REAL-TIME OPTIMISATION FOR A HEAT-RECOVERY SECTION WITH EQUIPMENT DEGRADATION

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Abstract

This work aims to optimise the operation of an industrial heat-recovery section in a fibre-production factory. The section is formed by a network of heat exchangers able to be supplied with different hot sources. The goal is minimising the resource utilisation in real time (the sources usage) while satisfying a set of operational constrains. Hence, problems of economically optimal hot-sources allocation to heat exchangers arise. The problem is formulated and solved via mixed-integer nonlinear programming. Furthermore, concerns about the practical implementation and the degradation of the equipment due to the fouling effect are also taken into account in the optimisation. In this way, the decision-support tool not only provides the optimal allocation, but also suggestions on which heat exchangers are potentially beneficial to be clean.

Keywords: grey-box modelling, fouling, heat-exchanger network, RTO, decision support

1 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/maintenance scheduling and economic planning [1]. Improvements on all these levels, as well as coordination among them, can lead to huge savings in energy and resources consumption, and consequently to a 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 real systems has to be done [3]. In particular, RTO tools need to be supplied with inputs in real time, 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 proposes an RTO development for the heat-exchanger network of the heat-recovery section in Lenzing A.G., one of the world-leading factories of human-made cellulose fibre production, located in Austria. In this paper we present and describe the approach and a prototypical tool for the optimisation of the hot-source distribution in such heat-recovery system. For such a task, grey-box models for the heat exchangers have been obtained using data reconciliation (in order to correct measurements and estimate the heat-transfer coefficient) and constrained regression (to build up an experimental model for the heat-transfer coefficient) [5].

Moreover, as the heat exchangers are affected by fouling (decreasing their performance and involving a maintenance cost), we extended the RTO with additional discrete decisions in order to suggest which heat exchanger is more beneficial to be clean out at each execution. The optimisation has been coded in Pyomo [6] and, currently, tested offline with plant data.

The rest of the paper is organised as follows. Next section briefly describes the heat-exchanger network which is going to be optimised. Section 3 presents the mathematical modelling procedure and the considerations taken into account to develop the equipment models. In Section 4, a suitable way to monitor the equipment degradation due to fouling and considering it into the mathematical formulation of the RTO is presented. Finally, a summary of the work done and the next steps are given in Section 5.

2 NETWORK DESCRIPTION

The industrial heat-exchanger network considered in this work is a large-scale system owned by

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Lenzing AG, an industrial factory located in Austria that produces man-made cellulose fibres using wood as raw material. In one part of the main production process there is needed a heat recovery network, consisting in fifteen heat exchangers.

This network should be able to heat different products until achieve the required setpoints by using four heat sources. The heat sources are different waste water streams that comes from other parts of the plant. Nevertheless, their use involves a shadow cost, due to the fact that they are shared among other processes too.

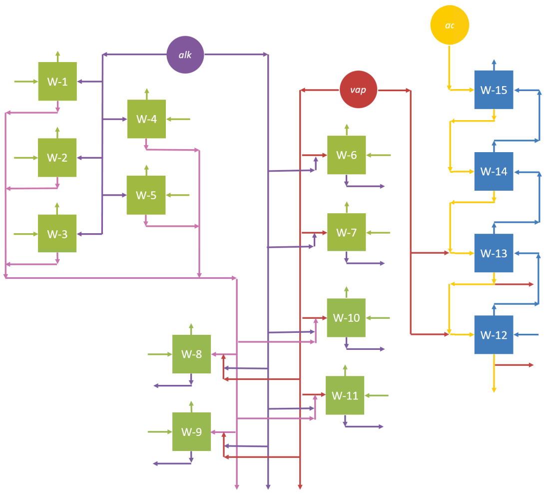

Figure 1: Network scheme

Each source has a different temperature and the total amount of available water is also limited. The different heat sources are:

- Alkaline waste water, called *alk* hereinafter, represented in purple in Fig. 1
- Used *alk*, i.e. alkaline waste water that has been used as hot source in a previous heat exchanger, called *ualk* hereinafter, represented in pink in Fig. 1
- Vapour condensate, called *vap* hereinafter, represented in red in Fig. 1
- Acid waste water, called *ac* hereinafter, represented in yellow in Fig. 1.

