Quality Control in the Storage of Potatoes for Industrial Processing

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Abstract

A novel control structure for a potato storage facility is presented that is directly geared at the optimal preservation of product quality. The quality of the stored potatoes is defined as frying colour that depends on sugar concentration. The optimal storage conditions are estimated using models of both product behaviour and storage process to optimise quality and costs. The control structure is implemented in an industrial storage facility. Results show an improved product quality and lower energy cost. An important extension to the nominal product model is the consideration of product quality with its variation.

INTRODUCTION

Storage is an important part of the production cycle in the food industry. Although harvesting is season-bound, the food industry demands year-round supply of product. Potatoes are usually stored in large storage rooms where climate conditions are controlled using ventilation with outside air. This means that an a priori imposed product quality is translated into specifications for the process (storage) temperature. In potato storage product quality is defined as the sugar content, that is expressed in the so-called frying colour index, and the total mass of product. The sugar content is affected by a variety of processes such as cold-induced sweetening, senescent sweetening, respiration and sprouting. The intensity of these processes strongly depends on the storage conditions. The total mass of stored potatoes is mainly affected by evaporation. The evaporation rate depends on temperature and air humidity inside the storage facility. Cost of storage that can be controlled during the process is the energy usage expressed in hours of ventilation.

At present, most storage processes are controlled mainly on air temperature inside the storage facility. Using outside air ventilation for climate control means that potatoes have to withstand the large fluctuations in outside temperature during autumn, winter and spring. By applying controlled ventilation in the storage room, using outside air at convenient times, the temperature of storage is kept as good as possible at an acceptable temperature (e.g. 6°C for Bintje). Thus, these storage processes are not controlled directly by relevant aspects of product quality as sugar content and weight-loss.

The industry is enforced to improve process control to increase the added value of processing/storing agro-material. This is caused by different actors and includes:

- high quality demands from consumer,
- more efficient processing,
- environmental regulations.

Improving storage operations asks for direct product quality control is necessary that takes the characteristics of processing agro-material like variation into account. For this reason a (semi-) commercial application was developed to optimise the storage conditions for batches of potatoes. This adds another layer to the normal control structure. The aim of this research was to:

- improve product quality (taking its variation into account),
- limit the energy usage.

In this paper, the required models of both product and process are discussed and the resulting novel control structure is shown, and some results are shown of an implementation of the presented approach in an industrial facility.

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MATERIALS AND METHODS

To improve product quality and at the same time limit the energy usage we developed a new control structure for storage of potatoes that strongly depends on available models. The model of the product, of product quality and its variation, and of the storage climate are discussed. Also, the control structure is shown and the different control components are presented. Notation is listed below.

Notation

ΔH_v	evaporation energy	[J/kg]	T	air temperature	[K]
ΔP	pressure difference	[Pa]	U	heat convection coef.	[J/m^{2}s]
Θ	product temperature	[K]	k_v	evaporation coef.	[kg/m^{2}s]
ε	product air ratio		t	time	[s]
φ	density	[kg/m^3]	x	horizontal direction	
λ	heat conduction coefficient		y	vertical direction	
A_{sp}	heat exchanging surface	[m^2/m^3]			
Cp	specific heat	[J/kg K]	Subscript		
D	air moisture		a	air	
G	air flow	[m/s]	p	product	
M	product moisture				

Product Modelling

At high temperatures, quality decay is rather fast, limiting directly the keeping quality of the potatoes. At low temperatures, the process of sweetening is increasingly gaining in importance, limiting indirectly keeping quality. In both cases, processing quality in terms of frying colour will be quite low. Measurement of sugar content results from lab analysis of product samples taken frequently from the storage facility. The process of potato sweetening during cold storage and the senescence has been modelled extensively by Hertog et al. (1997). The reactions that are important for quality in potato storage can be written as

$$\begin{gathered} S + O_2 \xrightarrow{k_{resp}} H_2O + CO_2 \\ Starch + En_{cold} \xrightarrow{k_{cold}} S + En_{cold} \qquad Starch + En_{sene} \xrightarrow{k_{sene}} S + En_{sene} \\ En_{cold} \xrightarrow{k_{dena}} En_{cold\ non-active} \qquad En_{sene} \xrightarrow{k_{form}} En_{sene\ non-active} \end{gathered} \tag{1}$$

