Modelling and real-time optimisation of an industrial cooling-water network

María P. Marcos
Systems Engineering and Automatic Control Department
Universidad de Valladolid
Valladolid, Spain
maria.marcos@autom.uva.es

José Luis Pitarch
Systems Engineering and Automatic Control Department
Universidad de Valladolid
Valladolid, Spain
jose.pitarch@autom.uva.es

César de Prada
Institute of Sustainable Processes (IPS)
Systems Engineering and Automatic Control Department
Universidad de Valladolid
Valladolid, Spain
prada@autom.uva.es

Christian Jasch
Lenzing Aktiengesellschaft
Werkstraße 2, 4860
Lenzing, Austria
c.jasch@lenzing.com

***Abstract*—This work deals with the problem of distribution of cooling water in an evaporation process. The aim is to develop a Real-Time Optimisation (RTO) tool which improves the resource efficiency by supplying the optimal water distribution within a surface-condensers network for a given production demand. The approach includes experimental models and the automatic update of fouling factor. The problem is formulated and solved via non-linear programming. Production constraints and concerns about the practical implementation are also taken into account in the design of the RTO tool.**

***Index Terms*—modelling, optimisation, evaporation plant, optimal distribution, experimental models, RTO**

I. INTRODUCTION

In the process industry, there is an increasing consensus on the importance of how to manufacture the products in the best possible way. To do this, we must take into account the real-time production situation and the global energy and resource efficiency. Furthermore, we must add that the regulation of environmental matters is increasingly restrictive. As a result, if an industry wants to keep being competitive in a global market, it will have to perform optimisation at different levels: control layer, Real-Time Optimisation (RTO), production scheduling and economic planning [1]. Improvements on all this levels can lead to huge savings in consumption of energy and resources, and consequently to the reduction of production costs [2].

In order to do that, it is necessary to provide computer-based tools which facilitate the decision-making process to the operator and plant managers. These tools are normally model-based so that an important effort in adapting theoretical models to the real system [3] has to be done. In particular, RTO tools will need real-time inputs, so they must be integrated with the information technology (IT) infrastructure of the plants, e.g., via a neutral deployment platform that connects to different IT systems [4].

This work deals with RTO in the cooling system of the evaporation network in Lenzing A.G., one of the world leading factories of human-made viscose fibre production, which is located in Austria. Hence, in this paper the approach and a prototypical tool for the optimisation of the cooling water distribution in the cooling system is described , with the goal of minimizing the trade-off determined by the cost of the steam and the cooling water consumption. The optimisation has been programmed in CasADi [5] using MATLAB, and then linked to the PI System in the plant.

The paper organizes as follow. Next section briefly describes the industrial process and the network which is going to be optimised. Section 3 shows the models that have been obtained from experimental data, and the considerations taken into account to develop those models. In Section 4 the mathematical formulation of the optimisation problem is exposed, i.e the cooling water distribution and the concerns about the practical implementation. Some results and a summary of the work done are given in Section 5. Finally, in Section 6 the future work is shown.

II. DESCRIPTION OF THE PROCESS

As earlier was pointed out, this work is done in collaboration with Lenzing AG, a factory which produces viscose fibres based on a renewable resource: wood. Once the wood is shredded, the cellulose pulp that contained the wood is chemically treated and it becomes a viscose solution. The key stage of production is the spinning, i.e the conversion of this solution into fibres by passing it through fine diameter sieves under pressure, and introducing it into an acid bath (called *spinbath* hereinafter). In addition to the new solid fibres, sodium sulphate (Na_2SO_4) and water are also produced

This research is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 723575, and by the Spanish Government (MINECO/FEDER DPI2015-70975-P).

978-1-5386-4444-7/18/$31.00 ©2018 IEEE

as by-products. This causes the degradation of the spinbath, and, consequently, the quality of the fibres decreases.