The layout of the network can be divided in two groups, one where each heat exchanger heats a different product (represented in green in in Fig. 1) and the connection of the heat sources is done in parallel, and the second one which is formed by four heat exchangers connected in series by the product (represented in blue in in Fig. 1). Furthermore, in this second set, the acid waste water (yellow) goes also in series if connected to the exchangers. Note that some of the heat exchangers can be connected to different sources, but just one at a time. As a result of that, the heat exchangers can be grouped in finer subsets depending on their physical possible connection to sources, as follows:

Table 1: Allowed source connection.

Block	Heat Exchanger	Hot sources
$\mathcal{B}1$	W-1, W-2 W-3 W-4, W-5	*alk*
$\mathcal{B}2$	W-6, W-7	*alk, vap*
$\mathcal{B}3$	W-8, W-9 W-10, W-11	*alk, vap, ualk*
$\mathcal{B}4$	W-12, W-13	*vap, ac*
$\mathcal{B}5$	W-14, W-15	*ac*

An important issue to point out is that the total amount of *alk* that use the heat exchangers of $\mathcal{B}1$ will be the available *ualk*.

The blocks 4 and 5 are the ones where the product stream is serial, i.e. the product enters by W-12, goes sequentially through the rest of exchangers in blocks 4 and 5, and leaves by W-15. In this way, the temperature setpoint of the product has to be fulfilled just at the outlet of W-15. The *ac* source, if connected to the exchangers, goes in series too but in counterflow to the product. An important feature to take into account is that, as the product is connected in series, there is no need to connect all these heat exchangers to sources as long as the setpoint can be reached with a few of them. If one heat exchanger of the chain is not connected, there will not be heat transfer and, consequently, the outlet temperature of hot and product streams will be assumed the same that the ones at the inlets.

The heat exchangers have different efficiency because of their different sizes, i.e., transmission areas. Furthermore, the state of fouling progressively reduces such efficiency over time. Consequently, more water from the heat source is needed to reach the product setpoint. At some point, the exchanger needs to be cleaned to recover its efficiency. This task is currently done by operators in a heuristic way, with a policy just based on cleaning the exchangers that have been in operation for more days beyond a minimum.

The goal of this work is investigating whether the current network operation and cleaning policy is economically optimal, as well as providing the operators with a model-based optimisation tool to support them in their decisions.

3 WATER DISTRIBUTION

As mentioned above, the heat recovery network is formed by fifteen heat exchangers that take hot water from three different sources. The first aim

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of the optimisation is to distribute such sources among exchangers, taking into account the cost of each one, in order to fulfil the outlet product setpoints.

3.1 MATHEMATICAL MODEL

We have established a set $\mathcal{HE} = \mathcal{HE}_\mathrm{p} \cup \mathcal{HE}_\mathrm{s}$ which includes all heat exchangers, either with parallel and with serial connection. For formulation reasons, $\mathcal{HE}_\mathrm{s}$ has been defined as an order set. $\mathcal{HE}$ can also be divided in five subsets depending on the heat sources that each heat exchanger can use $\{\mathcal{B}1, \mathcal{B}2, \mathcal{B}3, \mathcal{B}4$ and $\mathcal{B}5\}$. The other important set to take into account is $\mathcal{S}$ which appoints all the different hot sources in the network. It is important to note that, although there are different products having different flows, inlet temperatures, and setpoints, they are fixed for each heat exchanger, so these are just data for the optimisation problem.

Two sets of decision variables are defined for optimisation:

- $X_{h,w}$: Binary variables which link the heat source h to the heat exchanger w.
- $F_{h,w}$: Real variables stating the heat-source flow of h that goes to the exchanger w.

