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A computational tool for analysing the response of complex heat exchanger networks to disturbances

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Abstract:

The heat exchanger networks (HEN) in industrial heat recovery systems often consist of large and complex subsystems. Calculating the response of such HENs to disturbances, such as varying inlet conditions or changing heat transfer capacities, may be challenging due to the presence of, e.g. stream splits and recycle loops. Extensive modelling and/or trial and error calculations may be necessary. This applies also for the analysis of different retrofit proposals. Retrofit opportunities in industrial heat recovery systems are often constrained by operability considerations, i.e. retrofit actions are supposed to have as little impact as possible on the production process to maintain the quality of the core product. Consequently, there is a clear demand for a tool to effectively screen design proposals at an early stage in the design process. In this work, a computational analysis tool is proposed to meet this demand. The proposed analysis tool allows fast evaluation of the network response when operating conditions change and/or operational settings are manipulated, and it is applicable for a wide range of HEN structures. The practical use of the analysis tool is demonstrated in a case study on the HENs of a large state-of-the-art Kraft pulp mill.

Keywords:

Flexibility, Heat integration, Operability, Pulp and paper industry, Retrofit.

1. Introduction

In accordance with the updated 2012 EU Energy Efficiency Directive, the EU member states have committed to increase the efficiency of final energy use by 32.5 % by 2030, compared to 2007 [1]. In Sweden, the national energy agency has been commissioned by the government to ensure a reduction in energy intensity (primary energy consumption per unit of GDP) by 50 % by 2030, compared to 2005 [2]. In 2015, the total Swedish final energy use was reported to be 370 TWh of which 140 TWh was accounted to industry [2]. The process industry was responsible for a significant share of the final industrial energy use in Sweden, of which the pulp and paper industry accounted for more than 50 % [2]. Moreover, a number of studies have shown that there is a substantial potential for energy savings in the pulp and paper industry [3]–[6]. Increased heat recovery is one important measure for increasing the energy efficiency in the pulp and paper industry. It has been estimated that about 25 % reduction in steam demand can be achieved by heat integration measures in a typical chemical market pulp mill [4].

Industrial heat recovery systems often consist of large and complex heat exchanger networks (HEN) to transfer heat between different processes. In pulp and paper mills, secondary heating systems may be designed, as a complement to process-to-process heat exchange. In these secondary heating systems, a heat transfer medium (commonly water) is used to recover/distribute heat from/to primary processes, in order to avoid operability issues resulting from the direct interconnection of different processes. One example of such operability issues is that cooling and heating demands may vary over time. The heat transfer medium may be stored in tanks to enable decoupling of the cooling and heating demands. The resulting hot and warm water systems are used for secondary heat recovery, but also for distributing process water for use in, e.g. dilution and washing steps. The interconnections between the secondary heating system and the primary processes are commonly characterized by a high degree of complexity, e.g. through stream splits, recycle and closed circulation loops.

Industrial plants are subjected to different kinds of time-dependent variations [3]. In this work, these variations are characterized in the following way:

- Short-term variations (daily and smaller).
- Medium-term variations (monthly and seasonal variations).

Heat recovery systems are normally designed to cope with expected short and medium-term variations (e.g. seasonal variations) to ensure operability. It is essential to maintain this flexibility during retrofitting processes, i.e. retrofit measures should have as little impact as possible on the operability of the heat recovery system and thus on the core production process to maintain the quality of the manufactured products.

For investigating heat integration projects in the pulp and paper industry, the pinch methodology is a commonly used approach. Several examples of pinch-based heat integration studies for different kind of pulp mills are found in the literature (see e.g. [4]–[6]), which are based on (annual) average and steady state values. The results of these studies suggest a potential of 15-25 % of reduction in steam use. However, Persson and Berntsson [3] showed that considering annual average values for a retrofit heat integration project in a pulp mill can lead to 15 % lower steam savings, when the studied mill is subjected to short and medium-term variations.

