Optimization of Milk Powder Production using MPC with Minimum Energy Consumption

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ABSTRACT

In the food industry it is often preferable to produce milk in the form of powder. There are several reasons, such as changing market conditions, long distances of transportations for further processing and environmental circumstances. Milk powder as intermediate product creates also more freedom for flexible logistics.

Milk powder is traditionally dried in a large spray dryer with heated drying air to reach desired powder moisture content. The spray dryer unit is a huge energy consumer and in principle not very energy efficient. In milk powder production skimmed milk is first concentrated to a desired solid content in an evaporator. In this process unit also a lot of energy is used to remove a big amount of water. In some cases these both process units are dynamically quite strongly coupled together via a limited intermediate volume.

Valio Oy in Seinäjoki, Finland, has recently accomplished an Advanced Process Control (APC) project to increase skimmed milk powder production in co-operation with its APC vendor, Neste Jacobs Oy. The basic idea was to maximize the production with minimum energy consumption using real time optimization with multivariable model-predictive control (MPC) technology. The combination of the evaporator and the spray dryer in the MPC system created highly potential improvements in the milk powder production. The realized MPC system is designed to maximize the production by pushing continuously both units against dynamically varying process constraints as well as product quality constraints. The MPC solution utilizes measured and real time calculated process and product quality variables as controlled or constraint variables. The controlled product quality key variables are provided by on-line near infrared (NIR) analyser. The MPC application is equipped with a recipe system, which allows several product qualities to be produced with the same control structure.

The MPC application package has shown within long term production campaigns to be capable of keeping the production 8 % higher than before the MPC installation. The operation of the plant is more stable and the drying batches are more equal to each other than before. After MPC installation it has become much easier for the control room operators to produce repeatable drying batches.

The paper is organised as follows: first the process is presented together with the client's expectations towards the real-time optimization and control. The control and optimization strategy is presented with some final performance examples such as normal production maximization with energy minimization at times when maximum production is not available. The MPC implementation projects steps and timeline are roughly outlined and finally project results are presented.

1 INTRODUCTION

Specific milk powder production occurs by manipulating the drying process through a continuously changing operational window. There are several dynamic product property and process constraints to limit the operating window. Continuously changing global optimum may from time to time be within the operating window or totally beyond the constraints of the window. In practice the optimum is defined as a maximal available production rate within product property and process constraints of the combined evaporator and spray dryer.
The final product of the drying process is the milk powder with maximum allowed moisture, including other specified product properties. From the dryer operability point of view, the sticky point of the milk powder is the most important constraint as well as the constraints of the atomizer, which enable optimal spraying conditions in the dryer. There are also several important process constraints related to the real time material balances of the process units.
From the energy point of view it is required to optimize the ratio of water removals of the process units, the evaporator and the spray dryer. More economical is to remove water in the evaporator as much as possible to reduce the specific energy consumption in the dryer. In practise it means maximizing the solids content in the evaporator outlet against constraints of the both process units. Handling of the material balance over the total drying process enables the continuous optimal drying.
The real time drying optimization has been implemented by the NAPCON MPC technology by Neste Jacobs Oy. The real time material and energy balances implemented by NAPCON Information System have been also utilized in the optimization.

2 PROCESS DESCRIPTION AND MILK POWDER OPERABILITY

The evaporator consists of the pasteurization part and the evaporator itself, Figure 2.1. Combined skimmed milk and permeate flow is first fed from the feed tank through a steam heat exchanger to the pasteurization unit by the total feed flow rate controller. The pasteurization is carried out in the combination of two different ways. First the indirect pasteurization occurs in the ordinary heat exchangers. Secondly using direct steam injections into the milk or milk into a steam atmosphere is used.
The advantage of the indirect heating is that the product will not be mixed with the condensing steam and either will the product be diluent. The disadvantage is that it takes long time for the product to be heated from 80 ˚C to 110 ˚C resulting in a concentrate with high viscosity. The advantage of the direct pasteurization is the short time to reach the desired temperature resulting in low viscosity.
For improved efficiencies these systems have been incorporated in the pasteurization unit of Figure 2.1. The temperature of the skimmed milk is raised step by step; first in the indirect pasteurization up to 60 – 80 ˚C, and secondly in the direct steam injection units up to 90 – 95 ˚C prior to the evaporation unit. The internal levels of the direct pasteurization units are controlled by basic level controllers. The temperature of the pasteurization is mainly controlled by the outlet temperature controller of the indirect heat exchanger.