Therefore, it is necessary to regenerate the acidity of the spinbath through the continuous extraction of water and Na_2SO_4. In order to do that, an evaporation network and a crystallisation section, attached to the principal process are used.

The evaporation network is composed of fifteen evaporation plants with different nominal capacities. This network should be able to regenerate the acid baths that come from spinning, taking into account that the plant produces different fibres. The efficiency of each plant depends on different factors: the evaporation load, the operation conditions (i.e spinbath temperature and flow), the performance of the cooling system and the fouling state.

For a further explanation of the evaporation network and the characteristics of each plant and its control system, the reader is referred to [6], [7].

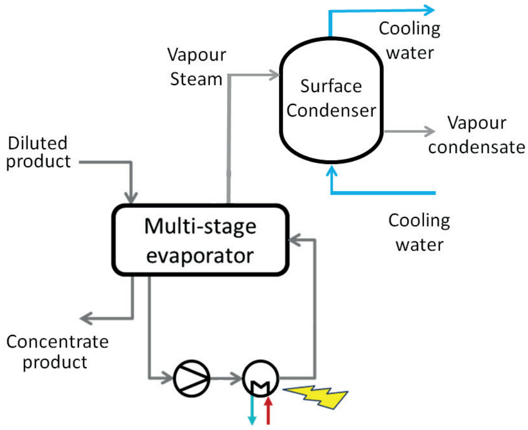

Fig. 1. Simplified scheme of an evaporation plant

A. Cooling system network

The evaporation plants could have two different cooling systems: one is based on Surface Condensers (SC, Fig. 1) and the other one on cooling towers (out of the scope of this work). There are fifteen evaporation plants which use SC as cooling system. This $\mathcal{E} = 15$ evaporators are grouped in two sub-networks depending on their cooling water source (see Fig.2). The aim of this SC is to condense the steam vapour that comes from the evaporation plants, to be used later in other parts of the factory.

Hence, the cooling water distribution problem is, the more cooling water is provided to the SC, the more efficient the evaporation plant becomes, because less specific steam vapour is needed. Nevertheless, the total available cooling water from sources is limited and shared with other departments of the factory, therefore its use implies a cost.

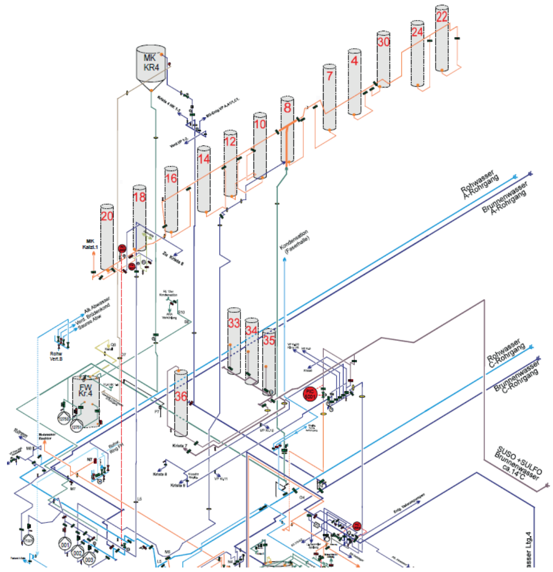

Fig. 2. Cooling system network

III. MODELLING

Several experiments have been done in order to study the behaviour of SC in steady state[1] in different operating conditions. These experiments consist of running the SCs in different conditions covering their usual range of operation and collect data of the inlet and outlet temperatures of the cooling water. It has to be taken into account that for all the experiments, the evaporation capacity (EC), i.e the flow of evaporated water from the spinbath, is kept constant. From collected data, different static models have been built to represent the cooling system of each plant.

A. Outlet temperature

First, models providing the outlet temperature of cooling water T_{out} with respect to the cooling water flow F have been obtained. It has to be emphasised that the inlet cooling water temperature is assumed constant in all the experiments. As a result, the relation between outlet temperature and cooling flow can be fitted to a polynomial curve, different for each evaporator. (See an example in Fig. 3.)