Another approach to heat integration problems is mathematical programming, which is a powerful tool for dealing with variations in operating data. Floudas and Grossmann [7] introduced a multiperiod approach to the HEN synthesis problem in the 1980s. More recently, the multiperiod approach has been developed further [8], [9] and has been applied to industrial case studies [10].

To be applied to retrofitting problems, additional work has been done for both pinch-based approaches [3], [11]–[13] and approaches based on multiperiod optimization [14], [15]. Independently of the chosen approach, a sufficient number of sets of operational data (scenarios or periods) needs to be considered. However, the complexity of the problem increases with increasing number of sets of operational data. Especially for large-scale industrial case studies the computational capacity can be a limiting factor when approaches based on multiperiod optimization are applied.

In the case of pinch based approaches, a common strategy is to develop different optimal design proposals for a number of selected sets of operating conditions [3]. The different design proposals are then either compared or combined to achieve an operable and energy efficient design for all operating points considered. To evaluate the different designs over various operating conditions, extensive simulation and/or iterative analytical calculations may be required to determine the response of the network, i.e. the network temperatures and heat loads, when the different designs are exposed to variations and operational settings are varied.

1.1. Aim

The aim of this paper is to propose an effective computational tool for convenient modelling of HENs that allows for calculation of temperatures and heat loads in a HEN that is exposed to variations in inlet conditions and operational settings. The tool is intended as an alternative to detailed simulation models and/or iterative trial-and-error calculations which can be computationally burdensome, especially for large-scale problems. Furthermore, the tool includes a systematic method for defining complex network topologies. As a result, the derivation of all modelling equations necessary to describe any given HEN physically and thermodynamically can be automated. This enables the analysis of HENs of any size, with stream splitting and mixing, and with recirculating streams and closed circulation loops. The proposed analysis tool is intended to provide guidance for design engineers when screening different design alternatives at an early stage in the design process. Usage of the proposed analysis tool in the screening process of a retrofit design project on the HENs of the secondary heating system of a Kraft pulp mill is presented in a case study at the end of this paper.

2. The computational tool

The proposed analysis tool determines temperatures, heat exchanger duties and utility duties of a HEN given the network topology, heat exchanger areas and the operational setting of network parameters, such as split ratios or bypass ratios. It can be used to screen HEN retrofit measures as well as HEN greenfield design proposals. For a heat recovery system that is subject to varying operating conditions, the analysis tool can be used in the design process following the procedure below:

1. Identification of different sets of operational data (e.g. data which varies with respect to seasonal variations).
2. Identification of magnitude of potential savings (e.g. steam savings in a Kraft pulp mill) through Pinch Analysis for one or several sets of operating conditions.
3. Proposal of retrofit measures (based on one or several set(s) of operational data) to achieve savings.
4. Test of proposed retrofit measures with each data set using the proposed analysis tool.
5. Adjustment of operational settings (e.g. split ratios) and consideration of (minor) design changes to ensure operability and maintain achieved savings during the entire operating period.

The proposed analysis tool does not generate network design proposals but rather enables the designer to identify bottlenecks in existing design proposals, and to conveniently assess the effect of manipulating operational parameters such as split ratios and bypass ratios. By adopting a systematic methodology for defining any given network design topology, followed by automated network modelling and calculations, highly efficient screening of different design proposals can be achieved at an early stage in the design process. The proposed analysis tool allows for fair comparison of more design proposals under various operating conditions than if, e.g. simulative approaches are chosen, which should increase the chances of identifying the most favourable design.

2.1. Physical and mathematical modelling

The purpose of the proposed analysis tool is to calculate all network temperatures for any kind of HEN. The number of unknown network temperatures can be specified a priori [16]. For a network with N streams, n_E process-to-process heat exchangers, n_S number of stream splits, n_M number of streams mixing and n_U number of utility exchangers, the number of unknown temperatures N_T is:

$$N_T = N + 2 \cdot n_E + 2 \cdot n_S + n_M + n_U. \tag{1}$$

The number of unknown temperatures N_T is reduced by N if the supply temperatures for all process streams are known.