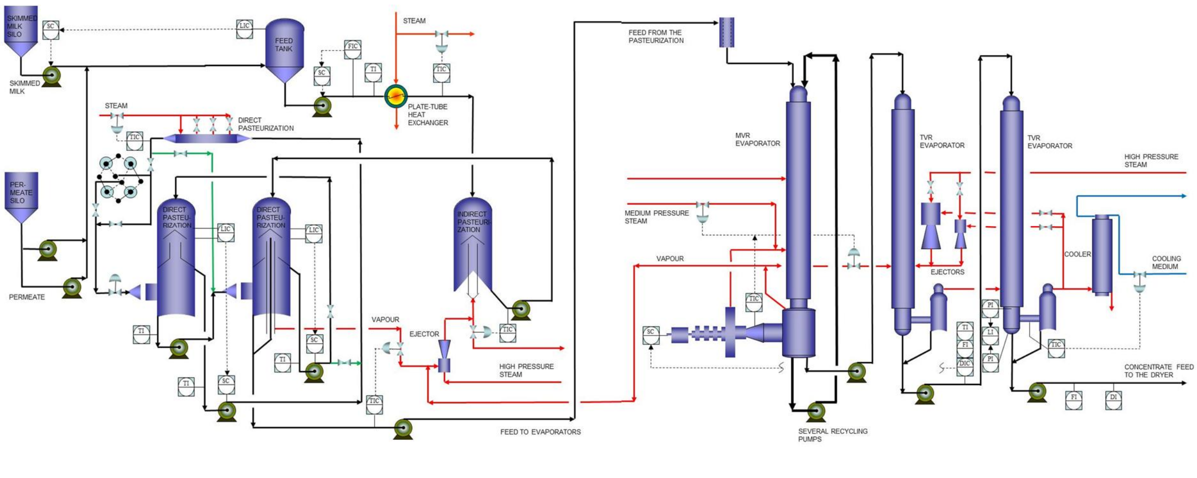

Figure 2.1 The pasteurization unit and the evaporator.

The evaporator section consists of three falling film evaporators in series. The evaporations take place effectively in the huge surfaces of the tubes, which are heated indirectly by superheated steam.

The first evaporator is of MVR (Mechanical Vapour Recompression) type, where the applied energy for the compressor is electricity. The desired milk powder quality defines the usage of the MVR evaporator, which produces a very short residence time, resulting in low viscosity of the concentrate.
The following two evaporators are of TVR (Thermo Vapour Recompression) type, which will increase the temperature/pressure level of the vapour, i.e. compress the vapour from lower pressure to a higher pressure by using steam of a higher pressure than that of the vapour. Thermo-compressor operates at very high steam flow velocity and has no moving parts. The best efficiency of the thermo-compressor, i.e. the best suction rate and thereby a good economy, is obtained when the temperature difference (pressure difference) between the boiling section and the heating section is low.
The main controlled variable of the evaporator is the milk density. The other important controlled variable is the temperature of the cooled milk in the evaporator outlet.
There is no particular feed tank to the dryer section. Only the relative small bottom volume of the last phase of the evaporation is acting as a feed tank. The level of this volume is closing the material balance between the evaporator and the spray dryer, and it is important to keep the level within its limits to guarantee sufficient feed to the dryer.