As the use of each m^3 from a heat source has a cost[1] P_h, the objective function minimises the total cost of operating the network. This cost will be the sum of the cost of usage in each heat source.

For all the heat exchangers connected in parallel, the consumption of each heat source will be the sum of the flows, as stated in (1). Of course, for the subnet connected in series with ac, the consumption will be just the flow which passes through one of the connected exchangers (2).

$$J_\mathrm{p} := \sum_h^{\mathcal{S}} \sum_w^{\mathcal{HE}_\mathrm{p}} \mathrm{P}_h \ F_{h,w} \tag{1}$$

$$J_\mathrm{s} := \mathrm{P}_\mathrm{ac} \frac{\sum_w^{\mathcal{HE}_\mathrm{s}} F_{\mathrm{ac},w} X_{\mathrm{ac},w}}{\sum_w^{\mathcal{HE}_\mathrm{s}} X_{\mathrm{ac},w}} \tag{2}$$

The objective function to minimise is then the sum of both contributions:

$$J = J_\mathrm{p} + J_\mathrm{s} \tag{3}$$

There are some constraints that the mathematical model needs to incorporate. These are:

[1]Note that *ualk* gets zero cost.

1. **Energy balances.** Assuming that there is no energy loss to the environment, the heat that the hot source gives, has to be equal to the heat that the product gains.

$$Q_{k,w} = F_{k,w} \ \rho_k \ \mathrm{Cp}_k \ \Delta T_{k,w} \qquad \forall k \in \mathcal{S} \cup c \qquad \forall w \in \mathcal{HE} \tag{4}$$

$$\sum_h^{\mathcal{S}} Q_{h,w} = -Q_{c,w} \qquad \forall w \in \mathcal{HE} \tag{5}$$

In (4), ρ and Cp are the density and the specific heat respectively, ΔT is the difference between the inlet and the outlet temperature's flow and the index c makes reference to the product stream. Note that the minus sign in (5) is due to ΔT for the product stream is negative as the outlet temperature will be greater than the inlet temperature, and consequently $Q_{c,w}$ is also negative.

2. **Heat transfer.** Also, we need to ensure that all the heat that the hot source gives, is the same that the total heat transfer that can achieve each heat exchanger due to its characteristics.

$$\sum_h^{\mathcal{S}} Q'_{h,w} = \sum_h^{\mathcal{S}} Q_{h,w} \qquad \forall w \in \mathcal{HE} \tag{6}$$

$$Q'_{h,w} = U_w A_w \mathrm{LMTD} \quad \forall h \in \mathcal{S} \ \forall w \in \mathcal{HE} \tag{7}$$

Where in (7), A is the heat transfer area, LMTD is the logarithmic mean temperature difference, and U is the global heat transfer coefficient.

3. **Temperature setpoints.** The product streams have to reach the temperature setpoints.

$$T\mathrm{out}_{c,w} \geq SP_w \quad \forall w \in \mathcal{HE}_\mathrm{p} \cup \mathrm{W15} \tag{8}$$

As there are some heat exchangers connected in series, except the last heat exchanger in the chain, the other ones do not have a real setpoint.

4. **Exclusivity.** Each heat exchanger can only connect to a single hot source at a time, taking into account that some heat exchangers can not be used if it is not necessary.

$$\sum_h^{\mathcal{S}} X_{h,w} \leq 1 \quad \forall w \in \mathcal{HE} \tag{9}$$

5. **Impossible connections** of exchangers to sources.

$$X_{h,w} = 0 \quad \text{for certain pairs } w, h \in \mathcal{M} \tag{10}$$

The allowed connexions $\mathcal{M}$ are the ones described in Table 1.