If the CP-value (heat capacity flow rate) for each stream is constant and known as well as the UA-value (overall heat transfer coefficient and area), type and flow arrangement of each process-to-process exchanger, $2 \cdot n_E$ linear equations in T (unknown network temperatures) can be obtained by the P-NTU method. The P-NTU method is used to model and solve rating equations for different types of heat exchangers [17]. A detailed description on the derivation of the equations can be found in [18]. Furthermore, if the heat load Q_u or outlet temperature $T_{out,u}$ of the respective process stream for each utility exchanger is given, n_U additional equations linear in T are obtained via energy balances on the process side of the utility exchangers. The energy balance for one utility exchanger is:

$$Q_u = CP_i \cdot (T_{in,u} - T_{out,u}) \;\forall\; i \in N, u \in U. \tag{2}$$

In (2), CP_i is the CP-value of the respective process stream and $T_{in,u}$ is the temperature of the process stream at the inlet of the utility exchanger. The heat load Q_u in (2) will be positive if the respective process stream is cooled. If the process stream is heated, the sign of the temperatures needs to be switched in order to obtain a positive value for Q_u.

For the two unknown temperatures after a stream split ($T_{out,1}$ and $T_{out,2}$), trivial equations can be derived since isothermal splitting can be assumed. Thus, $2 \cdot n_S$ additional linear equations in T are obtained. The trivial equations can be expressed the following way:

$$T_{out,1} = T_{out,2} = T_{in,s} \;\forall\; s \in S. \tag{3}$$

Mixing of two streams gives one additional energy balance at the mixing point which is linear in T if the CP-value after mixing $CP_{mix,m}$ is known, and the split ratio SR is defined. In this context, the split ratio SR describes the ratio of the CP-values of the two streams which are mixed ($CP_{split,1}$ and $CP_{split,2}$) and the CP-value after mixing ($CP_{mix,m}$). The split ratio can therefore be expressed by $CP_{split,1}/CP_{mix,m}$ and $1 - CP_{split,2}/CP_{mix,m}$, respectively. If the energy balance is solved for the outlet temperature after the mixing point $T_{out,m}$ it is expressed in the following form:

$$T_{out,m} = \frac{SR \cdot CP_{mix,m} \cdot T_{mix,1} + (1 - SR) \cdot CP_{mix,m} \cdot T_{mix,2}}{CP_{mix,m}} \;\forall\; m \in M. \tag{4}$$

In (4), $T_{mix,1}$ and $T_{mix,2}$ are the temperatures of the two streams which are mixed. Overall, the number of equations is equal to the number of unknown temperatures for any HEN with respect to (1).

Recirculation of streams or closed circulation loops result in an identity change of the respective stream. In this context, the identity of a stream is defined by whether the stream releases heat (hot stream) or receives heat (cold stream) in the heat exchangers on the stream. Thus, recirculation of a stream or a closed circulation loop results in a stream that changes from cold to hot or from hot to cold, respectively. If a stream's identity changes, the temperature and the CP-value are theoretically unknown but trivial equations describing the relation between the temperatures and the CP-values over the identity change can be derived. The relation between the temperatures and the CP-values over a stream's identity change is visualized in Fig. 1. A switch model known from flowsheet modelling is used. Consequently, recirculation of streams or closed circulation loops add the same number of unknown temperatures as of linear equations in temperature to the problem.

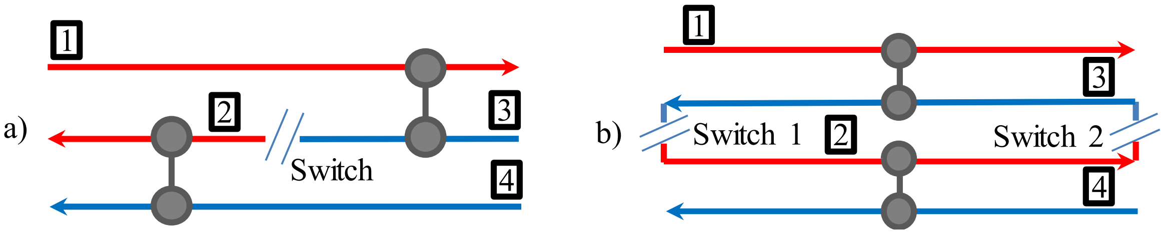

Figure 1. Visualisation of the identity change of a stream (i.e. a hot stream becomes a cold stream or vice versa) which is (a) a re-circulating stream and (b) a stream in a closed circulation loop.