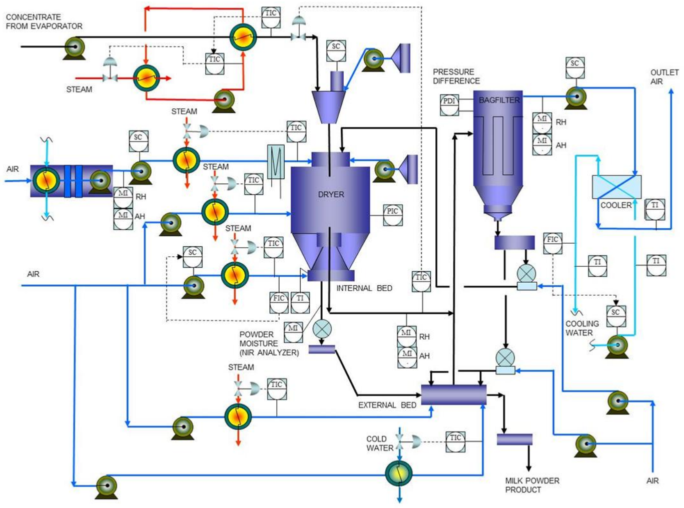

Figure 2.2 Spray dryer and bag filter

In the dryer the feed concentrate is preheated and sprayed into the dryer through the atomizer, which is the most critical part of the drying. With appropriate viscosity and solids content (density) of the feed the atomizer is functioning properly and creates optimal spaying into the chamber of the dryer. The drying air is used as the drying media, which is heated to a specific temperature. This is defined as a recipe value and represents the usage of the minimum drying energy. The degree of the drying is defined by the dryer outlet air temperature controller, which manipulates the loading of the dryer by the concentrate feed rate. The pressure of the dryer chamber is controlled by the drying air feed pump with a basic pressure controller.
At the bottom of the dryer there is an internal fluidized bed with a separate drying air feed and its temperature is controlled by a steam heater. The milk powder is falling from the chamber to the fluidized bed, where the drying continues with the heated air. This is followed by an external fluidized bed, where the powder is first heated by a separate temperature controlled air flow and at the end of the external bed the powder is cooled with a cool temperature controlled air flow. After that the product is led to storage.
The out coming drying air from the chamber and external fluidized bed is led out through a bag filter, where the small particles are collected into the bags of the filter and removed totally away from the outflowing air to avoid any easy food for the birds. They may cause serious salmonella problems. The functionality of the bag filter is monitored by the pressure difference over the filter and the functionality is kept in an appropriate level by the chamber pressure controller and the bag filter outlet air pump.
Humidity of the drying air is measured in the incoming and outgoing flows. The moisture of the outgoing milk powder is measured by a continuous real-time NIR analyser. These measurements help the operability of the dryer, which is quite demanding for manual operation.

3 CLIENT'S EXPECTATIONS

For the starting point of the APC implementation project the client's personnel raised their functional expectations. This knowledge disclosed the functional APC framework to be clarified in more details during the performance analysis and the feasibility study of the actual APC project.
The general goal was to set up a system to optimize in real time both the evaporator and the spay dryer. The main target for optimizing was to reach more capacity. Also optimization of the drying air was to be included in the APC scope. Process stability, flexible operation and better product quality were brought out. Also the bottle necks such as managing the dust content was kept important.
More expectations were brought out with the real time NIR analyser implementation at the outlet of the dryer in the later phase of the APC project.

4 OPTIMIZING APC CONTROL STRATEGY

Based on the above mentioned client's expectations, process pre-tests and the performance analysis the optimizing APC control strategy with profit estimates was generated together by the representatives of Valio Oy and Neste Jacobs Oy. The corresponding APC control targets were also submitted.