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6. **Hot-sources availability.** The total usage of each hot source by the heat exchangers has to be lower than the maximum available.

$$\sum_{w}^{\mathcal{HE}} F_{h,w} \leq \mathrm{F}_{\mathrm{T},h} \ \forall h \in \{alk, ualk, vap\} \quad (11)$$

For the source ac, as it is connected in series, the flow in each *connected* exchanger has to be lower than the maximum available.

$$F_{ac,w} \leq \mathrm{F}_{\mathrm{T},ac} \quad \forall w \in \mathcal{HE}_s \quad (12)$$

7. **Flow limits.** There is a maximum flow per heat exchanger.

$$F_{h,w} \leq \overline{\mathrm{F}_w} \cdot X_{h,w} \quad \forall w \in \mathcal{HE} \quad (13)$$

Multiplying the limit by the binary variable, we force the flow to be zero when the exchanger is not linked to such source.

8. **Serial flow.** For the heat exchangers connected in series by ac, their ac flow has to be equal.

$$\sum_{\alpha \neq w}^{\mathcal{HE}_s} F_{ac,\alpha} \leq F_{ac,w} \sum_{\alpha \neq w}^{\mathcal{HE}_s} X_{ac,\alpha} + M(1 - X_{ac,w}) \ \forall w \in \mathcal{HE}_s \quad (14)$$

Where M is a big enough value, for instance $M = 3 \cdot \mathrm{F}_{\mathrm{T},ac}$.

9. **Serial temperature.** The inlet temperature of the heat exchangers connected in series depends on whether the previous heat exchanger in the chain is working.

$$T\mathrm{in}_{ac,w} = \sum_{j=\mathrm{W15}}^{w-1} \Big(T\mathrm{out}_{ac,j} X_{ac,j} \prod_{j=\mathrm{W15}}^{w-1} (1 - X_{ac,j+1}) \Big) + T\mathrm{in}_{ac,\mathrm{W15}} \prod_{j=\mathrm{W15}}^{w-1} (1 - X_{ac,j}) \ \forall w \in \mathcal{HE}_s \quad (15)$$

The data for the optimisation are: A, ρ, Cp, $\mathrm{F}_{c,w}$, SP_w, $\overline{\mathrm{F}_w}$ and P_h. There are other data, $T\mathrm{in}_h$ and $\mathrm{F}_{\mathrm{T},h}$, that are just known for some sources: *alk*, *vap* and *ac*. As the heat source *ualk* depends on the amount of *alk* used in the heat exchangers of Block 1 ($\mathcal{B}1$), its $\mathrm{F}_{\mathrm{T},ualk}$ and $T\mathrm{in}_{ualk}$ will be:

$$\mathrm{F}_{\mathrm{T},ualk} = \sum_{w}^{\mathcal{B}1} F_{alk,w} \quad (16)$$

$$T\mathrm{in}_{ualk} = \frac{\sum_{w}^{\mathcal{B}1} T\mathrm{out}_{alk,w} \cdot F_{alk,w}}{\sum_{w}^{\mathcal{B}1} F_{alk,w}} \quad (17)$$

Moreover, $T\mathrm{in}_c$ is only known for some heat exchangers. In particular for those connected in parallel and for W-12. For W-13, W-14 and W-15, $T\mathrm{in}_c$ is $T\mathrm{out}_{c,w}$ at the previous heat exchanger in the chain.

The value of U depends on the heat exchanger but also on its operating conditions. Nevertheless, as there is not an established equation that relates the operating conditions of flow and temperature of hot and product source with U, we developed a model based on experimental data.

3.2 DATA-BASED MODEL OF U

To develop a model of U, we used historical data of Lenzing AG. of flow and temperature operating conditions of both sources for different moments after a cleaning. Nevertheless, as the measurement data can be incoherent with physics due to noise or fault in sensory, we have to perform a data reconciliation. This technique is based on the concept of redundancy (duplicated sensors or algebraic constraints) in order to satisfy physical laws [7]. In this case, the constraints of the optimisation problem for the data reconciliation are (4)-(5), and the objective is to minimise the error between the decision variables that fulfil the constraints ($T\mathrm{in}_c, T\mathrm{in}_h, T\mathrm{out}_c, T\mathrm{out}_h, F_c, F_h$) and their respectively measured data.

