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Cross-sectorial real-time sensing, advanced control and optimisation of batch processes saving energy and raw materials (RECOBA)

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Duration:	36 month

Set of evaluation criteria for the technical evaluation of different components and the overall results of the integrated process control

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Lead contractor for this deliverable:	BFI

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Dissimination level

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CONTENT

1 Introduction

The purpose of the deliverable D9.1 is to set up a list of criteria for technical evaluation of the performance of the different components and the integrated process control for the three industrial processes. This deliverable is referring to the Checklist for success control which has been provided in D2.6 at the beginning of the project. The evaluation criteria which have been set up already in this deliverable are either confirmed or adapted where necessary due to the actual evolution of the project work.

All evaluation criteria regarding the different components (sensors, models, control strategies) of the integrated process control solution as well as for the achievement of the expected project results (improved product quality, reduced energy and resource consumption) are further listed separately for the three industrial processes.

2 Evaluation criteria for emulsion polymerization process

Within scope of RECOBA, one of the case study for batch process improvement is polymerization process. The complete process is described somewhere else (D. 2.6). Few of the shortcomings responsible for non-optimal process operation are summarized as:

a. Lack of understanding of the emulsion polymerization coupled with nonlinearity of the process
b. Unpredictability of the process conditions (e.g., variations in inlet water temperature, monomer quality etc.)
c. Lack of insight into the process – longer batch time, inhomogeneous product quality
d. Variance in product quality – process control using implicit product quality (e.g., reaction temperature)

Use of hard sensors, process models and real time control can overcome most of the above mentioned problems for the polymerization batch processes.
The use of model based soft-sensors and hard sensors for real time monitoring, and feedback control can exploit:

i) Energy utilization improvement – manipulation of manipulated variables based on model predictions
ii) Shortening of batch time (recipes based on product quality rather than time)
iii) Improved product quality (with information about particle morphology)

Other benefits of the model based methods are:

- Better utilization of plant wide resources – monitoring and prediction based on model help to forecast energy utilization

- Better process insight – homogeneous process operation

2.1 Energy utilization

A normal polymerization batch starts with initial charge in the reactor, which is heated to certain given temperature, mainly based on experience, followed by dosing of reactants with given rate for specific time. For most of the part of the batch, the reactor temperature is kept constant (at set-point) since temperature is considered to be implicitly affecting product quality. The start of batch is time dependent based on experience. An illustration of sample batch temperature is shown in **Fig. 1**. The reaction heat released during the batch time is cooled by some type of cooling (jacket, coils, or evaporative).

Availability of hard sensors (Raman, TEM, viscosity meter) provide better information about the polymerization process, thus allowing to start the reaction at lower temperature as well as maintain the reactor temperature within given bounds, rather than given set-point. Since the control variable is product quality, it is easier to conserve energy while operating the batch process at optimal conditions.

Within scope of RECOBA, hard sensors, such as RAMAN, will be used to get the information of reactant concentrations. Process models, consisting of reaction kinetics and morphology, are developed and validated, which will give improved insight to the process. This ensures to conduct batch operation at optimal conditions, thus saving the energy in heating batch, followed by cooling of reactor at optimum.

The better insight to polymerization process will result in better control of the temperature. On the one hand, the reaction can be started at lower temperature (about 2-3 K) which is directly reducing heating and cooling effort. On the other hand, the reactor temperature is then not controlled at a set-point (e.g., 95 ^{o}C), rather within given bounds (80-95 ^oC), positively influencing the cooling operation. Due to that, the heating and cooling effort can be reduced. A start of reaction at lower temperature and better temperature control will reduce the energy consumption for about 3-4%.