4.1 Control targets

The APC control targets were defined as follows:

- Keep the measured outlet air humidity (RH) steady in all circumstances. This also keeps the product moisture as steady as possible.
- Maximize continuously the production rate by decreasing the outlet air temperature of the dryer within the product and process constraints
- Optimize the inlet air temperature related to the production rate and within the process constraints
- Keep the dryer temperature below the real time sticky point constraint of the product
- Keep the concentrate feed rate and feed pressure, feed pump load and atomizer load below the predefined individual constraints
- Keep the pressure difference over the bag filter below a predefined constraint and avoid blocking up the bag filter
- Keep the solids concentrate of the feed steady under continuous maximization to avoid evaporator disturbances to proceed to the dryer and to ease the operation of the dryer
- Adapt continuously the capacity of the evaporator according to the continuously maximized production rate of the dryer

Further there are plenty of process specific constraints, such as valve positions, temperatures and steam pressures, which are continuously modifying the operational window.
NAPCON controller utilizes also recipes, where optimal control parameters for each product grade have been defined. Based on the recipe system the designed control strategy covers all the product grades.

4.2 Control strategy

The multivariable control strategy has been designed to realize the above presented control targets. Also the involved basic controls of DCS level have been verified, which are utilized in the control strategy. The control strategy covers the automatic operations of the evaporator, the dryer and the bag filter taking also into account the drying air and concentrate feeds. The implemented control strategy invoked the needed stability of the drying within the whole operational area and created even wider repeatable operation area allowing the operation closer to the constraints. As a result more economical optimization with products of higher moisture content within process and product quality constraints was gained.
The most important basic control loop in the DCS is the dryer outlet air temperature controller, which manipulates the concentrate feed into the dryer. This is also the main control loop utilized by the APC and it is ought to be tuned in accordance with APC actions. All the incoming disturbances from evaporator into the dryer can be detected by the concentrate feed density measurement. The main disturbance variable is the incoming water content, which causes changes in solids concentration and viscosity. These disturbances affect strongly on the operation of the atomizer and thereby on spraying. The disturbances can be neglected by the feedforward controls of the APC.
Variations of the inlet air humidity can be detected by a measurement (RH). Normally the air humidity is quite constant within the used control frequency domain, but e.g. in the presence of thunder storms or sudden rain falls

the air humidity changes can cause rapidly dramatic results in the drying and product quality or even collapse the operability of the dryer. These effects can be predicted and ignored by the feedforward controls of the APC.
By increasing the inlet air temperature the capacity can be increased, but simultaneously the energy consumption will increase. Especially in high humid weather conditions optimal increase in the inlet air temperature gains extra increase in the capacity.
The process tests showed clear and repeatable responses from the outlet temperature to the outlet air humidity. This created a good basis for controlling the water balance over the dryer and for the optimization of the production rate against the maximum constraint of the product moisture, measured by on-line NIR analyser. The outlet air humidity, and also product moisture, is increased by decreasing optimally with minimum energy the outlet temperature (simultaneously increasing the production rate) in accordance with the outlet air and product constraint margins.
The product moisture measured by on-line NIR analyser is kept below a specified maximum constraint. Separately also the outlet air humidity is kept below its maximum constraint. When either of these constraints gets activated the outlet temperature is increased and/or the inlet air temperature is decreased to get rid of the activated constraints. In both cases the outlet temperature controller decreases the concentrate feed rate and also decreases the product moisture and outlet air humidity.
From the dryer operational point of view the most important constraint is the product sticky point. This constraint is defined in the circumstances of the dryer chamber with existing relative humidity (RH) and temperature. When the dryer temperature or its prediction is breaking the sticky point constraint, the APC stops decreasing or starts increasing the dryer temperature (reduces the production rate) to avoid the temperature go over the sticky point constraint. Simultaneously the inlet air temperature in decreased, if it is not already at its minimum value.
The product moisture can be reduced by optimizing the temperature of the dryer internal fluidized bed below its separate sticky point constraint of the bed circumstances. This optimization alloys using higher relative humidity (RH) in the dryer chamber and thereby more production.
Blocking up the bag filter will bring serious problems in dryer operation. In the worst case the whole drying process will be shut down. The APC solution is to utilize the pressure difference over the bag filter with its predesigned constraint value to predict the blocking up of the bag filter. When the pressure difference measurement or its prediction is breaking its constraint value, the production rate and/or outlet pump speed is decreased to avoid problems. Meanwhile the dryer chamber pressure must be kept negative all the time.
To guarantee the optimality of the drying the atomizer must be operating under the circumstances defined by the vendor. Based on those requirements several constraints have been specified in the APC to guarantee optimal spraying, i.e. maximum mass and volumetric feed flow rates and maximum load of the atomizer based on the electric motor consumption.
Extra production can still be reached also increasing the outlet air pump speed. This action increases the production rate via the basic controls unless no constraints are activated. Especially the outlet air pump can be utilized in balancing the material balance between the evaporator and the dryer. This manipulation can be based on the constraint control of the level of the dryer feed volume. But mainly the pump speed is smoothly optimized to increase the production rate.
The evaporator feed rate is adapted all the time to the maximized production rate of the dryer. This is based on handling the material balance between the evaporator and the dryer by controlling the feed volume level in the dryer. This level is guarding the total material balance between these units. The level is controlled predictively within its minimum and maximum constraints by the APC. Eventually the dryer production rate is decreased if the minimum constraint of the feed volume level is activated.
The concentrate density control is included in the APC with feedforward actions from several disturbance measurements. The density is maximized continuously against evaporator and dryer constraints. This increases the solid content of the concentrate feed to the dryer and enables better specific energy consumption and more economical drying.