Once we got a reliable data of temperatures and flows, we can compute U from (4)-(7). Then, we try different polynomial adjusting, fitting the parameters to the computed U by constrained regression. After the computation of several models, we obtain that the best model that represent U from the operating conditions of temperature and flow is:

$$U = a_0 + a_1 \ F_h + a_2 \ F_h^2 + a_3 \ F_h^3 \quad (18)$$

Where U just depends on the hot source flow due to the temperature influence have resulted negligible and the product flow was nearly constant. The parameters $\theta = \{a_0, a_1, a_2, a_3\}$ are independent of the operating conditions. The Fig. 2 shows the difference between the values of the heat transfer coefficient obtained from the data reconciliation (U) and the predicted one ($\hat{U}$) with (18).

We have to take into account that, in order to ensure that the equation 5 is fulfilled for all the hot streams, including the ones that there have not been used, and consequently the heat is zero, we need to multiply the independent term a_0 in (18) by the corresponding binary variable, $X_{h,w}$. Hence, when a hot source has not been used, the binary will force that the independent term will be zero, and due to (13), the flow will also be zero, causing that the heat will be zero too.

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$$U_{h,w} = a_0 X_{h,w} + a_1\ F_{h,w} + a_2\ F^2_{h,w} + a_3\ F^3_{h,w} \quad \forall h \in \mathcal{S}, \quad \forall w \in \mathcal{HE} \quad (19)$$

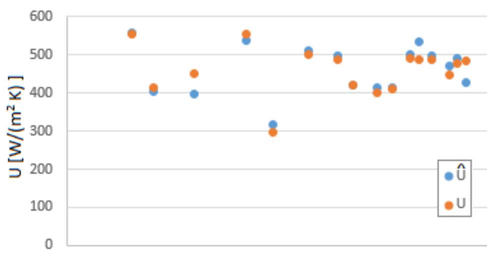

Figure 2: The goodness-of-fit of the model.

3.3 DISTRIBUTION OPTIMISATION RESULTS

Hence, the optimisation problem is to minimise (3) subject to (1)-(19). Note that this is a mixed-integer nonlinear programming (MINLP) problem, as there are discrete decisions ($X_{h,w}$) and $\Delta T(\cdot)$, $U(\cdot)$, are nonlinear functions in $F_{h,w}$. Once the problem is formulated, we coded it in Pyomo-Python and solved it using the NLP-based branch-and-bound algorithm Bonmin [8].

The optimisation has been tested offline with plant historical data[2]. The problem size is 195 decision variables (40 binaries) and a solution with zero relative gap is proven in about 30 seconds over an Intel® i7-7700 CPU machine.

HE	X(alk)	X(ualk)	X(vap)	X(acw)	F_h (m³/h)
w1	1	0	0	0	41.50
w2	1	0	0	0	35.72
w3	1	0	0	0	52.71
w4	1	0	0	0	55.64
w5	1	0	0	0	63.56
w6	0	0	1	0	33.71
w7	0	0	1	0	33.71
w8	0	1	0	0	135.14
w9	0	0	1	0	53.80
w10	0	1	0	0	78.07
w11	0	1	0	0	35.91
w12	0	0	0	1	18.12
w13	0	0	0	0	0.00
w14	0	0	0	0	0.00
w15	0	0	0	0	0.00

Figure 3: Example of results

Some results are depicted in the Fig. 3. In this case, as there is enough availability in the hot sources, the tool connects each heat exchanger to the cheaper source within its permitted connections. We can observe that, for the Block 3 (W-8 to W-11), the RTO tries to connect as many exchangers as possible to *ualk*, as this source is cost free. For the heat exchangers connected in series (W-12 to W-15), the RTO shows that the product temperature setpoint can be reached with just one equipment connected.

[2]These values are omitted due to confidentiality reasons with Lenzing AG.