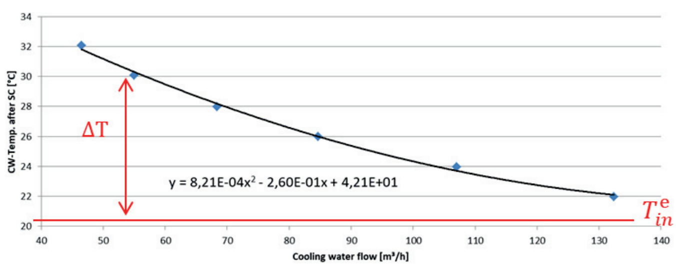

Fig. 3. Experimental model temperature vs. flow

[1]Dynamics of pressure drop and heat transfer in the SCs are neglected because of them being quite fast in comparison to the time the plant is going to operate in the optimal steady state.

Nevertheless, these models depend on the inlet water temperature, so that we propose removing the reference inlet water temperature $\mathrm{T_{in}}$ recorded at the time the tests were carried out. Hence, we get an incremental model (1), so that, given a real-time measurement of the inlet temperature, denoted by $\hat{\mathrm{T}}_{\mathrm{in}}$, the outlet temperature can be computed by (2).

$$\Delta T = f(F) - \mathrm{T_{in}} \tag{1}$$

$$\bar{T}_{out} = \Delta T + \hat{\mathrm{T}}_{\mathrm{in}} \tag{2}$$

Where $f(\cdot)$ is a non-linear function that represents the experimental model, e.g. the polynomial curve depicted in Fig. 3.

In addition, the SC suffers from typical fouling effects as in other similar industries, provoking that the heat transfer decreases with time and, consequently, the outlet temperature of the cooling water will also decrease. Thus, assuming the tests were carried out with the SC fully clean the real time outlet temperature will be lower than the predicted as it is shown in Fig. 4.

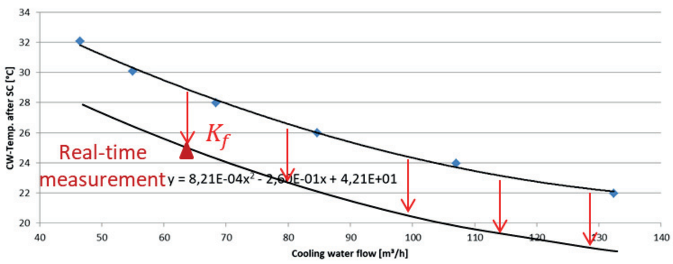

Fig. 4. Model adaptation to current fouling state

To overcome this issue, the idea is to add a bias parameter $\mathrm{K_f}$ to the above base model which adjusts the curve to the real-time measurement:

$$T_{out} = \Delta \mathrm{T} + \hat{\mathrm{T}}_{\mathrm{in}} - \mathrm{K_f} \tag{3}$$

In this way, the current state of fouling in the SC is taken into account for further optimisation. The bias $\mathrm{K_f}$ can be easily updated with real-time measurements of the outlet temperature ($\hat{\mathrm{T}}_{\mathrm{out}}$) by:

$$\mathrm{K_f} = \bar{T}_{out} - \hat{\mathrm{T}}_{\mathrm{out}} \tag{4}$$

Note that this approach allows to isolate the fouling effects in the SC system from the ones in the spinbath heating line (Fig. 1), which also affects the overall specific steam consumption. Fouling in the heating line is out of this work, for details on how to deal with it see [8].

