FEEDBACK CONTROL SYSTEM DESIGN FOR A FRESH CHEESE SEPARATOR

Markus Hoyer[1] **Reimar Schumann**[2] **Eberhard Wüst**[3] **Giuliano C. Premier**[4]

[1,2,3] *University of Applied Sciences and Arts Hannover, Research Centre AUBIOS, 30459, Hannover, Germany*
[4]*University of Glamorgan, School of Technology, CF37 1DL, Pontypridd, Wales*

Abstract: In the food industry, automatic control of quality parameters is limited by the availability of sensors for such parameters. For fresh cheese production the installation of NIR (near infrared) sensors opens the path for the design of automatic control schemes for dry matter and protein content. This paper describes a design procedure for such control schemes, including design and identification of process models and simulation of different control schemes, and presents results for an industrial dry matter control application on an industrial fresh cheese production line.

Keywords: Food processing, process models, process identification, computer aided control system design, industrial control.

1 INTRODUCTION

Today the use of automatic feedback control in most companies of the dairy industry is still restricted to simple flow, temperature and pressure control applications. As soon as feedback control of product quality parameters like fat content, dry matter or protein content becomes available, a huge potential for quality improvement and cost reduction could be tapped. A typical example is the fresh cheese (quarg) production: In Germany fresh cheese is produced in large quantities (700 000 tons/year) from skimmed milk (low fat), generating large quantities of sour whey (two million tons/year) as a by-product. According to these figures the efficient supervision and control of the product quality parameters, dry matter and protein content, plays a key role for the economic production of fresh cheese, determining the amounts of energy and raw material required. This paper deals with the design of an advanced control system for a fresh cheese separator, where the standard flow control system is complemented by dry matter (and protein content) control – a practical research task not yet treated in the state-of-the-art literature. After a general description of the fresh cheese production plant, including conventional instrumentation and control, the first part of the paper deals with various aspects of the design procedure: the selection of an NIR (near infrared) inline sensor for the detection of fresh cheese dry matter and protein content, the design of a qualitative process model from heuristic descriptions and the simulation based design of alternative separator control schemes. The second part describes the path towards practical implementation of the separator control system on an industrial fresh cheese production line. This starts with a general discussion of the technical environment in an actual, realistic dairy scenario which does not have an advanced process control system with a comfortable user interface. An analysis based on online measurements of the input/output process behaviour of the industrial separator is then described and leads to a quantitatively described separator model. Taking into account the views of the process operators who would accept only an accessible, practical and simple control system, application results are shown for dry matter control of an industrial fresh cheese production line demonstrating the efficiency of the implemented control system. The paper ends with concluding remarks.

2 FRESH CHEESE PRODUCTION PROCESS

A typical fresh cheese production line is shown in Figure 1. After pasteurisation the skimmed milk is pumped into a ripening tank (1) in which culture and rennet are added. After the coagulation process

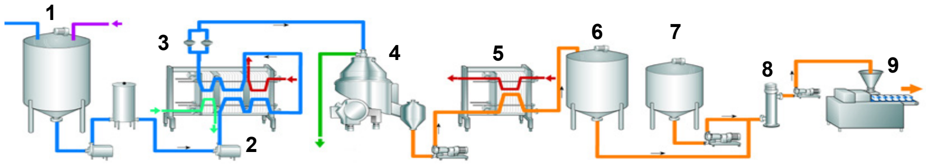

Fig. 1. Fresh cheese production line (Tetra, 1995)

(about 16-20 hours) the curd is stirred and pumped through the first heat exchanger (2) where it is heated in the first and cooled in the second section (thermisation). The curd is fed to the separator (Figure 2) through filters (3). The separator divides the flow into fresh cheese and sour whey by centrifugal separation. The fresh cheese is pressed through nozzles at the periphery of the separator bowl and delivered to a vat. The sour whey leaves the separator through an outlet at the top. From the vat the fresh cheese is pumped through the second heat exchanger (5) (cooling) to a buffer tank (6) before it is mixed (8) with cream (7) or other ingredients and packed (9).

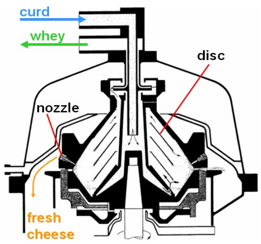

Fig. 2. Fresh cheese separator (cross section)

3 INSTRUMENTATION AND OPERATION OF A FRESH CHEESE PRODUCTION LINE

Typically a fresh cheese production line is operated with a minimum of instrumentation and control support. The start-up of the production line is still done manually only marginally supported by instrumentation and automatic control functionality. A typical instrumentation set-up comprises temperature and pressure indicators on tanks and heat exchangers, on/off switches for most pumps and limited flow and other control systems, Figure 3.