4 EXTENSION TO CONSIDER FOULING

The problem described in Section 3.1 does not take into account the performance degradation due to fouling, as the regression models (18) have been obtained with the heat exchangers fully clean. Hence, over time, the actual U will be lower than the predicted one, so more water usage from sources will be needed to fulfil the setpoints in practice. To tackle this issue, we added a term in (19) that accounts for the *state of fouling*, K_w, which is computed online [9]. In addition, by monitoring the state of fouling, we can not only decide over the hot-sources distribution, but also suggesting which heat exchanger should be cleaned according to an economic tradeoff criterion.

4.1 CLEANING POLICY

Current cleaning policy of the heat exchangers in Lenzing AG is only based on how many days the equipment has been in operation. Nevertheless, this way may not be the more economically beneficial: As each heat source gets a different cost and the heat exchangers have different transmission areas (size) to process different products (specific-heat differences), it might occur than cleaning the dirtiest first is not the cheapest operation.

To incorporate the suggestion of which heat exchanger should be cleaned, we extended the previous RTO formulation with a set of binary variables, denoted by Y_w. These variables will determine if the heat exchanger w should be cleaned or not. Therefore, models U in (19) are extended with Y_w and K_w, as follows:

$$U_{h,w} = \big(a_0 - K_w(1-Y_w)\big)X_{h,w} + a_1\ F_{h,w} + a_2\ F^2_{h,w} + a_3\ F^3_{h,w} \quad \forall h \in \mathcal{S}, \quad \forall w \in \mathcal{HE} \quad (20)$$

Moreover, the cleaning task involves also a fixed cost (P_C), that is somehow amortised over the time of operation since last cleaning, t_w. Hence, the cleaning cost is depreciated over time, whereas the cost of operation progressively increases with time due to fouling. The normalised cost of all the suggested cleaning tasks is:

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$$J_{clean} = \sum_{w}^{\mathcal{HE}} \frac{Y_w \cdot \mathrm{P_C}}{t_w} \tag{21}$$

Therefore, the objective function of the RTO will now be a tradeoff between the heat-sources usage cost (3) and the normalised cost of the suggested cleaning tasks (21). Note however that, when a heat exchanger is not used, its fouling state does not increase. Consequently, to avoid unnecessary equipment degradation in the subset of exchangers with serial connection, we additionally penalise using exchangers with negligible hot flows (meaning that these are not really needed to reach the product setpoint in fact).

Hence, the new objective function reads:

$$J' = J_p + J_s + J_{clean} + \sum_{w}^{\mathcal{HE}_s} \sum_{h}^{\mathcal{S}} X_{w,h} \tag{22}$$

Note that the new problem will also work as an RTO tool, which helps the operators and plant managers with the decision making process on how to distribute the hot sources and which heat exchanger should be clean. However, note importantly that this does not address the *maintenance scheduling* [10], task that still relies only on the plant personnel.

4.2 RESULTS

To test the consistency of the extended RTO, we started from a particular situation in the plant historian and we rolled out the optimisation offline for several days. During this test we assumed that the heat exchangers suggested cleaning in each run (day of operation) have been cleaned for the next run[3].

In Fig. 3 we show the results of running the RTO for two consecutive days, i.e we run the RTO with actual plant data for the first day, and we take the optimised values as the starting situation for the next day, updating t_w and K_w for each exchanger accordingly, of course. As we can see in the depicted results, the optimised hot-sources distribution is basically the same for both days, which is consequent with the fact that no change in the product setpoints has been induced, and desirable to avoid *nervousness* issues [11, 12]. Nevertheless, as the state of fouling has increased in one day, a little bit more of hot water is needed to achieve the same setpoints. The only significant difference is that, for the heat exchangers connected in series, the optimiser decides to connect only the cleanest one, which is sensible.

[3]The maintenance scheduling is out of the scope of this work. However, note that we can trivially include a constraint limiting the number of exchangers that can be cleaned per run.