5 APC CONTROL STRUCTURE AND INTERFACES

The total evaporator and dryer APC application has been implemented in one NAPCON controller with ten Controlled Variables (CV's), six Manipulated Variable (MV's), four Disturbance Variables (DV's) and a number of constraint variables. Several NAPCON operator interfaces have been presented in Figure 5.1. The APC operation is possible through the variable windows of each display of Figure 5.1 in an equal way.

a) Total drying process display:

b) NAPCON list display:

c) Evaporator display:

d) Dryer display:

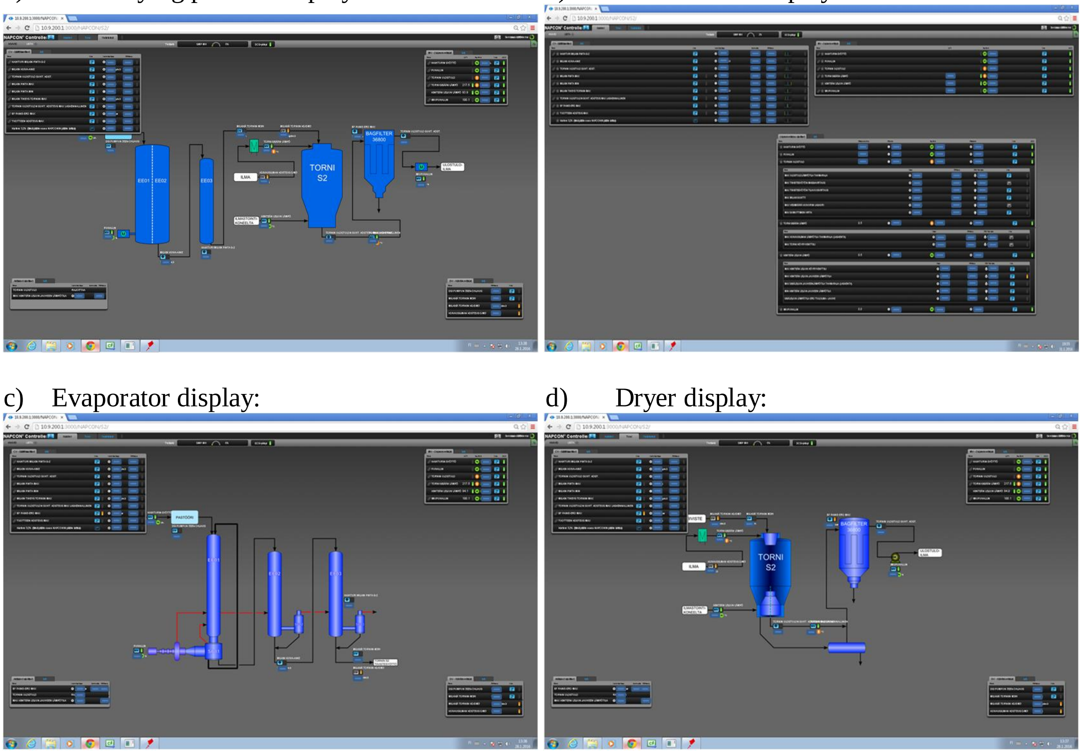