The first reaction represents the respiration, and the second and third reactions are enzymatic reactions representing cold-induced and senescent sweetening. Senescent sweetening is an irreversible reaction. This can be included in the model by constraining the corresponding yield-coefficient to positive values. The fourth and fifth reactions are reactions describing the changing of the assisting enzyme concentrations. From the reactions the following model can be derived

$$\begin{bmatrix} \dot{En}_{cold} \\ \dot{En}_{sene} \\ \dot{S} \end{bmatrix} = \begin{bmatrix} -k_{dena}(T) & 0 & 0 \\ 0 & k_{form}(T) & 0 \\ k_{cold}(T)Starch & k_{sene}(T)Starch & k_{resp}(T)O_2 \end{bmatrix} \begin{bmatrix} En_{cold} \\ En_{sene} \\ S \end{bmatrix}, \tag{2}$$

with,

En_{cold} = enzyme concentration, En_{sene} = enzyme concentration,

S = sugar content, $k_i(T)$ = reaction rate.

The parameters $k_i(T)$ are the yield-coefficients that are assumed to be only temperature dependent following an Arrhenius-type equation. The model can be extended to describe O_2 and CO_2 dependencies (of yield-coefficients) and concentrations.

Modelling Product Variation

Most often in practice variation in product quality is dealt with using so-called quality classes. Measurement data is available in terms of these discretised quality classes. As the model structure for quality variation has a control purpose the use of a complicated continuous distribution model for the quality variation is not a feasible possibility. As an alternative, a three-step approximation procedure is proposed in Verdijck et al. (2001):

- Discretise the main quality variable (sugar content) into separate intervals/classes,
- Model the transfer of products between the classes,
- Express the variation in sugar content as an extension to the nominal model structure.

Nominal or average behaviour of the sugar content determines the time-evolution of the classes and class boundaries. The benefit of these (nominal) changing class boundaries is that transfer between classes only occurs if variation in the assisting state variables effects the product behaviour. In that case a product does not show nominal behaviour and may transfer. The number of products in a class can be described with

$$\dot{n}_i = -n_{i,i+1} + n_{i+1,i} - n_{i,i-1} + n_{i-1,i} \qquad (3)$$

where e.g. $n_{i,i+1}$ represents the transfer from class i to class i+1. Transfer between classes occurs if the difference in value of the assisting state variable between this product and a nominal or average product is large enough.

With the extensions to the nominal model structure, variation in the main product state caused by initial variation in the main and assisting state variables can be described. This extended model will be used to control quality variations.

Modelling the Process

In the process model the storage facility is divided in different parts (Figure 1) with their own function. The air room uses air from either outside or inside the storage facility. Ventilation with air from outside is called external ventilation and is mainly performed for cooling purposes. Internal ventilation uses air from inside the facility and is mainly performed for ensuring a homogeneous distribution in the potato stock with respect to temperature and CO_2. The air is blown into one or more air channels that distribute the air in the storage facility, through the potato stock. This potato stock consists of the solid product and the gas phase (air). Energy and moisture is exchanged between the two phases. Air is leaving the potato stock into the upper space of the storage facility and is, to some extent, mixed with the air in this part. In case of external ventilation pressure tends to rise and air is released outside of the storage facility. In case of internal ventilation, air is forced to flow to the air room.

The differential equations for the moisture content and temperature of both air and product are obtained from the mass and energy conservation laws. The main assumptions with the modelling on macroscopic level are:

- constant potato volume,
- uniform distribution of the potatoes in the facility,
- uniform air stream and
- constant specific heats (temperature independent).