B. Specific Steam Consumption

On the other hand, from the collected data of inlet and outlet temperature and volumetric flow of the cooling water, the actual cooling capacity in the SC can be computed by:

$$C_{pow} = \frac{4.18}{3600} F(T_{out} - \mathrm{T_{in}}) \tag{5}$$

Moreover, by recording the live steam consumption of the evaporation plant in the tests, we can depict the specific steam consumption (SSC) versus the available cooling power in the SC system and fit a model for it. However, analogous to the temperature model, to remove the dependency on the operating point (load) from the base model is needed. To do so, the simplest idea is to compute the best specific steam consumption (BSSC), i.e the minimum SSC obtained in the experiments, and to build an incremental model:

$$\Delta SSC = g(C_{pow}) - \mathrm{BSSC} \tag{6}$$

Where $g(\cdot)$ is another non-linear function that represents the experimental model, e.g. the polynomial curve depicted in Fig. 5.

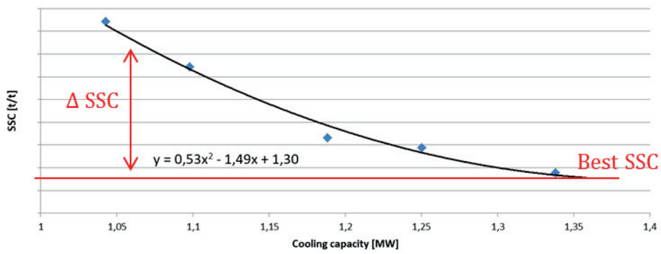

Fig. 5. Specific steam consumption vs. cooling power

For that to be true, two assumptions are made:

- The tests were carried out with clean SC.
- The model for ΔSSC (i.e., the shape of the curve in Fig. 5 for instance) does not vary significantly from one operation point to another (plant evaporation loads).

C. Modelling methodology

The polynomial functions $f(\cdot)$ and $g(\cdot)$ have been obtained fitting the curves to the experimental data by least squares method independently for each evaporator.

Based on the data, polynomials with degrades no greater than three are enough to get a good fit. These models represent satisfactorily the system in the operation range and are suitable for the optimisation. Nevertheless, this methodology does not take into account possible out-layer points in the experimental data due to disturbances or noise. Consequently, these fits might not be the best to represent the real behaviour of the system. Thus, a more sophisticated modelling routine to obtain these curves, as it is proposed in [9], could be taken into account.

Once both models, $f(\cdot)$ and $g(\cdot)$, have been fixed by identification, they can be used for prediction, receiving the water flows F and the inlet temperatures $\hat{\mathrm{T}}_{\mathrm{in}}$ as inputs and providing the water outlet temperatures T_{out} and the increase of specific steam consumption ΔSSC. Note that although the measured outlet temperature $\hat{\mathrm{T}}_{\mathrm{out}}$ is also used to update the parameter $\mathrm{K_f}$, it is not considered as a model input in the prediction state.

IV. NETWORK OPTIMISATION

As mentioned above, the evaporation network that uses SC as cooling system can be grouped in two sub-networks: the first one (SN1) is composed of $\mathcal{E}_{SN1} = 4$ plants and the second one (SN2) includes the others $\mathcal{E}_{SN2} = 11$. It should be taken into account that all the SCs are connected in parallel and that SN2 can receive water from SN1 but not the other way around.

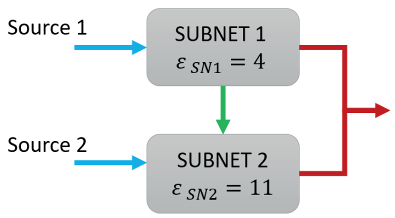

Fig. 6. Simplified scheme of the cooling system network

The optimal distribution strongly depends on the efficiency of each plant, i.e the nominal specific-steam consumption SSC, determined by the assigned evaporation capacity EC and the fouling state $\mathrm{K_f}$.

Thus, the problem objective is minimizing the trade-off between the cost of live steam and water usage, which is given by the absolute steam consumption (ASC) times its price ($\mathrm{P_{steam}}$) plus the water flow (F) times its price ($\mathrm{P_{water}}$).

The $\mathrm{P_{steam}}$ is given by the energy department, meanwhile, the $\mathrm{P_{water}}$ is calculated by negotiation between all involved departments.

