. Flesh firmness is one of the most important quality indicators for apple quality. The model to predict the postharvest evolution of firmness developed by Gwanpua et al. (2012) was used to model quality loss in apples during storage (Eq. 1)

$$
\begin{aligned}
&\frac{d[\mathrm{P}]}{dt} = -k_{\mathrm{pect}}[\mathrm{P}][\mathrm{E}_{\mathrm{pect}}], \ \text{with}\,[\mathrm{P}](t=0) = [\mathrm{P}]_0 \\
&\frac{d[\mathrm{E}_{\mathrm{pect}}]}{dt} = k_{\mathrm{E}_{\mathrm{pect}}}[\mathrm{C_2H_4}] - k_{\mathrm{E}_{\mathrm{deg}}}[\mathrm{E}_{\mathrm{pect}}], \ \text{with}\,[\mathrm{E}_{\mathrm{pect}}](t=0) = [\mathrm{E}_{\mathrm{pect}}]_0 \\
&\frac{d[\mathrm{C_2H_4}]}{dt} = \frac{V_{max,\mathrm{C_2H_4}}\,\mathrm{p}_{\mathrm{O_2}}\sqrt{\dfrac{[\mathrm{C_2H_4}]}{[\mathrm{C_2H_4}]_{\mathrm{ref}}}}}{K_{m,\mathrm{O_2},\mathrm{C_2H_4}} + \mathrm{p}_{\mathrm{O_2}}\left(1 + \dfrac{\mathrm{p}_{\mathrm{CO_2}}}{K_{mu,\mathrm{CO_2},\mathrm{C_2H_4}}}\right)} - k_{\mathrm{C_2H_4}}[\mathrm{C_2H_4}] \qquad (1) \\
&k_i = k_{i,\mathrm{ref}} \exp\left(\frac{E_{a,i}}{R}\left(\frac{1}{T_{\mathrm{ref}}} - \frac{1}{T}\right)\right) \\
&F_{loss} = F_0 - \left(F_c + \gamma[\mathrm{P}]\right)
\end{aligned}
$$

where $\left[\mathrm{P}\right]$ (mmol m^{-3}) is the concentration of pectin; $\left[\mathrm{E}_{\mathrm{pect}}\right]$(mmol m^{-3}) is the concentration of the pectin degrading enzyme; $\left[\mathrm{C_2H_4}\right]$ (mmol m^{-3}) is the internal ethylene concentration; k_{pect}(m^{-3} mmol^{-1} d^{-1}), $k_{\mathrm{E}_{\mathrm{pect}}}$ (d^{-1}), and $k_{\mathrm{E}_{\mathrm{deg}}}$ (d^{-1}) are the rate constants for pectin breakdown, the synthesis of $\left[\mathrm{E}_{\mathrm{pect}}\right]$ and the turnover of $\left[\mathrm{E}_{\mathrm{pect}}\right]$ respectively; $V_{max,\mathrm{C_2H_4}}$ (mmol m^{-3} d^{-1}) is the maximum rate of ethylene production; $K_{m,\mathrm{O_2},\mathrm{C_2H_4}}$ (kPa) and $K_{mu,\mathrm{CO_2},\mathrm{C_2H_4}}$ (kPa) are the Michaelis-Menten constants for ethylene production and uncompetitive inhibition of ethylene production by carbon dioxide respectively; $\mathrm{p_{O_2}}$ (kPa) and $\mathrm{p_{CO_2}}$ (kPa) are the external partial pressure of oxygen and carbon dioxide respectively; $k_{\mathrm{C_2H_4}}$ is a rate constant related to the rate of diffusion of ethylene from inside the fruit to the surrounding; t (d) is time; k_i is a rate constant, having $k_{i,\mathrm{ref}}$ as a reference value at a certain reference temperature T_{ref} (283.15 K); $E_{a,i}$ (J mol^{-1}) is the activation energy for the respective reactions; R (8.3144 J mol^{-1} K^{-1}) is the universal gas constant, and T (K) is the temperature; ρ (kg m^{-3})is the density of the fruit; F_{loss} (N) is the loss in firmness; F_0 (N) is the initial value of the firmness; F_c (N) is a fixed part of firmness that is not affected by enzymatic breakdown and γ is a conversion factor that relates the amount of unhydrolyzed pectin to firmness. The reader is referred to the above mention reference for details of the firmness model. In this study, it is assumed that the apples were stored at an optimal CA of 1% O_2 and 2.5% CO_2. The initial apple firmness was taken as 75 N.