Furthermore, we assume that moisture and temperature profiles inside the potatoes, and heat conduction in the air phase can be neglected. For the gas phase in the potato stock this results in

$$\varepsilon\rho_a \frac{dD}{dt} = -G\rho_a \frac{\partial D}{\partial x} + A_{sp}k_v\Delta P \qquad [kgm^{-1}s^{-1}]. \qquad (4)$$

The first term of the right hand side (r.h.s.) of Equation (4) represents the moisture flow caused by the air stream. The second term represents the evaporation from the solid phase. Temperature in the gas phase is described by

$$\varepsilon\rho_a(Cp_a + D(x)Cp_{wd})\frac{dT}{dt} = -G\rho_a(Cp_a + D_{in}(x)Cp_{wd})\frac{\partial T}{\partial x} + UA_{sp}(\Theta - T) \qquad (5)$$

$$\frac{\partial M}{\partial t}\frac{1}{\delta x}Cp_{wd}(x)(\Theta - T) \qquad [J s^{-1}].$$

The first term of the r.h.s. represents the energy flow that is associated with the air stream. The second term is the heat exchange between solid and air phases. The energy involved in the mass stream from solid to air phase is represented by the third term. The other parts in the storage facility consist only of a gas phase and can be modelled following the same procedure as for the gas phase in the potato stock. A difference is the absence of interaction terms between product and air phase. Further, external ventilation introduces outside air temperature and humidity in modelling the airshaft. The moisture content in the solid phase of the potato stock is described by

$$(1-\varepsilon)\rho_p\frac{dM}{dt} = -A_{sp}k_v\Delta P + c_1\rho_p(1-\varepsilon) \qquad [kg s^{-1}]. \qquad (6)$$

The first term of the r.h.s. in Equation (6) represents the evaporation, while the second term represent the respiration. Product temperature is described by

$$(1-\varepsilon)\rho_p Cp_p(x)\frac{d\Theta}{dt} = E_v - UA_{sp}(\Theta - T) - \frac{\partial M}{\partial t}\Delta H_v + \lambda\frac{\partial^2\Theta}{\partial x^2} + \lambda\frac{\partial^2\Theta}{\partial y^2}[J s^{-1}]. \qquad (7)$$

Equation (7) contains terms due to the respiration energy, the heat exchange between gas and solid phase, evaporation energy and the second order effect of heat conduction in the solid phase in horizontal and vertical directions. The energy consumption is determined by the ventilation periods. The amount of ventilation depends on the heat exchange between the storage facility and the environment, on the energy production by respiration and on the desired storage conditions.

Control Structure

In the storage operations three different time scales can be recognised. State variables can be defined on each of these time scales:

- primary state (x_p),
- direct environment state (x_d),
- indirect environment state (x_i).

The primary state variables are those product components that determine the product quality attributes, such as colour, shape, taste and smell. This is discussed in the previous sections, e.g. for sugar and enzyme concentrations. The direct environment is defined as that part of the process that directly interacts with the primary state variables, e.g. air temperature in the potato stock. The indirect environment defined as that part of the process that does not affect the product directly, but only through the direct environment, e.g. air temperature in the air room. What indeed happens is that one operates on a particular time scale. Consequently, the model granularity is adjusted to reflect the respective time scale. The term time scale thereby reflects not only the behaviour of the plant and its components but also the input that is applied. More details are discussed in Verdijck et al. (2002). In general, each substate is controlled with a separate control component as its dynamics can be decoupled from the other substates. This is reflected in the newly developed control structure for storage of potatoes that is illustrated in Figure 2.

Local Controllers

The local controllers manipulate the indirect environment with their control actions, u, to reach and maintain the setpoints, u_s. These setpoints are controlled by the short-term controller that controls the direct environment. In the current control structure, the local controllers, of the on-off type, are the only controllers in potato storage.

Short-Term Control

The Model predictive controller determines the optimal process condition (storage temperature) that keeps product quality and energy usage as close as possible to the reference quality trajectories as determined by the long-term optimisation. Constraints are included in the controller algorithm. These constraints are determined by the performance of the Local controller, the product, outside weather and the storage facility.