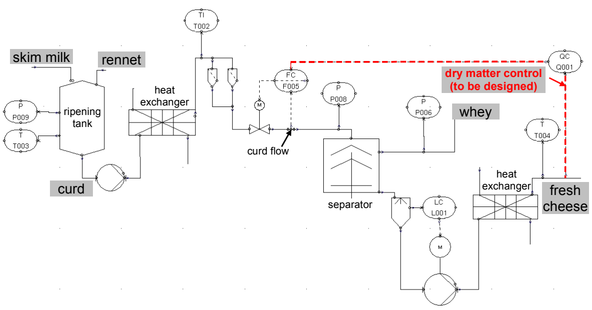

Fig. 3. P&I-diagram for fresh cheese production line

Standard instrumentation comprises a flow control loop for the curd feed to the separator with flow sensor and control valve and a level control loop for the fresh cheese vat behind the separator with level sensor and adjustable pump. The quality parameters, dry matter and protein content of the produced fresh cheese, are controlled manually by the operator by changing the curd feed to the separator which is adjusted by manipulating the curd flow set-point. To determine the quality parameters of the fresh cheese produced, samples are normally taken from the fresh cheese outlet of the separator and analysed in a laboratory. The determination procedure for the dry matter content value takes about 30 min, for the protein content value up to 120 min. Based on these off-line measurements, the curd flow to the separator is varied manually to achieve minimum dry matter and protein content above the allowed limits defined by German regulations. However, due to the large measurement time delays, the set-point values must be defined with large safety margins to the official limits, thus reducing the dairy's profit. Moreover, with only one control variable (curd flow), only one quality parameter can be adjusted optimally – in general dry matter – whereas the second (protein content) is in general kept above the allowable limit, thus producing additional losses of profit.

4 INLINE SENSOR FOR DRY MATTER AND PROTEIN CONTENT

The main obstacle to improve the control set-up for dry matter and protein content is the large sample processing time in the laboratory to determine the actual values of these quality parameters. To overcome this problem inline-sensors based on near infrared (NIR) spectroscopy, have been installed in fresh cheese production lines. Over the last decade, NIR technology has found increasing application in the food industry to measure quality parameters in fluid, solid or gaseous media, see e.g. (Williams and Norris, 2001; Osborne and Fearn, 1993). The near infrared spectrum comprises wavelengths between 700 and 2500 nm, i.e. it is very close to visible light. NIR spectroscopy uses the specific absorption properties of the analyte (product to be analysed) and tries to establish unique relations between the measured spectral response and the concentration of chemical components like protein content or general properties like dry matter. However, as measured NIR spectra consist of overlapping vibrational bands, advanced multivariate calibration algorithms and statistical methods have to be applied to produce reliably measurement values, which requires computational support often described as chemometric mathematical data processing. The principle nevertheless is rather simple: NIR electromagnetic waves interact with the product in the measuring device causing molecular vibrations. The loss in energy, called absorbance (A), is directly related to the number of molecules i.e. to the concentration (c) of the specific constituent. To differentiate between different molecules, i.e. different constituents in the product, the absorbance must be measured at different wavelengths. The single constituent concentration is calculated by making use of the following prediction (estimation) equation:

$$c = F_0 + F_1 \cdot A_1 + \ldots + F_n \cdot A_n \qquad (1)$$

The index (1,..., n) denotes the used wavelengths, A_i the absorbance value at the i-th wavelength and F_i the weight factors to be determined. Calibration is done by measuring teaching (calibration) samples with known concentration and absorbance values and calculating optimal F-values for a specific constituent using e.g. multiple linear regression or the "intelligent" regression strategy of Partial Least Square, see (Martens and Naes, 1989).