A. Mathematical formulation

For the two sets of SC evaporators, the problem constraints are as follow:

- The total flow in each subnet (SN1, SN2) has to be lower than the maximum limit ($\mathrm{F_{S1}}, \mathrm{F_{S2}}$ respectively).
- Exceeding water can go from SN1 to SN2 but not backwards.
- Upper and lower flow limits defined for each SC ($\underline{\mathrm{F}_e}, \overline{\mathrm{F}_e}$), i.e suitable operation range in order to avoid problems of entrainment[2] into the SC.
- The outlet water temperature per plant has to be lower than the maximum allowed ($\mathrm{T_{max}}$). This constraint is because the outlet cooling water goes to the river and it has to fulfil the current environmental constraints.

[2]Entrainment here is understood as the presence of the acid bath in the SC pipes. This effect is particularly harmful for the equipment, so it needs to be avoided.

Hence, the optimisation problem is:

$$\min_{F_e, F_{N12} \in \mathbb{R}^{\mathcal{E}+1}} \quad J = \sum_{e=1}^{\mathcal{E}} (ASC_e \cdot \mathrm{P_{steam}} + F_e \cdot \mathrm{P_{water}}) \tag{7a}$$

$$\text{s.t.:} \quad \sum_{e=1}^{\mathcal{E}_{SN1}} F_e + F_{N12} \leq \mathrm{F_{S1}} \tag{7b}$$

$$\sum_{e=1}^{\mathcal{E}_{SN2}} F_e - F_{N12} \leq \mathrm{F_{S2}} \tag{7c}$$

$$F_{N12} \geq 0 \tag{7d}$$

$$\underline{\mathrm{F}_e} \leq F_e \leq \overline{\mathrm{F}_e} \quad \forall e \in \mathcal{E} \tag{7e}$$

$$T_{out_e} \leq \mathrm{T_{max}} \quad \forall e \in \mathcal{E} \tag{7f}$$

Taking into account that F_{N12} states for the water from SN1 to SN2 and ASC_e can be obtained as of the specific steam consumption and the assigned load capacity of each plant, as shown in:

$$ASC_e = \Delta SSC_e \cdot \mathrm{EC}_e. \tag{8}$$

Where T_{out} has been calculated by the experimental model of each plant as stated in section III, formula (3), and ΔSSC can be obtained combining (5) and (6) as follows:

$$\Delta SSC_e = g\Big(\frac{4.18}{3600} F_e (T_{out_e} - \mathrm{T_{in_e}})\Big) - \mathrm{BSSC}_e \tag{9}$$

Finally, as the experimental models are C^1 non-linear functions, usually quadratic polynomials, the optimisation problem (7) is easily handled via non-linear programming (NLP).

B. Implementation

Once the problem is formulated, we coded it in CasADi-Matlab using an interior point optimiser [10]. Nevertheless, some considerations have to be taken into account.

First, as the experimental models have been built for an specific flow range, if the real-time cooling water flows $\hat{F}_e$ are out of range, the optimisation should not be executed, as the estimation of the fouling parameter $\mathrm{K_f}$ in (4) may be wrong due to plant-model mismatch. Therefore, a warning message should appear to inform of such situation.

However, if this happens because the plants are in maintenance, i.e they are not processing any spinbath, the flow of this evaporator must not be optimised, but the rest of the network must. To do that, if the load of an evaporator (EC) is less than 1, the flow of that condenser is set to the one that is measured at that moment, i.e we propose replacing constraint (7e) by the following expressions:

$$\underline{\mathrm{F}_e} \leq F_e \leq \overline{\mathrm{F}_e} \quad \forall e \in \{e \mid \mathrm{EC}_e > 1\} \tag{10}$$

$$F_e = \hat{\mathrm{F}}_e \quad \forall e \notin \{e \mid \mathrm{EC}_e > 1\} \tag{11}$$

Finally, it may be the case that, due to the state of fouling and/or the water inlet temperature to the condensers, the optimum cooling capacity is out of the range where the experimental models (6) were built. In this case, the optimisation should not run and a warning should be displayed, in order to inform the operators of this situation.