The calculation of the temperature setpoint is performed weekly. A problem is that measurements of the quality parameters are not continuously available. In potato storage, sugar content and weight-loss are measured only by taking samples and analysing these samples on a regular basis. Therefore, a measurement prediction was introduced to estimate these states. Information on energy usage, and product and air (both direct and indirect environment) temperatures are continuously available in the form of hours of ventilation. The Model predictive controller uses a linearised model of the storage process with respect to sugar content, total mass of product and usage of energy.

Long-Term Optimisation

The scheduler calculates the reference quality trajectories for product quality and energy usage. The Model predictive controller uses these setpoints. The optimisation is based on information about prices for different quality levels, costs involved with energy usage, and data on the stored product and the storage facility. The setpoints are calculated at the start of the storage process. The optimisation can be repeated in case of unexpected situations such as, an extreme cold winter, ventilation problems, product diseases, changing storage periods or a large update in the model parameters.

RESULTS

Results are shown of an implementation to control nominal product quality in an existing storage facility. Furthermore, an analysis of the quality variation model is shown.

Implementation to Control Nominal Product Quality

Results with the developed application are shown in Figure 3, where realised temperatures and sugar concentrations are shown (together with the setpoints) that result from a test with the implemented control structure on an industrial storage facility.

Results showed a higher product quality with lower energy cost using the new application as compared to the existing control structure. Temperature fluctuations result from fluctuations in outside air temperature that affect inside storage conditions as outside air is used for cooling. The sharp changes in the setpoint for the sugar content results from an update of the model parameters based on available measured data. These model parameters are used in estimating the most efficient sugar trajectory. Summarising the results one may conclude that the implementation of the new (product quality) controllers in an industrial storage facility lead to:

- a higher product quality,
- lower energy cost (not shown).

Analysis of Control of Product Quality Variation

In this case study, the variation in other variables is assumed to accumulate in the state variable, En_{cold}. Three different classes are defined. The modelling approach mentioned earlier has as state variables the sugar contents and both enzyme concentrations for each class, number of products for each class and the variation in the enzyme concentration En_{cold} in each class. The results obtained with this model are shown in Figure 4.

The results using the different classes improve the understanding of the behaviour of the product in the storage process with respect to the sugar content. The sugar contents for the different classes are within the measurement accuracy. The simulated variation shows similar behaviour as the measured variation between the measured samples. Differences can be explained by measurement noise. The (small) decrease of variation shown at the end of the simulations corresponds with empirical knowledge. This also explains the transfer of products between the classes (not shown) that shows a decrease in variation. The resulting numbers of products in each class are shown in Table 1.

$$x(t_f) = Px(t_0) \tag{8}$$

with

$$P = \begin{bmatrix} 0.75 & 0.6 & 0 \\ 0.25 & 0.5 & 0.25 \\ 0 & 0.4 & 0.75 \end{bmatrix}$$

This transfer matrix transfers the initial distribution to the final one.

CONCLUSIONS AND FURTHER RESEARCH

At present, most storage processes are mainly controlled on air temperature inside the storage facility. The controllers in these operations aim at keeping the process variables air temperature, and sometimes humidity, as close as possible to some pre-specified values. This means that an a priori imposed product quality is translated into specifications for the process temperature.

In this paper, the development of a controller is discussed that takes directly the quality of the final product into account. The regulation of the processing conditions is subordinate to the (economic and quality) objectives. This adds another layer to the normal control structure. This research showed an improvement of the storage process with respect to product quality and process efficiency by the use of the developed model-based controllers that directly include product quality and its variation.

Currently, other processes and products are investigated, such as the transport of apples and storage of exotic fruits. Firmness is then the main quality property for consumer acceptance.