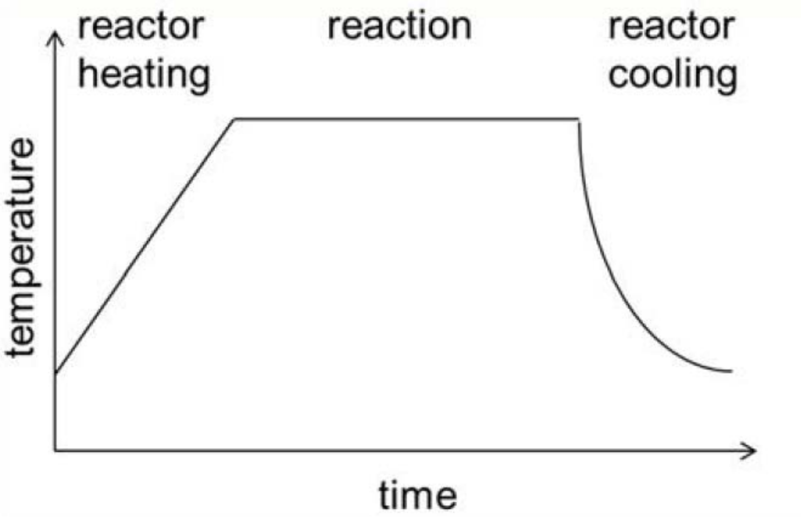

Figure 1: Example of batch reaction temperature

2.2 Batch time reduction

A higher batch temperature results in faster reaction, thus decrease in batch time. However, it can have negative impact on the product quality due to increasing influence of side reactions like branching and cross linking, etc. Furthermore, the reaction heat has to be removed, and the inlet temperature of the cooling medium is limited. Also without model-based optimization, a faster reaction is theoretically possible with impact on batch time, though this is not often implemented because of lack of insight into the polymerization process and the risk of bad product quality.

Use of hard sensor, model based soft-sensor and model predictive controller facilitate optimum process operation. This is achieved by controlling the product properties (particle morphology in this scenario) directly while manipulating the recipe reactants and inlet temperature of the cooling medium. As mentioned earlier, the models are in the validation phase. Furthermore, the hard-sensor and controller infrastructure is being implemented at demonstrators (lab and pilot plant). The validated models are essential part of model predictive controller and the process model (kinetics, morphology, reactor periphery) capture all important factors relevant for product properties.

Better insight to the polymerization process as mentioned in sub-section 2.1 result in batch time reduction without negatively impacting the product properties. The reaction can be started at an earlier state as the heating time can be reduced.

Furthermore, the possibility to work within certain temperature bounds instead of a given set-point will help to reduce the batch time as illustrated in **Fig. 2.**
The process model has been validated for the given recipe and process conditions (D 4.6).

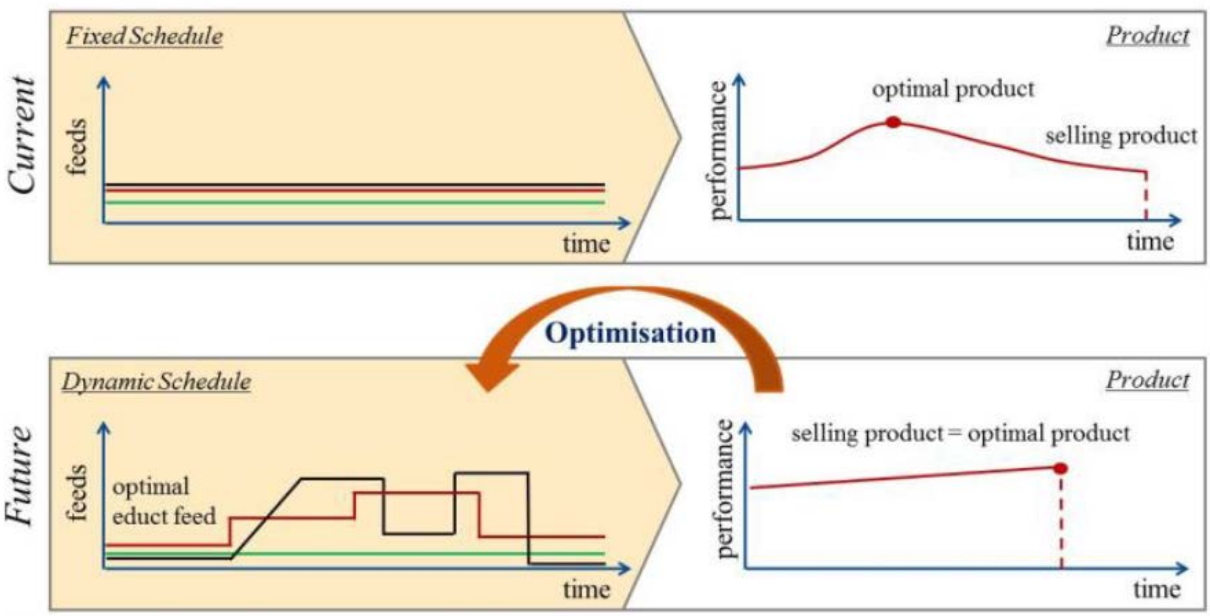

Figure 2: Advancing from time based recipes to state based process operation

2.3 Resources utilization

The absence of complete understanding of the complex process, such as emulsion polymerization, results in bad batches more often than anticipated. There could be multiple factors influencing the product properties, such as bad temperature control, variation in monomer quality, variation in heat transfer (coefficient). The product properties (latex particles) are affected by variations in process, initiating agglomerates which influence the application properties negatively. A rework is necessary in this case to make the product as per specifications, which is done by filtration followed by mixing. This costs extra time, energy as well as storage (for mixing). Moreover, the aggregates attachment to the reactor wall decreases the heat transfer capabilities of the reactor, worsening the product quality of future batches more often.
It is estimated that reduction of wasted material (which is attached to the reactor by fouling or needs to be filtered from the product) results in a 2% reduction of raw material and energy resources.