V. RESULTS AND DISCUSSION

The optimisation formulated in the section above has been tested offline with real sample data, recorded in a particular time instant. The values of the parameters[3] used to solve the problem are:

- Maximum allowed temperature, T_{max} = 31°C
- Cooling water available from source 1, $F_{S1} = 864\ m^3/h$
- Cooling water available from source 2, $F_{S2} = 943\ m^3/h$

In Figs. 7-9 the obtained results are shown along with the real-time measured data for the time that the parameters were recorded.

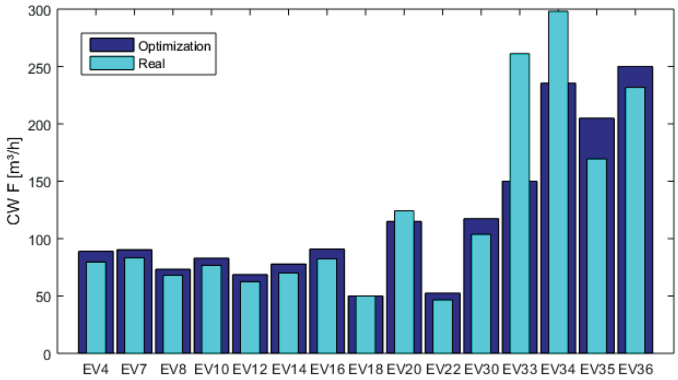

Fig. 7. Cooling water distribution

Comparing the optimised flows with the measured ones (Fig.7), it is observed that most evaporators must increase their cooling water consumption. Note that, this can look inconsistent a priori as the cooling water has a cost. However, as shown in the Fig.8, the consumption of steam has decreased because its price is 10 times higher than the water one, so when adding both costs in the objective function the result is that benefits have been obtained.

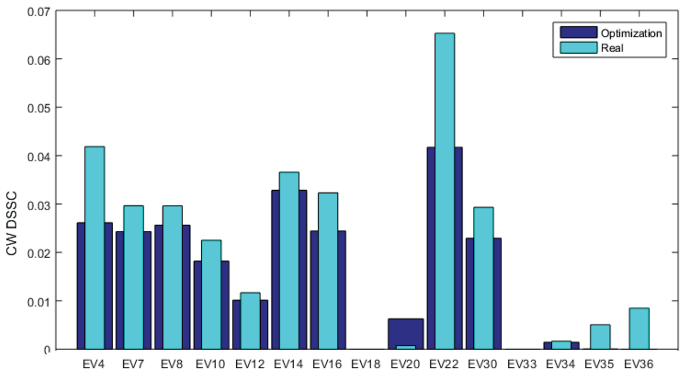

Fig. 8. Incremental Specific Steam Consumption

It should be noted that the ΔSSC of evaporators 18 and 33 is zero. This is because the experimental models to obtain the SSC are not consistent, so we assumed that the measured SSC is the best SSC that these evaporators can achieve. Doing that the flow to these SCs will fit within the operation flow range, with the unique constraint of complying with the maximum outlet water temperature. In contrast, for evaporators 35 and 36, there is a real specific steam consumption but the optimisation adjusts the flow in order to make that optimal SSC matches with the BSSC in both evaporators.

Analysing Fig.9 we can observe that the real-time measurement of the outlet temperature goes beyond the maximum allowed in several cases. In contrast to that, the optimal solution chooses the flows in order to fit the outlet temperature below the maximum, thus fulfilling the environmental restrictions.