Literature Cited

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Tables

Table 1. Number of products in a class (in total 1800 products)

Class\time	Initial time (t_0)	Final time (t_f)
1	560	597
2	600	600
3	640	603

These results can be described with a transformation matrix

Figures

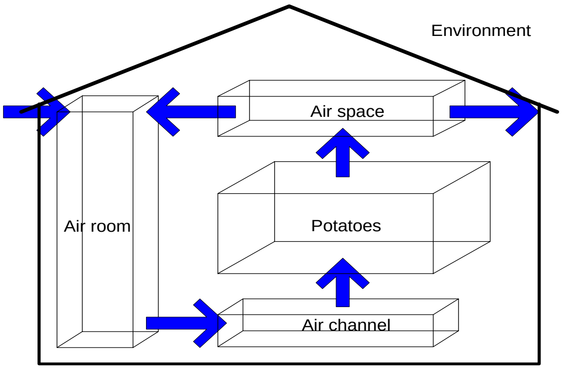

Fig. 1. Model parts of a storage facility

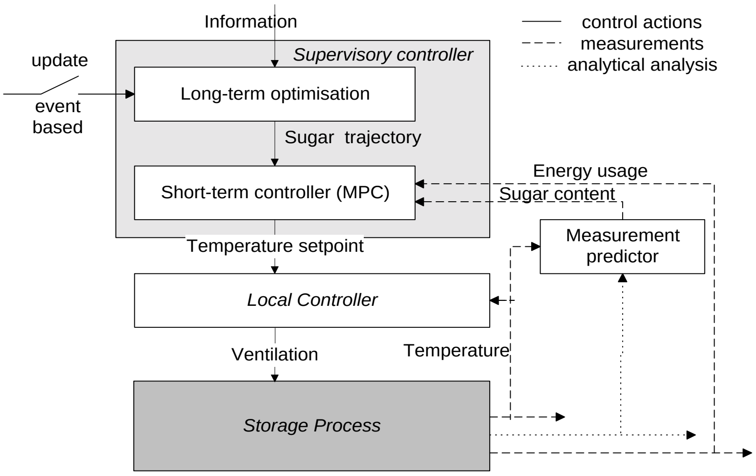

Fig. 2. Control structure for quality control in potato storage

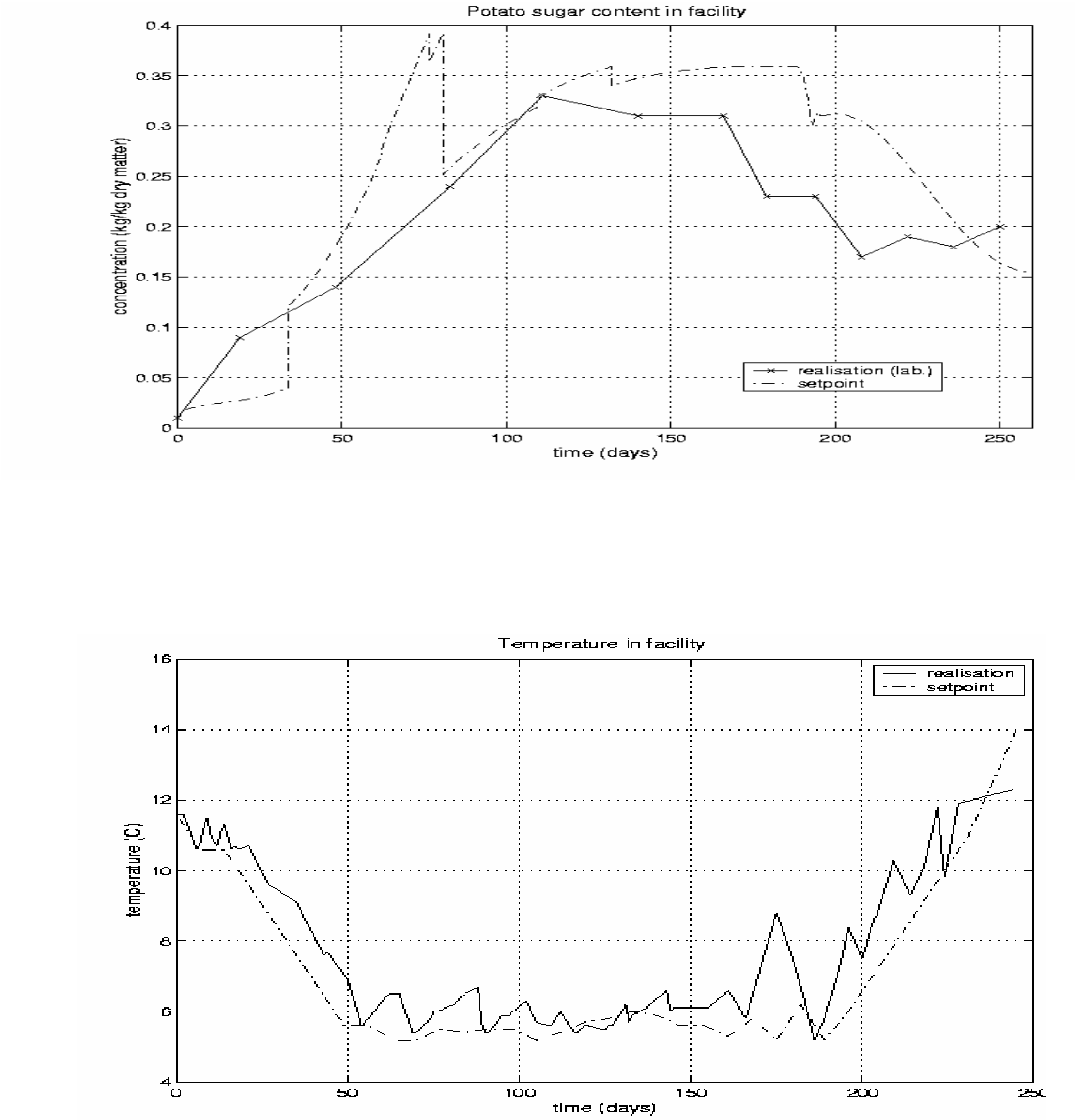

Fig. 3. Sugar content and temperature (setpoint and realised trajectories)

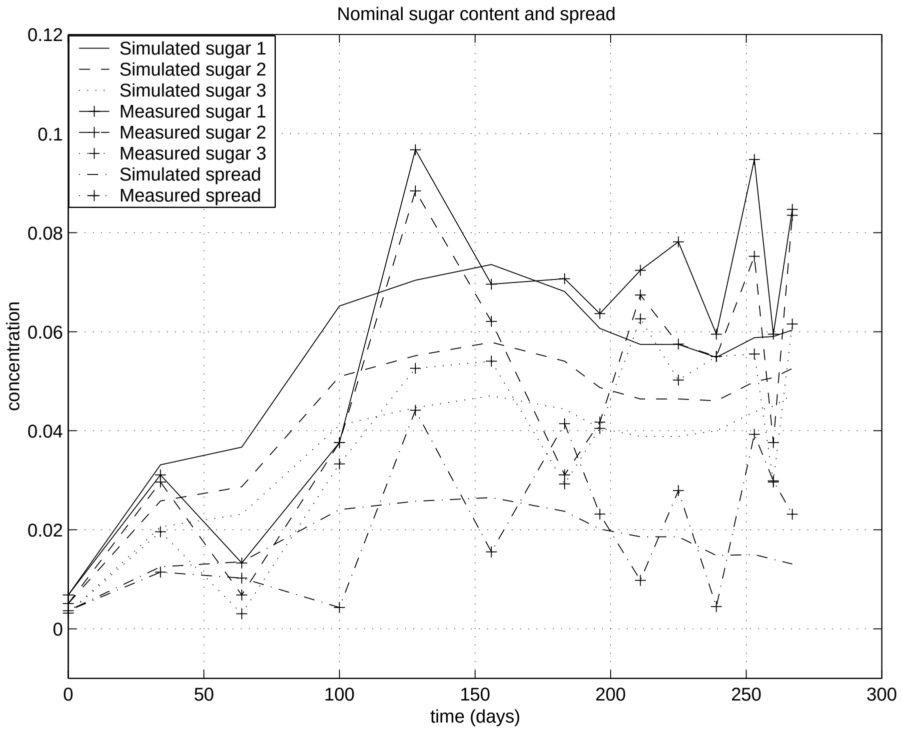

Fig. 4. Simulated and measured sugar concentrations