Monitoring and Optimal Management Approaches to Reduce Water and Energy Consumption in Milk Processing Processes

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***Abstract*— This paper proposes a methodology for the monitoring and optimal management of milk processing processes to reduce water and energy consumption. First, the key variables that should be measured to characterize the water/energy consumption are identified. Then, a monitoring system that is integrated with the current SCADA system already deployed in the production process has been developed that is able to evaluate the energy consumptions not directly computed from the available sensors. From real historical measurement records of the different subprocesses, their efficiency is determined. This information is used for developing an optimal management system that allows reducing the water/energy consumption. The work presented in this paper has been developed in the context of the European project named EnReMilk that aims to introduce significant water and energy in several milk processing processes by the introduction of new processing and management technologies. The assessment the proposed approach is based on the comparison with the current baseline consumptions.**

Keywords—Energy management; Data processing; Signal transforming and filtering; Diagnosis and prognosis; Manufacturing Execution Systems.

I. INTRODUCTION

The food and drink industry is one of the major European industrial sectors with over 4.1 million employees and turnover of more than €956 billions [1],[5]. These industries are important users of water and energy. Both large enterprises and SMEs in the sector are increasingly seeking to reduce their environmental impact, primarily through reducing water and energy consumption to enable cost savings [2],[3].

Water is used as both an ingredient within products and for cleaning and conveying purposes [4], [6]. Energy is primarily required for the generation of steam and hot water. Nearly 30% of energy is consumed as thermal energy for heating purposes and over 15% is used as electricity remaining 20% is consumed as electricity to drive machinery, refrigeration, ventilation, and lighting. Within the European food and drink industry, the dairy industry is an important sector with annual sales of €124.3 billion and added value of €17.4 billion. The dairy processing sector is considered one of the highest energy and water consumers, in both overall terms and in consumption per unit produced: up to 6.47 MWh (5.55 MWhth and 0.92 MWhel) and 60 m^3 of water for every tone of milk processed milk 3.98% of the fresh water used is of drinking water quality and 80% of energy is consumed for process heating, pasteurisation, sterilisation, drying and cleaning operations [7] (see Figure 1).

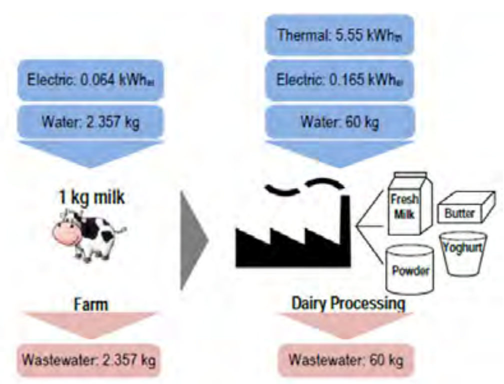

Figure 1. The electrical and water consumptions in the dairy processing

The European EnReMilk project aims to achieve significant water and energy savings in representative sectors and scales in the dairy processing operations, from primary collection, to processing and subsequent distribution. This reduction in the water/energy consumption will be possible by means of scientific and technological research and development that will be accompanied by environmental, economic, social and policy validation. During this project, energy savings of at least 20% and water savings of at least 30% will be achieved against existing performance that are replicable in both SME and large scale dairy operations. These performance savings will be validated by undertaking a diagnosis and establishing a baseline of existing operations against which savings achieved by the research activities will be validated in both model simulations and in physical trials. During the EnReMilk project, attention will be paid on energy-efficient processing and in-situ water recovery and reuse technologies at dairy processing operations. This will involve the optimisation of a set of emerging and novel food processing technologies and the integration of a number of innovative process engineering solutions (e.g. microwave heating, non-thermal microbial stabilisation via high-pressure, texturisation/plastification via extrusion, electro-membrane filtration, superheated steam drying, and various water and wastewater treatment technologies).

EnReMilk will target two representative European dairy sub-sectors: mozzarella and milk powder production, typical products of SMEs and larger enterprises respectively. These two case studies will enable wider replication not only in the dairy subsectors, but also across the food and drink industry where unit operations involved in dairy production are often employed (for instance, in the production of drinks, sauces and dried goods). In the latter phase of this project next year, over a period of six months, the EnReMilk's concept will be verified and demonstrated at an industrial scale in two dairy processing operations, one SME and one larger enterprise.