Objective 2: Minimize energy

The second objective is to minimize the amount of energy used for cooling the fruits during storage. Energy consumption was calculated using software developed for this purpose based on simple static models. The software is made of four main components:

Refrigerant thermophysical properties functions: these functions use equations based on Cleland (1986) to calculate refrigerant properties, i.e., saturated vapor pressures and temperatures, saturated and superheated vapor enthalpies, and liquid enthalpy.

Component functions: using the Number of Transfer Units (NTU) method to evaluate the outlet temperature of the fluids leaving the heat exchanger, and also to calculate the enthalpies for non-isentropic compression.

Cycle models functions: these are functions that are used to calculate the global coefficient of performance for the refrigeration cylce. Different cycle models have been implemented in the software: (i) one stage, direct expansion evaporator, direct system; (ii) one stage, multi temperature evaporators; (iii) two stage (cascade with 2 refrigerants), flooded evaporator, direct system; (iv) two stage (open inter-stage), flooded evaporator, direct system.

Evaluation functions: these are functions that use the calculated COP to calculate the yearly energy consumptions.

Objective 3: Minimize CO_2 emission

The third and final objective is to minimize the amount of CO_2 emission by the refrigeration technology during cold storage. The CO_2 emission was calculated using the Total Equivalent Warming Impact (TEWI), expressed in kg CO_2/ year, based on the following equations (Eq. (2)):

$$TEWI = \left(\underbrace{\underbrace{GWP \cdot L/100 \cdot n \cdot m}_{Leakage} + \underbrace{GWP \cdot m \cdot (1-\alpha)}_{Recovery\ losses}}_{Direct\ emissions} + \underbrace{\underbrace{n \cdot E_{annual} \cdot \beta}_{Energy\ consumption}}_{Indirect\ emissions} \right) \Big/ n \qquad (2)$$

where GWP is the Global Warming Potential of the refrigerant (depend on the infrared absorption properties of the gas and the elapsed time before it is purged from the atmosphere); L (%/year) is the leakage rate per year ; n (years) is the operational lifetime of the refrigerator; m (kg) is the refrigerant charge; α (0 to 1) is the recycling factor; E_{annual} (kWh) energy consumption per year (objective 2) and β (kg CO_2/kWh) is the CO_2 emission per kWh (depends on country, as different countries use different sources for electricity generation).

3.2. Temperature bounds

The lower temperature bound was set at 0°C to avoid chilling injury, while the upper bound was set at 3°C to avoid physiological disorders (other than loss in firmness) associated with long term storage of apples at high such temperatures.

3.3. Optimization of cold storage

The optimization was done for both a medium size storage facilities (typically the type used by the apple growers), and large size storage facilities (typically at the auction). Also, the optimization was done assuming different storage durations (3 months, 6 months and 9 months). Table 1 summarizes some of the main properties of the two types of storage facilities considered.

Table 1. Main properties of the medium and large size storage facilities.