Figure 5.1 NAPCON APC operator interfaces of the drying process.

NAPCON APC is connected to MetsoDNA DCS by using OPC UA interface. All measurements from DCS are read via OPC UA. The setpoint downloading is done via OPC UA as well. Additionally NIR analyzer was connected to NAPCON APC by using OPC UA. A dedicated NAPCON operator station is used for NAPCON APC operator displays by using IE Web Browser. A Remote Connection is available for APC maintenance and for performance review.

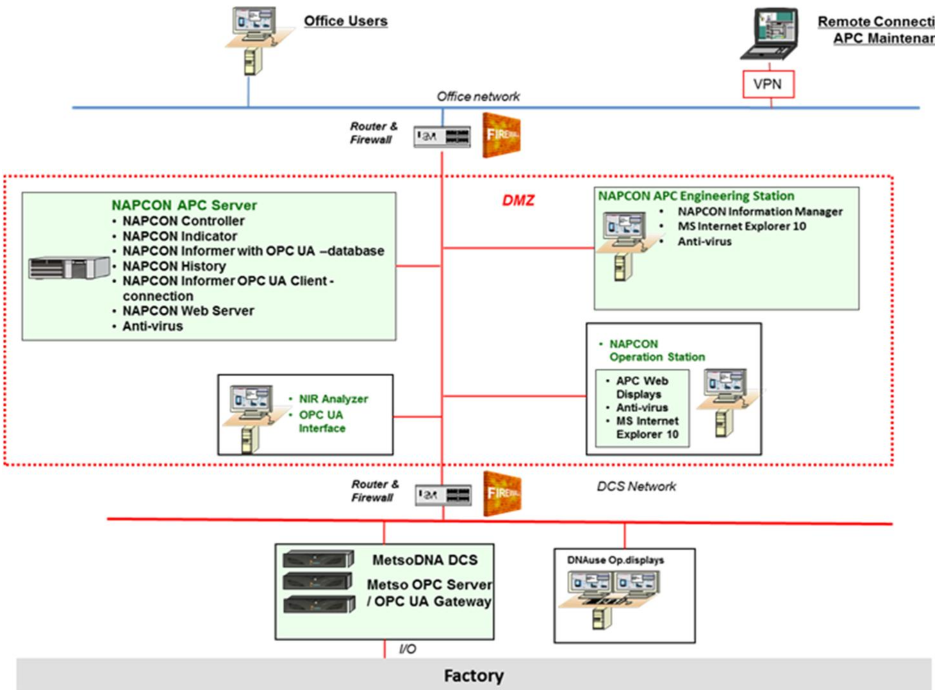

Figure 5.2 The total control system of the milk powder drying process.