This paper proposes a methodology for the monitoring and optimal management of milk processing processes to reduce water and energy consumption developed in the context of the EnReMilk project. First, the key variables that should be measured to characterize the water/energy consumption are identified. Then, a monitoring system that is integrated with the current SCADA system already deployed in the production process has been developed that is able to evaluate the energy consumptions not directly computed from the available sensors. From real historical measurement records of the different subprocesses, their efficiency is determined. This information is used for developing an optimal management system that allows reducing the water/energy consumption. The work presented in this paper has been developed in the context of the European project named EnReMilk that aims to introduce significant water and energy in several milk processing processes by the introduction of new processing and management technologies. The assessment the proposed approach is based on the comparison with the current baseline consumptions.

The structure of the paper is as follows: In Section 2, an overview of the proposed approaches is presented. Section 3, describes how the consumption monitoring of the process is considered. Section 4 describes the three different ways how the process management is improved to achieve the energy and water savings. Finally, Section 5 draws the main conclusions and proposed further work to continue the research presented i this paper..

II. OVERWIEW

In the EnReMilk project, emerging and novel food processing technologies will be optimised and implemented in key food processing unit operations. This will be to provide significant and simultaneous saving of water and energy in the milk sector, while ensuring food quality and safety. For that, it well be needed

(i) Identify and monitor consumption patterns of water and energy streams along the dairy supply chain,

(ii) Evaluate the savings potential of a vast array of technological scenarios through modelling and simulation in two representative dairy sectors, such us mozzarella and milk powder production,

(iii) Optimise the selected technological approaches with the highest water and energy saving potentials and adapt them to the requirements of the dairy industry,

(iv) Provide strategies for the overall management of resource supply and use, and finally

(v) Assess the benefits for food producers and food equipment manufacturers, while reconciling sustainability imperatives.

For these objectives one the most important work to do is the development of a Consumption Monitoring tool and Process Management solutions:

- To establish the baseline consumption of water and energy employing data recorded for a period of the considered production processes
- To develop a methodology and a software tool for water and energy consumption throughout the dairy supply chain as well as a global process management strategy that allows optimising the consumption of water and energy
- To validate the methodology and tool in the two case studies, mozzarella and milk powder production process, once the EnReMilk engineering innovations have been implemented at the demonstration level.

III. CONSUMPTION MONITORING

A. *Consumption assessment*

In order to apply the methodology for assessing the water and energy consumption of the different milk processing processes, a software tool implementing the water and energy consumption monitoring (either off-line or on-line) has been developed. The tool combines the mathematical computations associated with the consumption analysis obtained from the information provided by the available (or newly installed) sensors and estimations in the case of unavailable measurements.

The tool has been developed in MATLAB/SIMULINK programming environment. The selection of this environment is motivated by the fact that it allows a graphical representation (using a block diagram representation) of the different subsystems involved in the milk and mozzarella processes as well as an easy interface with SCADA and database systems used to monitor/control the processes under study by means of:

- *OPC interface*. OLE for Process Control (OPC) is a standard for communicating with different data sources, e.g. devices or controllers. The goal of this protocol is to standardize communication between different parts of a control system and its surroundings.

- *ODBC interface*. ODBC (Open Database Connectivity) is a standard protocol for accessing database management systems (DBMS). The designers of ODBC aimed to make it independent of database systems and operating systems. An application written using ODBC can be ported to other platforms, both on the client and server side, with few changes to the data access code.

MATLAB allows the OPC and ODBC interfaces by means of the OPC and Database toolboxes, respectively. The conceptual design of the tool for assessing the energy and water consumption of the milk/mozzarella process is presented in Figure 2.

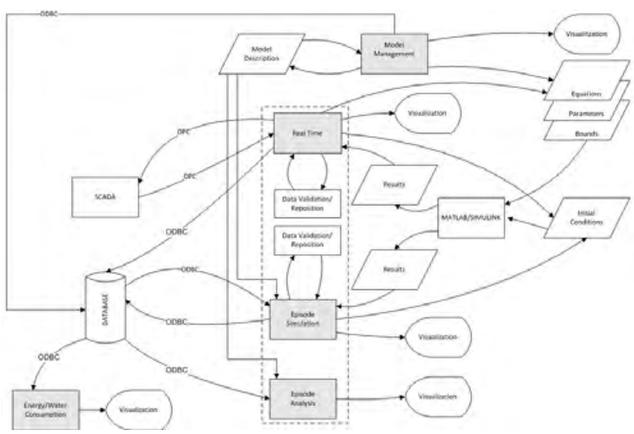

Figure 2. Conceptual design

B. *Real-time data adquistion ysytem*

In order to perform the consumption assessment of a real process, real measured data obtained from the available sensors is required. The real-time data acquisition system is developed using LabView altogether with the corresponding data acquisition boards both from[TE1] National Instruments. The acquired is processed in a LabView application, with Virtual Instrument (VI) block diagram and the corresponding VI Front Panel or Grafical User Interface (GUI) in Figure 3. The sensors are read at regular time intervals of 1 second taking into account the parameters established from the Front Panel by the operator.