Storage facility	Properties	
Medium size storage facilities	Room dimensions:	15m x 15m x 4.5m
(at the grower)	Storage capacity:	300 tons
	Cooling load:	12.21 kW
	Refrigerant:	R134a
	Compressor efficiency:	75%
Large size storage facilities	Room dimensions:	15 cells of (11.5m x 11.5m x 4.5m)
(at the auction)	Storage capacity:	2880 tons
	Cooling capacity:	91 kW
	Refrigerant:	NH_3
	Compressor efficiency:	80%

3.4. A multi-objective cost function

After the optimization, the optimal storage temperature was selected from the Pareto optimal solutions by defining a weighted cost function that relates quality, energy and CO_2 emission as shown in Eq. (3).

$$f_{profit} = Q_{sales} - E_{\cos t} - CO_{2,\cos t} \tag{3}$$

where f_{profit} (€) is the chain profit; Q_{sales} (€) is the expected income from sales of the fruits; $E_{\cos t}$ (€) is the expected cost of energy use in cooling, $CO_{2,\cos t}$ (€) and is the expected cost arising from the emission of CO_2 to the environment (CO_2 emission rights). It should be noted that both $E_{\cos t}$ and $CO_{2,\cos t}$ are proportional to the storage duration.

The Q_{sales} was calculated based on the trend of Jonagold apple prices in Belgium. The apples were divided into three grades depending on the firmness at the end of storage. Apples firmer than 70 N were classified as grade I and was valued at 0.95 € per kg; apples with firmness between 60 N and 70 N were classified as grade II and valued at 0.55 € per kg, and apples softer than 60 N were classified as grade III and valued at 0.35€ per kg. However, a critical firmness of 40 N was defined, below which the apples cannot be sold.

$E_{\cos t}$ was calculated using an average electricity pricing in Belgium, which was taken as € 0.0967 for energy use less than 2 GWh per year, and € 0.0871 for energy consumption larger than 2 GWh per year.

The $CO_{2,\cos t}$ was calculated from a CO_2 emission right of 20 € per ton CO_2 , based on the values reported for by the Committee on Climate Change (CCC, 2009, p68).

4. RESULTS AND DISCUSSION

The pareto frontier for the different storage scenarios is shown in Figure 1 (only the 2D pareto front for energy use versus quality loss is shown). From Figure 1, it can be observed that the best optimal solution for minimizing energy use is the worst solution for minimizing quality losses. By applying the weighted cost function in Eq. (3), an optimal solution was selected, which gives the maximum chain profit. The result of the selected optimal solution for all six scenarios is shown in Table 2. It can be seen from Table 2 that if the storage of Jonagold apples is expected to be less than 6 months, then the optimal storage to minimize energy use could be 3° C, instead of the traditional 1°C, which may result to more than 5% gain in energy. Energy use and CO_2 emissions seems to be correlated because emission is a direct consequence of the use of the refrigeration technology. However, different technologies can be expected to result into different emissions. In the current study, we directly used the actual β value for Belgium (0.29 kg CO_2/kWh) based on the current electricity sources, but without making the connection to the actual technologies. The objective was to optimize storage temperature and not to select optimal refrigeration technology.

Table 2: Selected optimal solution for different storage scenarios.

Scenario	Optimal temperature (°C)	Loss in firmness (N)	Energy use (MWh)	CO_2 emission (tons)	Chain profit (€)
Large size, 9 months storage	1.4	4.9	172.6	110.6	2,717,100
Large size, 6 months storage	3	2.5	110.2	70.6	2,723,900
Large size, 3 months storage	3	0.4	55.1	35.3	2,730,000
Medium size, 9 months storage	1.2	4.6	23.3	15.0	282,450
Medium size, 6 months storage	3	2.5	14.8	9.5	283,380
Medium size, 3 months storage	3	0.4	7.4	4.8	284,190