Use of the model based methods and hard sensors assist comprehend the better understanding of the emulsion polymerization at each stage of reaction, thus enabling control of particle morphology directly. This ensures accomplishment of product quality mostly, eliminating the need of filtration process as well as mixing, thus saving the energy, CO_2 foot print and improving overall safety. Furthermore, the stability of colloids has been investigated during the course of the project, thus directing the process to achieve desired product.

2.4 Improved product properties

Better understanding of the emulsion polymerization process through kinetic model and morphology descriptors helps to control the nonlinear and complex process optimally. The developed models are implemented in online application, i.e., real time control and optimization tool box, with feedback to find the optimum process operation and control the process at optimal conditions.

This was not possible before the start of the project. The project has enabled production of emulsion polymerization with real time monitoring and explicit control of product quality, e.g., particle morphology. This enables not only to reduce the reduction of carbon foot print by optimally using the energy resources and reducing the batch time by about 5-7%, but it also helps to decrease the bad batches, thus increasing the safety of workup (in case of bad batches).

The estimate of exact impact of project (eco-balance) is reported in D 9.2.

3 Evaluation criteria for liquid steelmaking process

The main objective of the RECOBA project regarding the liquid steelmaking process is to develop an improved process control for the steel melt temperature. For this purpose, new sensor technologies for in-line liquid steel temperature measurement as well as for monitoring of the thermal state of the reactors were to be developed and applied. Furthermore, dynamic process models to calculate and predict the steel temperature evolution for the complete chain of batch processes for liquid steelmaking were to be developed. Both components, sensors and process models, were to be integrated within new process optimization and control strategies.

First, the evaluation criteria for the main components (sensors and process models) of the process control system are set up separately. Secondly the evaluation criteria for the overall performance and the achievable results of the integrated process control system are defined.

The evaluation criteria regarding the sensors for in-line liquid steel temperature measurement as well as for monitoring of the thermal state of the reactors are listed in **Table 1** together with the currently / actually achieved values, as far as they are already available.

Table 1: Evaluation criteria for sensors applied at liquid steelmaking process

Sensor for in-line liquid steel temperature measurement		
Criterion	**Target value / property**	**Achieved value / property**
Temperature range	1475 °C to 1750 °C	1475 °C to 1750 °C
Reproducibility (Standard deviation)	1 – 2 K	<3 K
Measurement duration	Several minutes	>9 min using stirring lance at stirring stand, 6 min using hand lance at RH degassing
Response time	< 1 second	100 ms
Reliability & Robustness	High	High
Sensors to monitor the thermal state of the refractory-lined reactors		
Criterion	**Target value / property**	**Achieved value / property**
Temperature range	200 °C to 900 °C	200 °C to 976 °C
Accuracy	5 %	0,12 % = 1,5 K
Measurement duration	1 to 2 weeks	15 days at 600°C
Response time	< 1 min	NA
Reliability & Robustness	Applicable at least for measurement campaign	Low, instrumentation of refractory material not feasible (interrogator unit cannot travel with the batch, optical fibre too delicate to install in refractory material)

The evaluation criteria regarding the process models for monitoring and prediction of the liquid steel melt temperature evolution are listed in **Table 2** together with the currently / actually achieved values, as far as they are already available.

Table 2: Evaluation criteria for process models to calculate liquid steel melt temperature

Criterion	Target value / property	Achieved value / property
Response time for on-line monitoring	< 1 second	
Response time for prediction for one batch within optimisation algorithms	< 100 ms	
Model error standard deviation		
After homogenisation stirring	7 Kelvin	8 K for decarburised steels 13 K for alloyed steels
After RH degassing treatment	6 Kelvin	6 K for decarburised steels 4 K for alloyed steels
After final argon stirring	4 Kelvin	n./a. for decarburised steels 3 K for alloyed steels
Robustness		

The measurable evaluation criteria for the overall performance of the integrated process control system and the expected results (improved product quality, reduced energy and resource consumption, reduced batch times) are listed in **Table 3** with values for quantification as far as applicable.