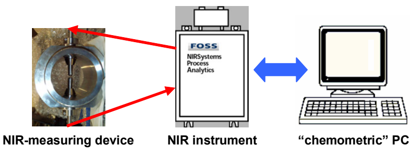

Fig. 4. NIR inline sensor set-up

A general NIR inline sensor set-up at the fresh cheese production line is shown in Figure 4. The NIR instrument basically contains standard NIR spectroscopic equipment, however, the measurement light is fed through an optical fibre to the NIR measuring device and similarly back to the instrument where it is superposed to the reference beam. The analysis of the measured NIR spectra is done by an external PC using chemometric software: after appropriate calibration dry matter and protein content values of the fresh cheese are calculated using two different estimation equations (1) within about 20 seconds – a dramatic reduction compared to 30 resp. 120 min for the conventional procedure. From time to time - first daily, then weekly - the calibration is checked by comparing the NIR measurement results with measurement values from the laboratory analysis. Wüst et al (1998) reported that, using NIR as base for manual control, the standard deviation of the dry matter could be reduced from 0,24% (conventional method) to 0,12% (NIR-method) and after further improvement of the process set up from 0,14% to 0,09%.

5 SEPARATOR CONTROL DESIGN

5.1 Qualitative separator model

The first step towards the design of the dry matter and protein content control system was the development of a dynamic separator model reflecting all static and dynamic relationships required (Figure 5). Model inputs are the curd flow to the separator as the essential manipulating variable and the two artificial signals (grey) representing the main disturbance sources: the blocking of a separator nozzle and the slow fouling of a separator disc. As model outputs, the two quality parameters, dry matter and protein content of the fresh cheese, were chosen together with the whey and fresh cheese flows from the separator where in practice the fresh cheese flow (grey) is not directly measured. A qualitative model was designed using the model information gained from interviews with dairy experts, describing the gain and time characteristics of the interactions between the model inputs and outputs: A decrease in the curd flow to the separator does not change the fresh cheese flow significantly but reduces the whey flow from the separator after a small delay. Also, the quality parameters, dry matter and protein of the fresh cheese, are lowered by a decrease in the curd flow.

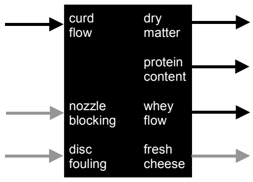

Fig. 5. Inputs and outputs of basic separator model

However, the detection of these changes is delayed by the instrumentation (calculation time) delay in the NIR sensor and the transport delay (dead time) of 120 seconds caused by the position of the NIR measuring device after the second heat exchanger in Figure 3. The blocking of a nozzle (one out of about 10) decreases (almost instantaneously) the fresh cheese flow and increases the whey flow thus changing their ratio. In addition, dry matter and protein content of the fresh cheese rise (with the same measurement delays as described above) to higher values. When a separator disc starts fouling, the dry matter and protein values ramp down, but this does not significantly affect the fresh cheese and whey flows.

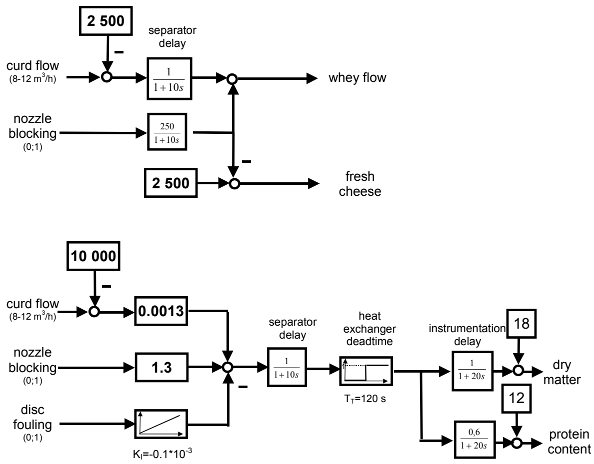

Fig. 6. Qualitative separator model

The behaviour described was modelled according to Figure 6 using simple first order lag and dead time blocks for instrumentation and transport delays between inputs and outputs. The model was simulated using DORA (Krause, 2003), assuming reasonable parameter values for gains and time constants appropriate for a standard fresh cheese production line thus reflecting the behaviour as described by dairy experts. The simulation results for a step change in curd flow, a blocked nozzle and a fouled disc with this model are shown in Figure 7.

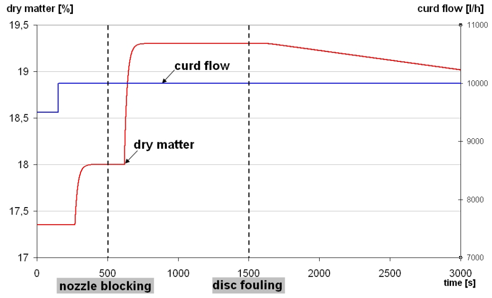

Fig. 7. Simulation of qualitative separator model

5.2 *SISO control design for dry matter*

The simplest control scheme for dry matter is shown in Figure 8 where the dry matter signal is used directly in a simple PID loop.