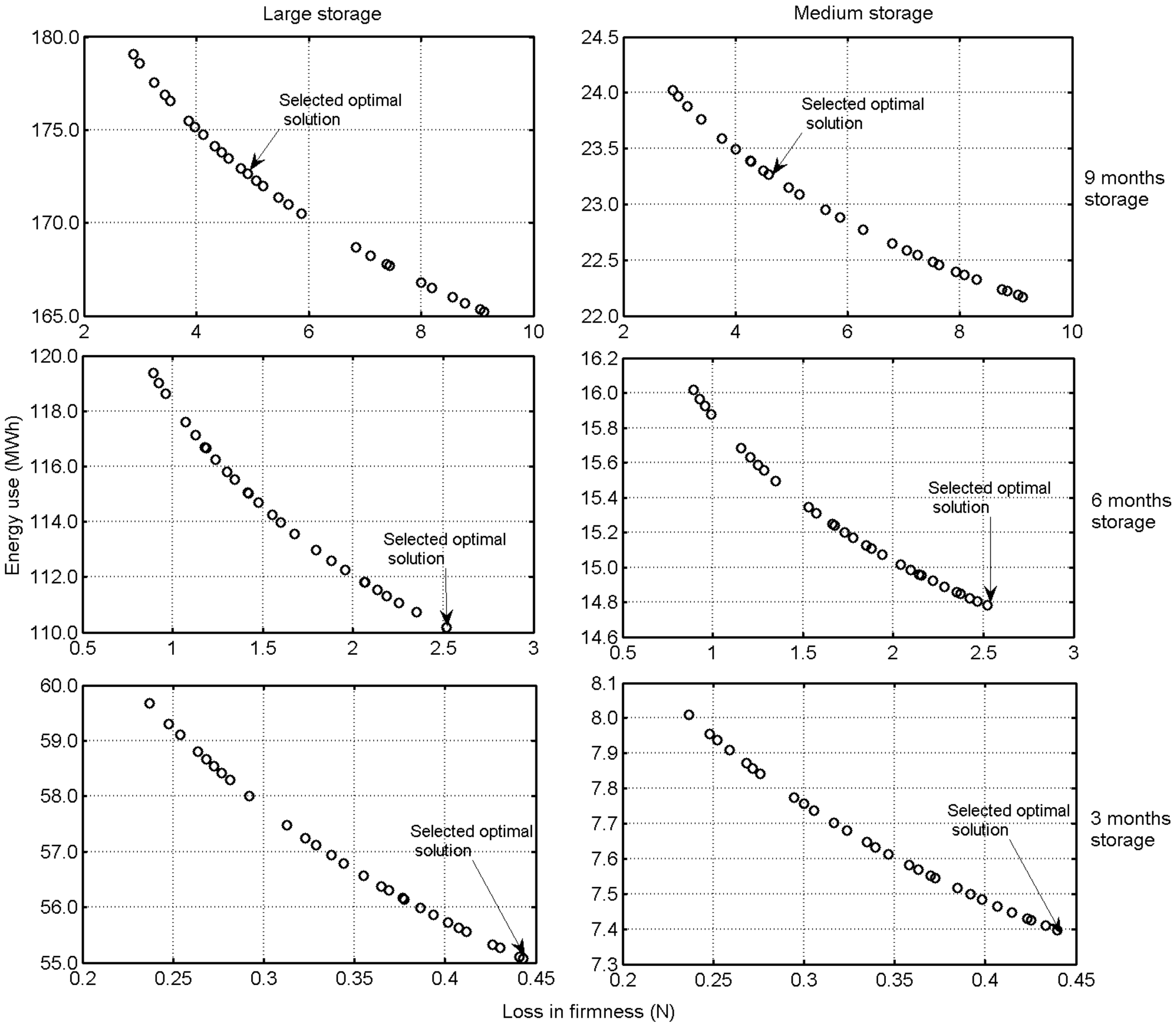

Figure 1. Pareto frontier of the six different scenarios. The graphs shows the tradeoff between energy use and quality losses in apple during storage. The selected optimal solution is also indicated for each scenarios.