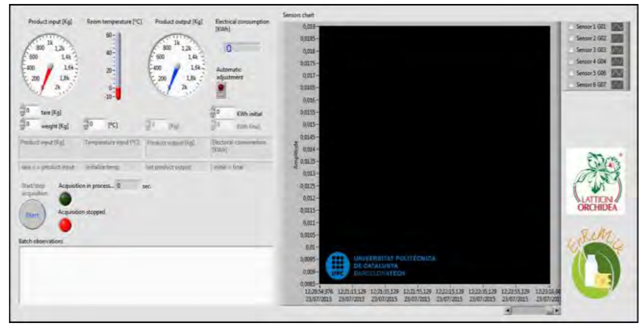

Figure 3. LabView VI acquisition tool for monitoring

C. *Data Validation and Correction*

The sensors measure physical quantities and convert them into signals that can be read by further instrumentation. then, the monitoring system converts the sensor signals to values that represent certain “real” physical quantities. These values, known as “raw data”, need to be validated before further use in order to assure the reliability of the results derived from these data.

Frequent operational problems in the communication system between the sensor set and the data logger, or in the monitoring and control itself, generate missing data during a certain periods. The data recorded by these sensors are sometimes uncorrelated and cannot be used to replace these missing data. Missing data should, therefore, be replaced by a set of estimated data. A second common problem is the lack of reliability of the sensors (e.g. due to offset, drift and breakdowns), producing false data readings. These false data must also be detected and replaced by filtered data.

In this project, we propose a procedure for data validation of sensor raw data inspired in the Spanish norm UNE 50050 for environmental stations and other works of our research group [16], taking into account five tests to check one by one all the raw data and to decide if these data are validated or not by these tests. And, in the case of some raw data are invalidated, a procedure is activated to correct and replace these wrong data using a time series model of the same sensor or a spatial model of other related sensors.

The five tests considered are:

- Level 1: The communication level monitors whether the data are properly recorded, considering that the supervisory system is expected to collect data at a fixed sampling rate, which may be violated e.g. due to problems in the sensor or in the communication system.

- Level 2: The bound level checks whether the data are inside their physical range. For example, the maximum values expected by e.g. flowmeters in a water network are obtained by pipes’ maximum flow parameters. In case that any data does not satisfy this test, the value is corrected by their owner limit (typically this test is useful to detect and correct non expected negative values).

- Level 3: The trend level monitors the data rate. Sensor data cannot change more than a certain magnitude per second in a real process (e.g. the evolution of the temperature of milk through time is very low and a threshold can be defined). In this case if any data do not satisfy this test, a correction procedure is applied.

- Level 4: Temporal model test. Usually the collected sensor data have a temporal pattern with a repetitive behaviour for each batch that can modelled using a Time Series (TS) model. TS models take advantage of the temporal redundancy of the measured variables. Thus, for each sensor with periodic behaviour, a TS model can be derived:

$$\hat{y}_{ts}(k) = g(y_m(k-1), \ldots, y_m(k-L)) \quad (1)$$

where g is the TS model, for data exhibiting a periodicity of L samples. Then, all the raw data are compared with the estimated data derived of the TS model for each sensor and in the case that this residual of the comparison is lower than a fixed threshold the data overcomes this test, otherwise the raw data is invalidated and a correction procedure is applied.

- Level 5: Space model test. From the energy and mass balances of different sub-processes of the mozzarella and milk powder, several equations relating several variables (sensors) can be derived to validated or invalidated the raw data, are the named Space Models (SP). One example, the mass inflow and out flow in the pasteurization sub-process are related to the temperature gradient in these flows following the equation:

$$\dot{m}_{M\_past\_cooler} = \dot{m}_{M\_past} \times \frac{(T_{M\_past\_i} - T_{M\_raw})}{(T_{M\_cooler\_i} - T_{M\_past})} \quad (2)$$

Then, this SP model can be used to estimate the data of one variable taking into account the data of the other variables. This test consists to compare all the raw data to the estimated data derived of spatial model to check the consistency of these data and to validate the raw data, otherwise the raw data is invalidated and a correction procedure is applied.