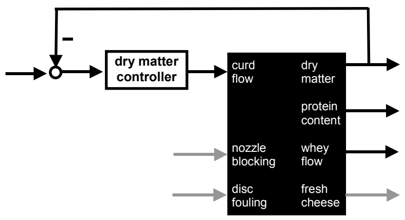

Fig. 8. SISO control scheme for dry matter

The time delays do not allow the application of high controller gains. Accordingly the simulation results for the heuristically identified model and an appropriately tuned PI controller are shown in Figure 9. It is obvious that this kind of control system reacts rather slowly to a nozzle blocking disturbance resulting in a control deviation of the dry matter of about 1,2 % at an assumed set-point of 18 %.

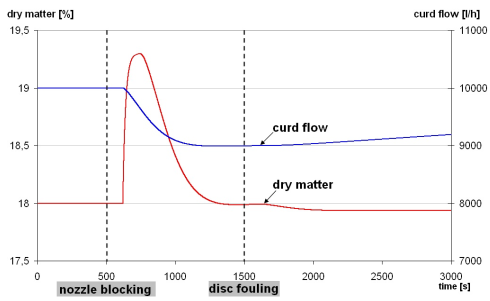

Fig. 9. Simulated behaviour of dry matter SISO control (set point 18 %)

However, the effect of disc fouling is almost completely compensated using this simple control scheme.

5.3 *Cascade control design for dry matter*

The large control deviations observed after the nozzle blocking are caused by the time delays on the dry matter measurement, preventing a fast control reaction. Such nozzle blocking is however indicated almost instantaneously by a change of the ratio of whey to fresh cheese flow. To make the control react more quickly a cascade control system was designed as shown in Figure 10, with an additional inner loop controlling the ratio between whey and fresh cheese flow. Two PI controllers are used such that the ratio controller can be parameterised with relatively high controller gains. In this control scheme the fresh

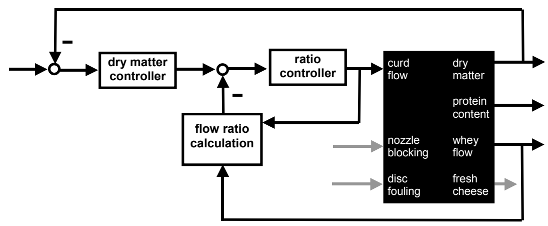

Fig. 10. Cascade control scheme for dry matter

cheese flow is not directly measured (and is difficult in practice due to technological problems attributed to the high viscosity of the medium). So the flow ratio is reconstructed based on the mass balance using the simple equation:

$$\frac{\dot{m}_{whey}}{\dot{m}_{freshcheese}} = \frac{\dot{m}_{whey}}{\dot{m}_{curd} - \dot{m}_{whey}} \qquad (2)$$

The simulation results for this control scheme, Figure 11, indicate a considerable improvement as the control deviations after nozzle blocking are now reduced to less than 0,2 % (Remark: The oscillations at the beginning of the simulation are due to the reconstruction of the ratio, in which an auxiliary second order lag was added in order to dampen such oscillations to

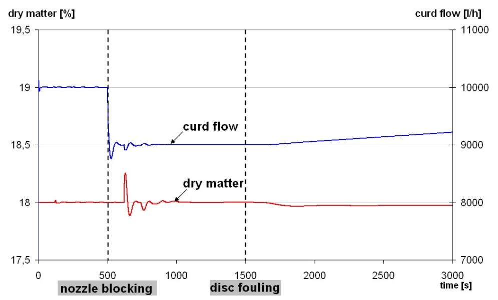

Fig. 11. Simulated behaviour of dry matter cascade control (set point 18 %)

an acceptable amplitude). However, the high controller gains of the ratio controller and the reconstruction scheme makes the control system rather sensitive to small changes of model and/or control parameters, which complicates its practical application.