The use of amount in € as a common weight factor is subject to debate. First of all, the prices of apples fluctuate throughout the year and depend on several factors that are not under the control of the grower or auctioneer. Furthermore, the price of energy depends on the source. For example, solar energy is free (apart from the onetime installation cost), while the cost of electricity varies within a single day depending on peak and off-peak hours. Also the cost of electricity might vary depending on the average day temperature for a particular month. Finally, the CO_2 emission rights also vary throughout the year (e.g. see CCC, 2009, p 68). Many models exists that are able to predict energy prices (Pflug and Broussev, 2009 and Caporin et al., 2012) and CO_2 emission rights (Daskalakis et al., 2005; Uhrig-Homburg and Wagner, 2006; Benz and Trück, 2009). These models could be coupled into the current approach to get an even better and more realistic optimization. The objective of this research is to provide a methodology that can be used to obtain optimal temperatures for apple storage, taking into count the quality, energy use and emission of CO_2.

5. CONCLUSIONS

This paper provides a multi-objective approach in selecting optimal storage temperatures for apples, taking into account the quality, energy use and environmental impact. From the result for Jonagold apples, it is possible that storage could be done at different temperatures, depending on when it is expected that the apples are sold. This is not so straight forward as it may seems, since it is not usually under the control of the grower or auctioneer to decide when to remove the apples from storage, but depends hugely on the market prices, which is highly stochastic. Several stochastic models already exist to predict energy prices and CO_2 emission rights. Though not trivial, developing a stochastic model to predict the price of apples will make the current algorithm a very practical approach in optimizing apple storage.

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REFERENCES

Caporin, M., Preś, J., Torro, H., 2012. Model based Monte Carlo pricing of energy and temperature Quanto options. Energy Economics 34,1700–1712.

Benz, E. and Trück, Stefan., 2009. Modeling the price dynamics of CO2 emission allowances. Energy Economics, 31 ,4–15

CCC (12 October 2009). Meeting Carbon Budgets – the need for a step change. Progress report to Parliament Committee on Climate Change. Presented to Parliament pursuant to section 36(1) of the Climate Change Act 2008. The Stationery Office (TSO). ISBN [[Special:BookSources/978-9999100076|978-9999100076]]. Retrieved 27 November 2012.

Cleland, A. (1986). Computer subroutines for rapid evaluation of refrigerant thermodynamic properties. *Int. J. Refrigeration* **9**, 346-351.

Daskalakis, G., Psychoyios, D., Markellos, R., 2005. Modeling CO2 emission allowance prices and derivatives: evidence from the EEX. ERIM Report Series ERS-2005-052-F&A

Deb, K., 2001. Multi-objective Optimization using Evolutionary Algorithms (Chichester: John Wilet & Sons).

Ehrgott, M. and Gandibleux, X. (Eds), 2002. Multiple Criteria Optimization – State-of-the-art Annotated Bibliographic Surveys (Dordrecht, Kluwer Academic Publisher).

Gwanpua, S., Coronado. K., Verlinden, B., Hertog, M., Nicolaï, B., Geeraerd, A. (2012). Modeling the effect of ethylene on rate of firmness breakdown and loss of background color of 'Jonagold' apple during CA storage. The 7th International Postharvest symposium (IPS 2012). Kuala Lumpur, Malaysia, 25th – 29th June 2012.

Kupferman, E. 1997. Controlled atmosphere storage of apples. In: E.J. Mitcham (ed) Proc. 7th Intl. Contr. Atmos. Res. Conf., Vol. 2: Apples and Pears. Postharvest Hort. Ser. No. 16. Univ. Calif., Davis CA, pp. 1-31.

Lau, O.L., 1998. Effect of growing season, harvest maturity, waxing, low O2, and elevated CO2 on flesh browning disorder in Braeburn apples. Postharvest Biol. Technol. 14, 131 – 141.

Pflug G.C. and Broussev, N., 2009. Electricity swing options: Behavioral models and pricing. European Journal of Operational Research, 197, 1041–1050.

Uhrig-Homburg, M., Wagner, M., 2006. Success chances and optimal design of derivatives on CO2 emission certificates. Working Paper, University of Karlsruhe.

Watkins, C., Jackie Nock. J., 2004. SmartFreshTM (1-MCP)—the good and bad as we head into the 2004 season New York Fruit Quarterly, 12 (3) , pp. 1–26