DAY	HE	X(alk)	X(ualk)	X(vap)	X(acw)	Y	F h	time	Fouling
Day 1	w1	1	0	0	0	0	19.20	1.00	2.00
	w2	1	0	0	0	0	32.59	2.00	4.00
	w3	1	0	0	0	1	48.91	8.00	16.00
	w4	1	0	0	0	0	54.56	3.00	6.00
	w5	1	0	0	0	0	62.17	6.00	12.00
	w6	0	0	1	0	0	32.45	6.00	12.00
	w7	0	0	1	0	0	30.90	2.00	4.00
	w8	0	1	0	0	0	170.36	25.00	50.00
	w9	0	0	1	0	1	50.13	9.00	18.00
	w10	0	0	1	0	0	24.34	0.00	0.00
	w11	0	1	0	0	0	39.26	4.00	8.00
	w12	0	0	0	0	0	0.00	13.00	26.00
	w13	0	0	0	0	0	0.00	11.00	22.00
	w14	0	0	0	0	0	0.00	18.00	36.00
	w15	0	0	0	1	0	17.80	11.00	22.00
Day 2	w1	1	0	0	0	0	19.28	2.00	4.00
	w2	1	0	0	0	0	32.68	3.00	6.00
	w3	1	0	0	0	0	48.91	0.00	0.00
	w4	1	0	0	0	0	54.61	4.00	8.00
	w5	1	0	0	0	0	62.24	7.00	14.00
	w6	0	0	1	0	0	32.51	7.00	14.00
	w7	0	0	1	0	0	31.02	3.00	6.00
	w8	0	1	0	0	0	170.20	26.00	52.00
	w9	0	0	1	0	0	50.13	0.00	0.00
	w10	0	0	1	0	0	24.40	1.00	2.00
	w11	0	1	0	0	0	39.29	5.00	10.00
	w12	0	0	0	0	0	0.00	13.00	26.00
	w13	0	0	0	1	0	17.81	11.00	22.00
	w14	0	0	0	0	0	0.00	18.00	36.00
	w15	0	0	0	0	0	0.00	12.00	24.00

Figure 4: Suggestions for two consecutive days.

Regarding the cleaning suggestions, it is noteworthy that the RTO does not chose to clean out the dirtiest heat exchanger. The reason is that this heat exchanger is using the cost-free source *ualk*. The next dirtier exchangers are the ones connected in series. However, as three of them are not used, there is no actual need of cleaning them. The fourth one, although it is connected and dirtier than the selected by the RTO to clean, its hot-water usage is lower due to a larger heat-transfer area (exchanger size). Consequently, there is less potential profit in cleaning this one (reduction of flow due to the cleaning) compared to the profit obtained by cleaning the suggested exchangers. Therefore, larger exchangers with relatively low loads won't be cleaned until they become really dirty.

With the extended formulation, the problem size increases up to 210 variables, but the time to get the solution with zero gap remains similar to the previous formulation.

5 CONCLUSIONS AND FURTHER STEPS

This work addresses a problem on resource efficiency in a real industrial heat recovery network. In particular, how to distribute the hot sources, used as utilities, in a heat-exchanger network. The modelling and optimisation concepts presented in this paper support the operators when it comes to taking better decisions in real time to improve the network operation. The resulting mathematical model is incorporated in a RTO scheme that solves a MINLP problem according to the current production constraints and the equipment fouling states. This scheme not only allows helping to know the optimal hot sources distribution but also suggests which should be the next cleaning task due to the explicit consideration of the fouling state of the equipments. This is an important issue due to we have proved that the nowadays cleaning policy of cleaning the heat exchanger that is dirtiest is not always the most efficient. Nevertheless, the instantaneous RTO does not take into account any prediction of the fouling effect, so the proposed maintenance actions by the scheme may be suboptimal in the long term.

For future work we would like to formulate the problem over a future time horizon in a scheduling fashion. In this way we could take the optimal decisions not just for the current day, but also for an entire week. To do that, we should be able to predict the fouling dynamics with time, apart from estimating the future availability of the hot sources. Of course, computational complexity of this scheduling problem will be much higher, so we should try to avoid non-convex constraints in the model formulation, e.g. by replacing the heat-transfer computation in energy balances by sets of previously computed lookup tables.

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