6 DYNAMIC MODELING

The needed process tests for the dynamic APC modelling were accomplished by Valio personnel according to the detailed instructions made by Neste Jacobs. A separately specified step sequence was applied to every NAPCON MV. In Figure 6.1 a) there is an example of one step sequence and its response.

a) Dryer temperature step sequence   b) Outlet air humidity with model fitting

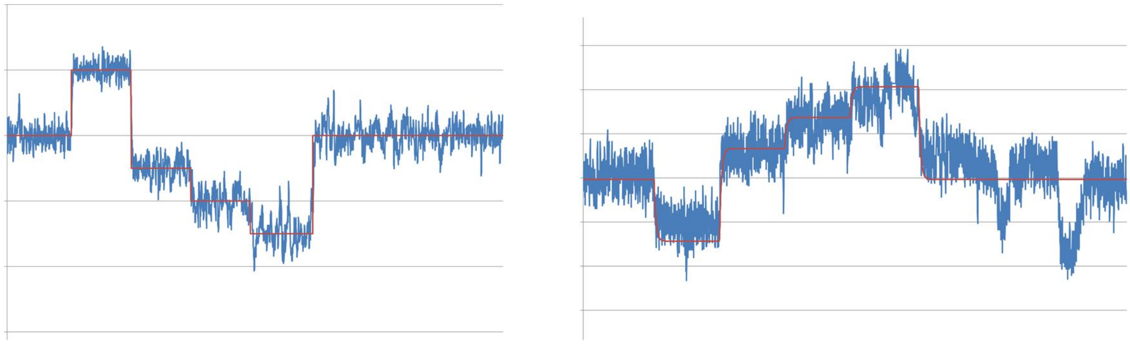

Figure 6.1 Example of a step sequence and a dynamic modelling.

Common identification methods were used in the modelling. The most common model structure is a first or second order linear model structure. But also more complicated nonparametric step or impulse response models can be utilized. A single step response gives always an approximate linear model around the process test point. But in case of nonlinearities, e.g. step sequences of the form of Figure 6.1 should be applied. Then a nonlinear identification is used or a compromised linear model identification, that covers the total process identification area. In Figure 6.1 b) there is an example of one linear model fitting.

7 APC DRYING EXAMPLES

In Figure 7.1 there are some APC key variables presented to illustrate the behaviour of the above described control strategy. The four following trends pages are shown:

a) The feed volume of the dryer is utilized as the buffer to suck the disturbances of the evaporator and the dyer via the process and control system. In normal unconstraint situations the APC is controlling the level (blue) of the feed volume using only the evaporator feed rate (red) letting the level float slightly between its the minimum and maximum constraints.
b) While unconstraint optimization the APC is minimizing the dryer outlet temperature (setpoint blue, measurement orange) against maximum move and absolute minimum hard constraints to reach the minimum energy consumption. When other constraints are activated, e.g. maximum water balance constraint, the APC is increasing the outlet temperature from the minimum constraint. Meanwhile the APC is optimizing the internal fluidized bed temperature (black) below its maximum sticky point constraint (red).
c) The APC is optimizing the drying air temperature (setpoint green, measurement purple) toward its dynamically changing optimum (blue) up to the absolute constant maximum constraint while outlet temperature is driven to its minimum constraint to reach more production capacity. Corresponding steam valve position (light blue) is also shown.
d) The APC is optimizing the drying air temperature (green) of the internal fluidized bed all the time towards its optimum value (purple) while the APC is keeping the internal fluidized bed temperature (light blue) below its dynamically changing maximum sticky point constraint (yellow).