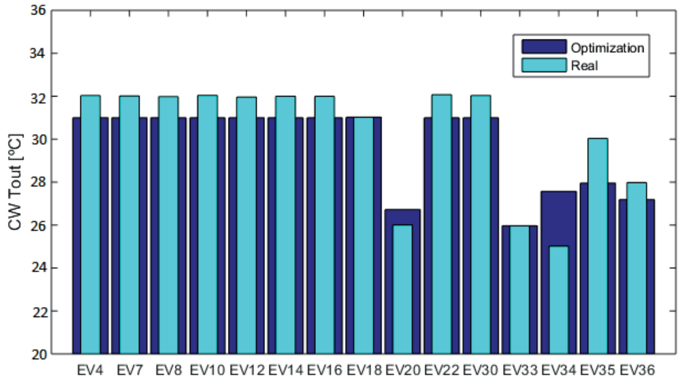

Fig. 9. Outlet cooling water temperature

Furthermore, flow from the subnet 1 to subnet 2, F_{N12}, is 19 m^3/h, so we can sum up that the total cooling water available in subnet 2 is not enough to operate the SCs in their optimal point.

Table I shows the costs due to the cooling system before and after the optimisation, as well as the value of the savings. Note that these values only represent a snapshot in a particular time instant, but the annual potential benefit that would be obtained by applying this optimisation tool in daily operation looks promising. Therefore, the tool is now deployed on site, currently under testing period.

TABLE I
RESULTS OF COSTS AND SAVINGS

Cost before optimisation	71.39€/h	625376.40€/year
Cost after optimisation	19.88€/h	174148.80€/year
Savings	51.51€/h	451227.60€/year

Summary and conclusions

In this work we addressed a problem on resource efficiency in a cooling system of a real industrial evaporation network. The modelling, optimisation and visualization concepts presented in this paper support the operators when it comes to taking better decisions in real time to improve the network operation. The models obtained allow to executes an automatic update of the SCs fouling state based on real-time measurements. Nevertheless, the models developed are very sensitive

[3]The values of the T_{in}, EC, $\underline{F_e}, \overline{F_e}$, P_{steam} and P_{water} are omitted due to confidentiality reasons with Lenzing AG.

to disturbances and noise error of the data used to obtained the polynomial functions, so a modelling routine to calculate these curves is recommended.

The resulting models are incorporated in the RTO scheme that solves an NLP problem according to the current production constraints and the plants fouling states. Nevertheless, the instantaneous RTO does not take into account any prediction of the fouling effect, so the proposed control actions may be suboptimal in the long term. In despite of that, significant steam consumption savings have been obtained in the tests.

The developed RTO tools are currently under evaluation at Lenzing AG: the implementation in existing systems and operational policies is performed step by step to get experience in live testing and to ensure acceptability from the plant personnel. About a year of normal operation is required to assess the impact, but preliminary tests with historical data predict savings around 400000 €/year.

However, the optimisation cannot run automatically in the current form due to existent out-of-range situations. In addition, the are some evaporators which miss consistent data sets. For this reason further tests are planned on site in order to improve the SCs models, therefore the tool reliability.

VI. FURTHER STEPS

The complete evaporation system in Lenzing A.G. can be mainly described by two networks of equipment. The first one concerns the evaporation plants where decisions on load allocation need to be taken [8]. The second one refers to the cooling systems attached to each plant, feed by a water distribution network, where decisions on water flows to plants need to be taken, i.e the problem addressed in this work.

Currently, independent optimisation setups are already developed for each network. However, both systems are coupled by the spinbath loads EC_e and the outlet water temperatures $T_{out,e}$ in the cooling systems, so that the decisions on the load allocation influence the cooling-water distribution and vice versa (see the formulation of the optimisation in [8] and compare with the one in Section IV-A).