The correction procedure consists in to replace the wrong data if any raw data does not overcome all the validation tests by the estimated data obtained by the most precise estimator in the previous data using the last tests, the TS model or the SP model.

After this validation/correction procedure, digital filter is applied in order to minimize the noise of the measurements. The proposed digital filter is a basic exponential filter defined as follows:

$$y_{filtered}(k) = \alpha y_{filtered}(k-1) + (1-\alpha) y_{validated}(k) \quad (3)$$

where $y_{filtered}(k)$ is the filtered data at the discrete time $t=kT_s$, T_s is the sampling time, $y_{validated}(k)$ is the validated data at the same instant of time of the previous procedure and α is the parameter of the filter (usually is a value between a fast value of 0.9 and a slow value of 0.99). An example of using this filter is shown in Figure 4, where raw data is plotted in red and filtered data in black.

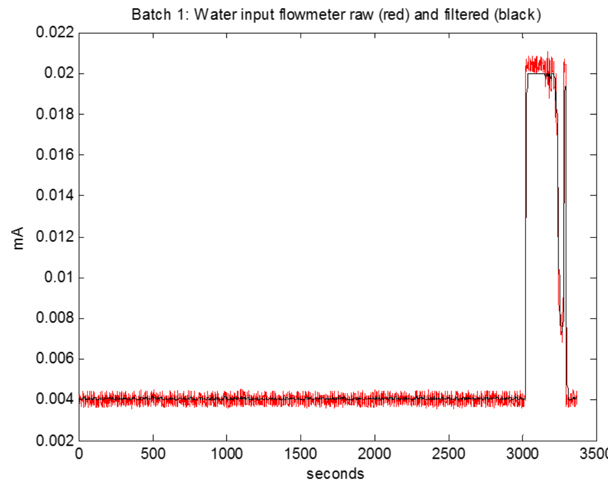

Figure 4. Raw and filtered data of the water input flow data

D. *Operatives models and SIMULINK simulator*

For each subprocess of the milk processing processes, an operative model based on energy balance equations deriving the water, gas, electrical and thermal consumptions form the existing data sensors and estimations has been developed. These operative models have been implemented in the consumption assessment tool, based on the assumptions introduced before. Figure 4 shows the operative model in case of milk powder. [TE2]

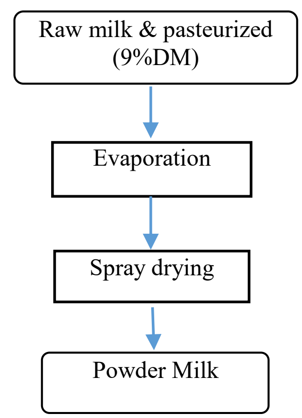

Figure 5. Process diagram of milk powder production

These models have been implemented using in Matlab/Simulink programming environment, leading to the block diagram representation presented in Figure 6. The simulator is fed with data coming from the installed available sensors, which are inserted to the simulator in a bus fashion. These sensor data is stored in an operational data base (DB) and supplied to the simulator in Simulink Time Series array format. These sensor data workspace is loaded to the Simulink model via user selection when the model is started, and should contain sensors information in the operational DB format, in order to let the model use this data properly. The corresponding bus containing information of the tag of the corresponding sensors is stored in BusTower3 workspace variable, which is also pre-loaded when the model is started. This bus includes the information of all the available measurements.

These sensor measurements are routed through a bus in the Simulink model under tag measured. However, in the current version of the simulator not all the data involved is measured, as pointed out previously. Hence, some data is set in the simulator and routed to an alternative bus under tag VirtualSensors.

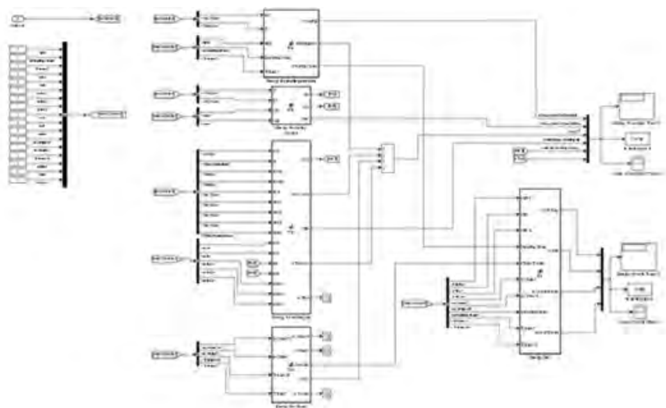

Figure 6. Simulink block diagram of the consumption model

Figure 7 illustrates for one scenario the steam consumptions of the spray drying derived from the model the instantaneous mass flow rate of the consumed steam and the mass of the consumed steam in Kg.