Table 3: Measurable evaluation criteria for overall performance and benefits of process control system for liquid steel melt temperature

Criterion	Expected	Achievable
Temperature losses during the chain of batch process can be reduced. Thus unnecessary heating or cooling can be avoided, which saves energy.	Up to 10 Kelvin	
Metallic yield can be increased	Up to 1 %	
Consumption of refractory material can be reduced	Up to 5 %	
Greenhouse gas (CO_2) emissions can be reduced		
Production, raw material and energy costs can be decreased due to increased yield, reduced batch times, increased uptime, fewer unplanned stops, and more stable process conditions.		

Further, not quantifiable evaluation criteria regarding the overall performance of the integrated process control system and the expected results are listed in **Table 4**.

Table 4: Non-quantifiable evaluation criteria for overall performance and benefits of process control system for liquid steel melt temperature

Criterion	Achievable
New developed sensors and models will provide important process parameters like melt temperature, accessible in a real-time and continuous manner.	Yes
Continuous temperature measurement allows to detect inhomogeneous temperature distributions and to provide a much more accurate average temperature value.	Yes
Reducing the percentage of unsuccessful batch runs reduces waste and saves resources.	
Based on extensive usage of in-line information on the process state, the batch processes of liquid steelmaking can be run closer to the optimal trajectory, leading to higher reliability and more consistent product quality.	
Operators are enabled to detect serious deviations from expected process runs in real-time and make the process safer and more sustainable, and the product quality more reliable	
Less product has to be discarded due to low quality. Production losses will be reduced.	
The production of new steel qualities, requiring tight and complex process control along the process route of liquid steelmaking becomes feasible.	

4 Evaluation criteria for silicon process

The project goal for the silicon process is to establish a model for refining of silicon that allows for real-time predictive control of the operation and utilization of the superheat in the liquid silicon. Secondary goals are use of new sensor techniques developed for steel applications in the silicon process, as well as bringing existing process measurements on-line in order to reach the full potential of a MPC-methodology.

The process of production, refining and casting of high Si-alloys was described in deliverable D.2.3. To evaluate the project results, the following key areas are of particular importance:

1) **Yield of silicon** – i.e. the ratio of Si poured from the refining ladle to the casting mold divided by the amount of Si received from the furnace.

2) **Lifetime of ladle** – the number of tapping cycles each ladle goes through before ladle refractory has to be rebuilt.

3) **Safety for operators** – number of operations/total duration during the refining and casting cycle that requires the presence of operators nearby vessels that contain molten slag or metal.

4) **In-spec product** – percentage of produced Si that meet the product specifications set by the production plan.

The evaluation criteria are established to determine whether improvements are made within these four areas. These reflect sensor performance, model performance and integrated performance.

Sensor technology tested in this project includes in-line temperature measurements of liquid silicon, temperature measurements of refractory lining and metal level in ladle. The criteria are shown in Table 5.

Table 5: Evaluation criteria for sensors used in silicon production

Sensor for in-line liquid steel temperature measurement		
Criterion	**Target value / property**	**Achieved value / property**
Temperature range	1475 °C to 1750 °C	
Measurement duration	2 hours	
Response time	< 5 seconds	
Reliability & Robustness	High	
Sensors to monitor the thermal state of the refractory-lined reactors		
Criterion	**Target value / property**	**Achieved value / property**
Temperature range	200 °C to 1100 °C	
Accuracy	5 %	
Measurement duration	1 week	
Response time	< 1 min	
Reliability & Robustness	Ladle lifetime	
Sensors to monitor the liquid silicon level in the ladle		
Criterion	**Target value / property**	**Achieved value / property**
Level range	0 – 2 meters	
Accuracy	2 %	
Measurement duration	2 hours	
Response time	< 5 seconds	
Installation	Retrofitted to existing infrastructure	
Cost	< 20 000 Euro	

The evaluation criteria for the model are given in Table 6.

Table 6: Evaluation criteria for sensors used in silicon production.

Criterion	Target value / property	Achieved value / property
Response time for on-line monitoring	< 5 second	
Accuracy	< 2% deviation from off-line complete model	

The integrated system (sensors+model) will be evaluated under the criteria given in Table 7.

Table 7: Evaluation criteria for integrated MPC-system used in silicon production.

Criterion	Target value / property	Achieved value / property
Silicon yield	Increase 1 %	
Ladle lifetime	Increase 2 % (number of refining operations)	
Manual operations near ladle	Remove 1 (metal level measurement)	
In-spec product	Increase 1 %	