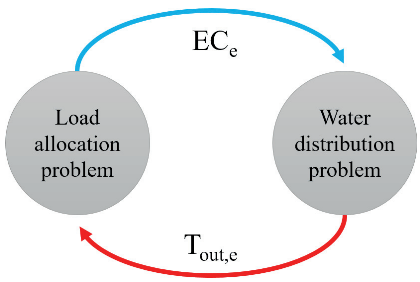

Fig. 10. Relation between networks

If both problems are solved independently, by treating these shared variables as “a priori” fixed data for each problem, the overall optimisation becomes an iterative procedure with no global optimality guarantees. On the contrary, if both formulations are merged into a centralized problem, the optimisation becomes an MINLP one, as the water distribution is an NLP problem and the load allocation involves discrete decisions (allocation of plants to products). Therefore, the complexity of the hypothetical centralized problem is much higher than the one for the two separate problems above, guessed to be unsuitable for real-time application.

To overcome the above issues, we propose as future work, to address the problem in a distributed fashion via Lagrangean decomposition [11] and price-coordination schemes [12], i.e., adding the shared constraints (variables in this case) as a penalty in the objective function J of each individual problem. The modified objectives for each problem will be in the form:

$$J_M = J + \sum_e p_e(R_e - \hat{R}_e) \qquad (12)$$

Where R_e are the shared variables that should be equal (to $\hat{R}_e$) in both problems and p_e are the associated Lagrange multiplier, also referred as “resource prices” in the literature. Then, a smart rule for updating $\hat{R}_e$ and p_e in each iteration is required. Research on this will be conducted in order to speed up the resolution.

REFERENCES

[1] C. S. Khor and D. Varvarezos, “Petroleum refinery optimization,” *Optimization and Engineering*, vol. 18, no. 4, pp. 943–989, Dec 2017.
[2] S. Krämer and S. Engell, *Resource Efficiency of Processing Plants: Monitoring and Improvement*. John Wiley & Sons, 2017.
[3] C. de Prada, D. Sarabia, G. Gutierrez, E. Gomez, S. Marmol, M. Sola, C. Pascual, and R. Gonzalez, “Integration of rto and mpc in the hydrogen network of a petrol refinery,” *Processes*, vol. 5, no. 1, 2017.
[4] LeiKon, “D4.1 requirement specification for the integrated deployment platform,” Outcomes of the MORE Project, 2014.
[5] J. Andersson, J. Åkesson, and M. Diehl, “Casadi: A symbolic package for automatic differentiation and optimal control,” in *Recent Advances in Algorithmic Differentiation*, S. Forth, P. Hovland, E. Phipps, J. Utke, and A. Walther, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 297–307.
[6] J. L. Pitarch, C. G. Palacín, A. Merino, and C. de Prada, “Optimal operation of an evaporation process,” in *Modeling, Simulation and Optimization of Complex Processes HPSC 2015*, H. G. Bock, H. X. Phu, R. Rannacher, and J. P. Schlöder, Eds. Cham: Springer International Publishing, 2017, pp. 189–203.
[7] C. G. Palacín, J. L. Pitarch, C. Jasch, C. A. Méndez, and C. de Prada, “Robust integrated production-maintenance scheduling for an evaporation network,” *Computers & Chemical Engineering*, vol. 110, pp. 140 – 151, 2018.
[8] M. Kalliski, J. L. Pitarch, C. Jasch, and C. de Prada, “Support to decision-making in a network of industrial evaporators,” *Revista Iberoamericana de Automática e Informática industrial*, 2018, In Press, DOI:10.4995/riai.2018.9233.
[9] M. P. Marcos, J. L. Pitarch, C. Jasch, and C. de Prada, “Modeling for optimal operation of an industrial cooling system,” in *Actas de las XXXIX Jornadas de Automática*. Universidad de Extremadura, 2018, Accepted.
[10] A. Wächter and L. T. Biegler, “On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming,” *Mathematical Programming*, vol. 106, no. 1, pp. 25–57, Mar 2006.
[11] M. L. Fisher, “The lagrangian relaxation method for solving integer programming problems,” *Management science*, vol. 27, no. 1, pp. 1–18, 1981.
[12] R. Martí, “Price coordination strategies in large-scale process control,” Ph.D. dissertation, Escuela de Ingenierías Industriales, Universidad de Valladolid, Spain, 2015.