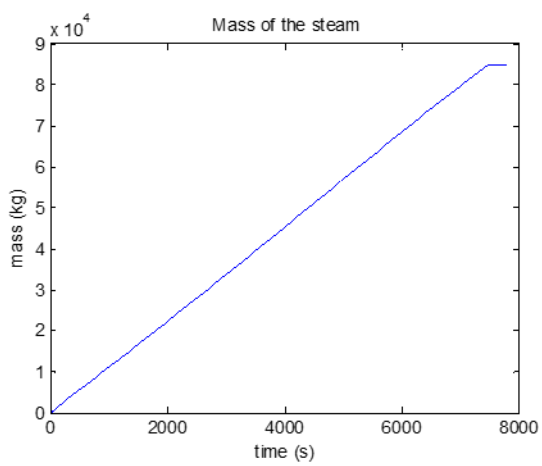

Figure 7. Mass of the steam consumed in the spay drying

IV. Process Management

In general industries not only produce a product, a methodology for the global process management has also been studied in the EnReMilk project. The three strategies presented in Figure 8 were considered (taking into account several aspects of the process management, namely: safety management, production optimization and system optimization.

Figure 8. Strategies for the global management of the production processes

A. *Safety management*

The safety management of the production process aims at:

- Preserving the reliability and safety of the critical equipment to avoid negative interactions between equipment and product safety

- Identify equipment failures to eliminate possible risks

- Planning maintenance procedures to keep the equipment health and to reduce unwanted shutdowns

In order to implement the safety management of production process, the subsystems presented in Figure 9 should be implemented. The data acquisition system provides information about the system relevant variables that allow the systems monitoring and the fault diagnosis. In case that some fault is diagnosed, the decision-making system is responsible of changing the system operating mode allowing the keep the safety and the production, if possible. Moreover, the data acquisition system provides data to the prognosis system that allows estimating the system health and estimated the remaining useful life.

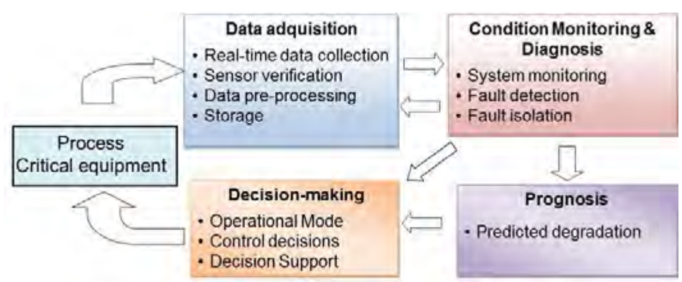

Figure 9. Safety management of the production process

B. *System optimization*

The system optimization aims to determine the optimal set-points of local controllers such that the global system operation is optimized (reducing water or energy consumptions). An optimization-based procedure based on a sensitivity analysis where a single variable is optimized at a time is proposed as presented in Figure 10.

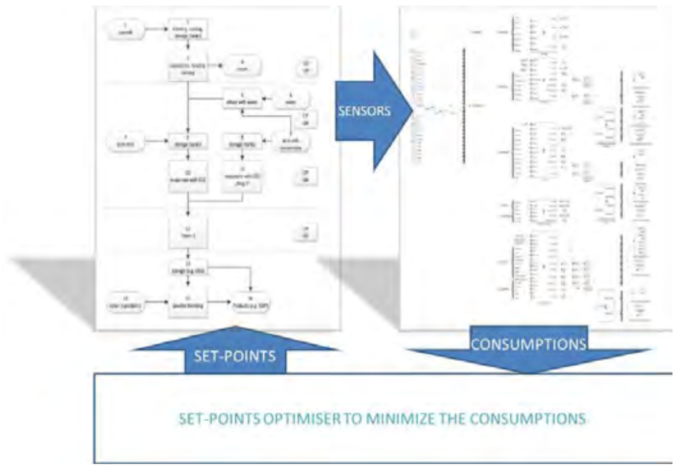

Figure 10. Optimization of the set-points of the local controllers of the production process

C. *Production optimization*

Another way of optimising the production without changing set-points or the layout of the production process is by means of scheduling the production. The idea is to decide in which sequence consumer orders should be produced taking into account the delivery date in order to:

- minimise cleaning (water) costs: The production is sequenced in order to minimise the times machines should be cleaned since the same type of products are produced in a consecutive manner.