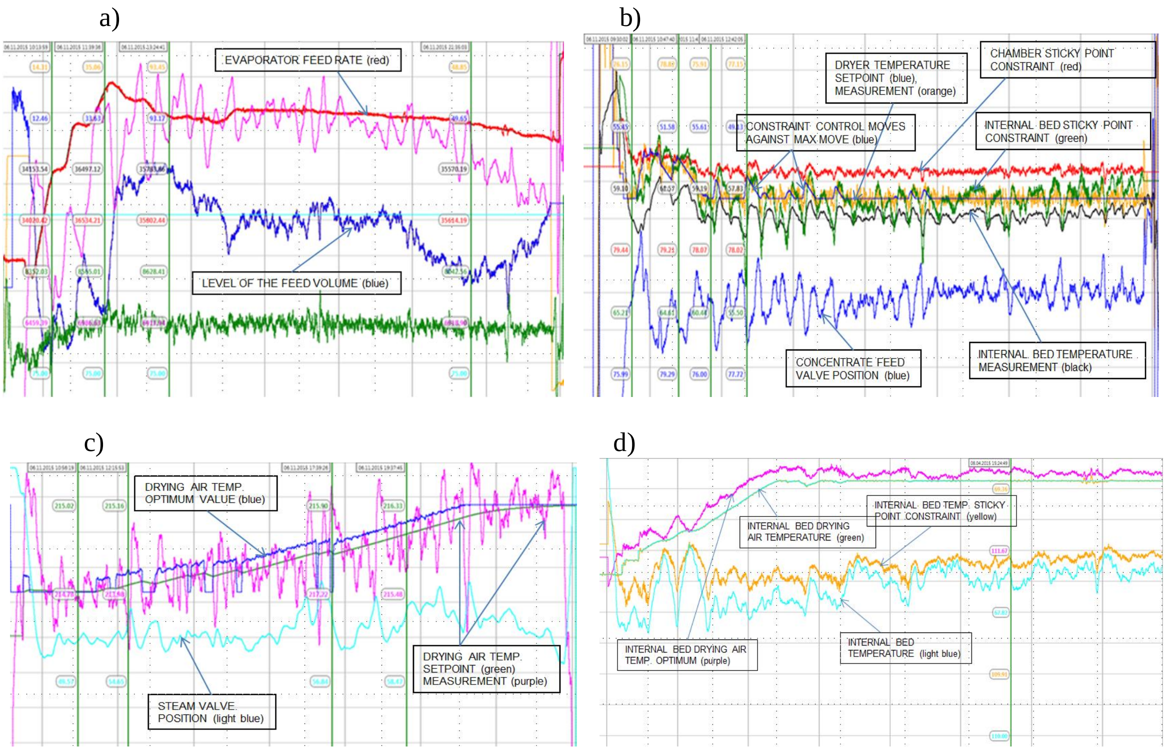

Figure 7.1 Behaviour of some APC key variables in the optimal drying procedure.

Before the APC application the dryer was operated in recipe based temperatures, which had quite big safety margins to the process and product quality constraints. Now APC is utilizing the margins more effectively and the dyer is optimized by APC closer to the specified constraints.

8 APC PROJECT PHASES AND APC PERFORMANCE RESULTS

NAPCON APC was implemented to Valio Oy, Seinäjoki plant with the standard NAPCON project procedure of Neste Jacobs. Before the actual implementation project a Feasibility Study and Performance Analysis was carried out. Based on the positive results of this study Valio Oy decided to order the implementation of the NAPCON APC.
The actual implementation project was executed with following stages:

1. Kick-Off Meeting
2. Purchasing the Hardware and installing the NAPCON APC software
3. Defining preliminary Control Strategy
4. Process Step Tests and Identification Of Models
5. Defining final APC Control Strategy
6. Building the APC in the in-house test system
7. Testing and pre-tuning the APC in the in-house test system
8. Installing the Hardware in the factory and OPC UA connection to DCS as well (by Valio)
9. Testing the NAPCON OPC UA connection
10. Install final configuration of the NAPCON APC to factory
11. Commissioning of the APC
12. Acceptance tests of the APC
13. Close the project

The implementation project total time was about 6 months from the kick-off meeting to the first stage acceptance (APC on 24 hours/day and over one production cycle). The Final acceptance was given after summer time (high humidity) production usage.

During the acceptance test runs it was verified the NAPCON APC reaches the mutually set criteria for the APC run of the milk powder production:

- drives the dryer feed density to the target or against the constraint
- maximizes the dryer and entire production capacity against maximum powder moisture limit or other limit as outlet air humidity or sticky point limit.
- with the NAPCON APC the production rate increases 8 % as minimum comparing to the reference level (mutually selected period without APC)

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