6 INDUSTRIAL APPLICATION

6.1 *Technical set-up at industrial production line*

On the Humana AG (Georgsmarienhütte) fresh cheese production line, all separator control functions are implemented using stand-alone industrial PID controllers, allowing the implementation not only of feedback control functions but also of PLC functions to support the start-up of the process. After an intensive cleaning procedure the production line is started-up by switching the separator feed from (cleaning) water to curd from the ripening tank. Two feedback controllers are used for the separator, as indicated in Figure 3: The first is used to control the curd feed flow via a control valve, the second to control the level in the fresh cheese vat directly after the separator, by adjusting the pump action. The level set point is fixed but the curd flow set point is adjusted manually by the operator in order to keep the dry matter value at the required value of 18 %. As the simulations indicated that automatic control may reduce the dry matter variations further during normal operation, it was decided to test automatic control by cascading the curd flow control loop with the simple control scheme for dry matter according to Figure 8. The operator would then be able to switch to automatic control of dry matter after starting-up the production line. The more advanced, but also more complicated, cascade control scheme of Figure 10 was not acceptable to the operators due to the need to operate a third cascaded controller. The implementation of the simple cascade control system was done with a stand alone controller ABB Protronic 500 (ABB, 2002), which can handle both, the curd flow control loop and the cascaded dry matter control loop, together with the PLC support for the start-up procedure.

6.2 Process identification for controller tuning

The first step towards practical implementation of the separator control system was the identification of a quantitative process model. To get a more sophisticated separator model, measurements for the separator input and output signals were recorded over 4 weeks at the fresh cheese production line of Humana AG, which was equipped with flow sensors for curd feed and whey and also with an NIR sensor for dry matter and protein content (Foss PA-NIRS 5500). The recorded signals in Figure 12 indicate that the curd flow to the separator was frequently changed by human operators to keep the dry matter value at a-

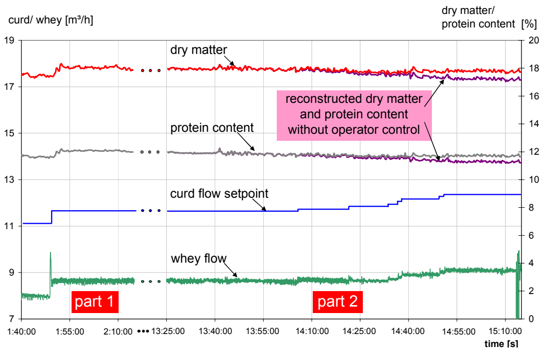

Fig. 12. Measurements on the Humana AG separator

bout 18 %, see part 1 of Figure 12. Here it should be noted that the operator changes the set point of the underlying curd flow control loop resulting in a delayed transition of the curd flow to the new set point. The fouling of a separator disc (slow disturbance) can be observed in the second part of Figure 12 where the operator tries to stabilise the dry matter by reducing the curd flow. A nozzle blocking and the expected effects on flows and quality parameters could not be detected during the observation period of 4 weeks. From the recorded signals linear models were identified from several step responses using DORA's correlation method characterising all interactions between the inputs (curd flow and disc fouling) and the outputs (whey flow, dry matter and protein content). The resulting transfer functions are listed in Table 1.

Table 1 Identified transfer functions

curd flow → dry matter	$F_{11} = \frac{(0.78+40s)\cdot 10^{-3}}{1+55s+3540s^2}\cdot e^{-90s}$
curd flow → protein content	$F_{21} = \frac{(0.59+56s)\cdot 10^{-3}}{1+127s+7130s^2}\cdot e^{-90s}$
curd flow → whey flow	$F_{31} = \frac{1+40s}{1+16s+94s^2+324s^3}$
disc fouling → dry matter	$F_{12} = \frac{-0.14\cdot 10^{-3}}{s}\cdot e^{-90s}$
disc fouling → protein content	$F_{12} = \frac{-0.12\cdot 10^{-3}}{s}\cdot e^{-90s}$

Model verification was done by comparing the simulated model responses with recorded output signals for various time windows. A typical verification result is shown in Figure 13. It should be noted that the analysis of the dry matter and protein content measurements was complicated by the asynchronous recording of the dry matter and protein content signal values as the NIR sensor produced them at arbitrary time intervals. The complicated transfer functions are at least partially due to the (oscillating) transient behaviour of the underlying curd flow control loop.

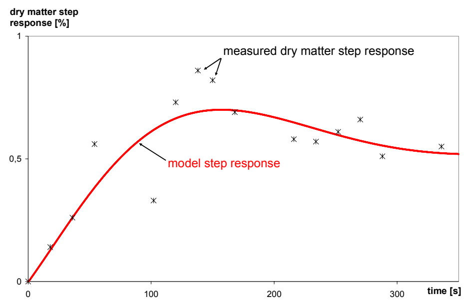

Fig. 13. Comparison of model output and recorded output (curd flow step 0,7 m^3/h)

The tuning of the dry matter PI controller was done by simulating the control loop with the identified process model F_{11} using manual optimisation: The main problem here was the large heat exchanger dead time forcing a small integral control portion.