- reduce energy costs: The production of the products in the right sequence can also help reducing energy since when changing the configuration for producing different types of products there is an amount of energy lost in before and after production period.

- maximise production time: the production of the products in the right sequence can also help in maximising the production by reducing the cleaning operations required and associated stopping times.

The scheduling process can be decomposed in two temporal layers as presented in Figure 11. The planning process at the dyeing factory is organised at two levels: mid-term scheduling (several weeks in Figure 12) and short-term scheduling (daily) [13], [14].

The production optimization problem involves the optimal batch scheduling of a real process that is solved by using a constraint programming approach. First, the process and production rules are modelled using a set of constraints. Then, an objective function that includes the process optimization criteria is defined [8-12]. After the definition of the constraints and objective function, an optimization problem that is formulated and solved using a constraint programming solver, namely the IBM ILOG Optimization Studio [15].

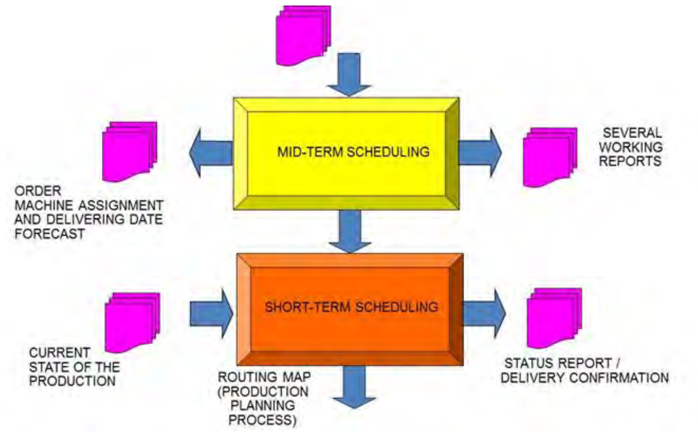

Figure 11. Scheduling process

The solution of mid-term scheduling involves determining the assignment of each task of each consumer order to a given machine according to the production rules satisfying the delivery date while maximizing the production and minimizing costs.

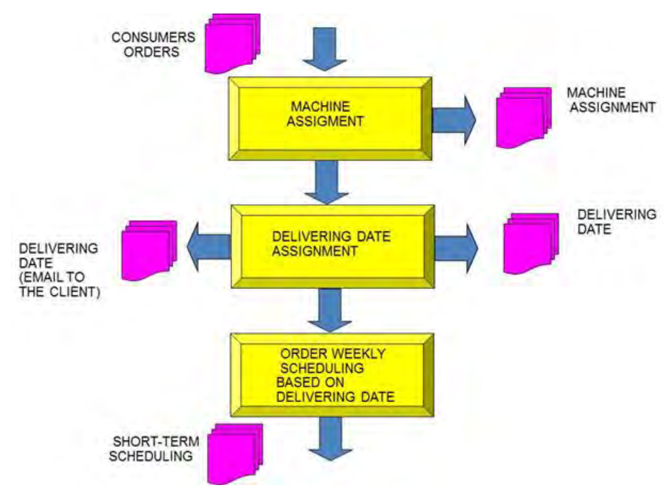

Figure 12. Mid-term scheduling process

V. CONCLUSIONS

This work presents a real-time data processing and process monitoring to certify the energy and water consumptions in the dairy industry and a methodology for the process management of the productions processes used as a case study in the EnReMilk project. At the beginning of the project, three strategies were considered taking into several aspects of the process management: safety management, production optimization and system optimization. The current focus of the project has been the development of the production optimization.

The production optimization problem consists in finding the optimal scheduling of the production such that minimizes the production costs while maximizes the production and satisfies the delivery date constraints. The scheduling problem is formulated and solved using the IBM ILOG Optimization Studio. The first results obtained in the milk powder production process show the powerfulness of the proposed approach to reduce energy and water consumptions.

In the next future, last period of the EnReMilk project, the consumption Monitoring and Process Management Approaches presented here must be applied for the new Mozarella and Milk Powder productions to demonstrate the milestones of this project that is an important water of 30% or more and energy of 20% or more savings.

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