6.3 Industrial control application results

After implementation of the dry matter PI controller at the Humana fresh cheese production line it was tested over a period of 4 weeks with excellent results: Comparison of operation cycles with and without automatic control have shown that the standard deviation of dry matter could be reduced from 0,08% (NIR with manual control) to 0,05% (NIR with automatic control). Also the process operators reacted positively as they were relieved from the time consuming task of manual control of dry matter content. Figure 14 illustrates the effectivity of the automatic controller: The decline of dry matter caused by a tank change was compensated after 3 minutes – this means after about the unavoidable process dead time.

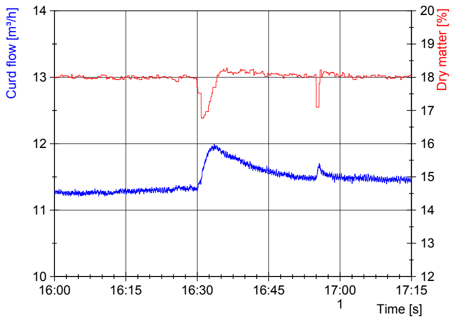

Fig. 14. Industrial dry matter control results

Further measurements and continuing process monitoring over a longer time period will follow.

7 MIMO EXTENSION OF CONTROL SYSTEM

At present, fresh cheese quality parameter control is practically restricted to dry matter as only the curd flow to the separator can be used as control signal at the process. So the second quality parameter, protein content, is not actively controlled and often far above the allowed minimum resulting in losses of profit. This is why alternative process set-ups and control schemes have been tried. One possibility is the addition of so-called fresh cheese concentrate (18 % dry matter and < 12% protein content) after the separator, which has already been tested in experimental set-ups on fresh cheese production lines. Using this second process control input the design of a simple MIMO control scheme can be done as shown in Figure 15. First simulation results indicate that such a MIMO control scheme is applicable in principal, reducing both, the control deviations for dry matter and protein

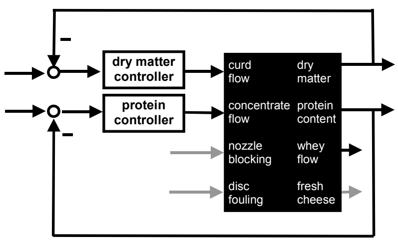

Fig. 15. Extended MIMO control scheme

content. However, for practical application of such a MIMO control scheme, a concentrate feed system must be installed on the production line and the influence of the concentrate flow input on the dry matter and protein content values has to be further analysed with respect to static and dynamic properties.

8 CONCLUSIONS

In the dairy industry, automatic control of quality parameters is limited by the availability of appropriate inline sensors. For fresh cheese production, NIR sensors for dry matter and protein content have become available, allowing a dramatic reduction of the quality variations, even with manual control. This paper has presented alternative designs of automatic control schemes for a fresh cheese separator. Simulations and practical results at an industrial fresh cheese production line have shown that with automatic control quality variations can be further reduced. For automatic control of dry matter only the simple control scheme was accepted by industrial operators due to practical handling conditions. The use of automatic control for both, dry matter and protein content will require the installation of a second control input at the process. Nevertheless, simulations demonstrated the principal feasibility of MIMO control for both quality parameters. With the availability of NIR sensors for fresh cheese production, new possibilities for efficient automatic control schemes for relevant quality parameters become possible which will reduce production costs by minimising quality variations.

ACKNOWLEDGEMENT

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REFERENCES

ABB (2002). Protronic 100/500/550 – Controllers for process engineering. *ABB manual 42/62-50011 EN Rev. 06*, ABB Automation Products GmbH.

Krause, P. (2003). Anwendungsfelder für DORA für Windows. *6. GMA Kongress Automation und Inform. in Wirtschaft & Gesellschaft*, Baden-Baden.

Martens, H. and T. Naes (1989). *Multivariate calibration*. John Wiley & Sons, New York.

Osborne, B. and T. Fearn (1993). *Practical NIR spectroscopy with applications in food and beverage analysis.* John Wiley & Sons, New York.

Tetra (1995). *Dairy Processing Handbook.* Tetra Pak Processing Systems AB, Lund, Sweden.

Williams, P. and K. Norris (2001). Near-infrared technology in the agricultural and food industries. American Association of Cereal Chemists, St. Paul, Minnesota, USA.

Wüst, E., U. Hülsen and H. Wietbrauk (1998). Ressourcen bei der Frischkäseproduktion (Teil 2). *Deutsche Milchwirtschaft,* **17**, pp. 714-716.