Under certain assumptions (known and constant CP-values, split and bypass ratios, and UA-values), it is therefore possible to express the unknown network temperatures by means of linear equations which can be solved as a linear equation system.

Since UA-values may depend on temperatures and CP-values, assuming a constant UA-value when variations in temperatures and flow rates are introduced, may be a simplification of the actual problem. To avoid this simplification, thermodynamic modelling may be necessary. However, it is assumed that in early design stage screening this simplification is a valid trade-off between accuracy and computational expense. Nevertheless, there exist approaches to account for the dependency of the UA-value if given CP-values differ from design values in form of correction factors. In the proposed tool, a correction factor which was introduced and studied by Persson and Berntsson in [3] has been implemented.

2.2. Network modelling

To model a HEN, the network structure or topology needs to be modelled. This can be challenging for large and complex networks due to the presence of a high number of units, multiple streams splits, recirculation of streams and closed circulation loops. A general methodology has been developed to model the topology in a straightforward way. In a first step, each stream of the network is numbered. To handle stream splits, recirculation of streams and closed circulation loops, streams are numbered with respect to their CP-values and identities. This means that a stream in the modelling sense needs to have a constant CP-value and fixed identity. A stream split where one stream is splitted into two streams is, thus, counted as three individual streams. If the two splitted streams are mixed back together a fourth stream is counted. In Fig. 2, an example network is presented in its classical grid representation. The streams are numbered according to the introduced numbering procedure. Furthermore, all unknown network temperatures with respect to (1) are marked.

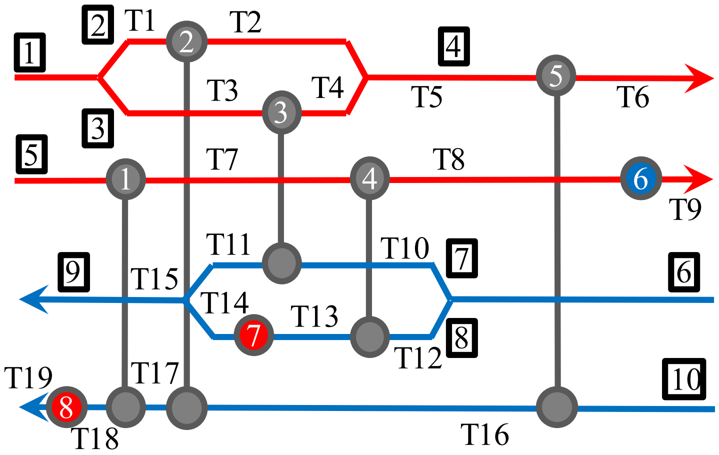

Figure 2. Example HEN illustrating the developed numbering procedure of streams and the unknown network temperatures in a classical grid representation.

For recirculation of streams and closed circulation loops, switches are used which define the locations where the identity of streams changes. Consequently, with each switch a new stream is introduced. This counting procedure can be recognized in Fig. 1.

Besides stream numbering, a generalized way to refer to the location of a specific process-to-process (P2P) or utility exchanger (utility) is needed. Basically, this includes the (process) streams which are exchanging heat by means of the exchanger as well as the location of the specific exchanger on those streams. For this reason, a system to specify the position of the exchangers is developed which is based on the stream numbering. For each exchanger, the hot and cold stream as well as the position of the exchanger on these streams must be known. For utility exchangers, a target temperature is specified in order to calculate the duty of each utility exchanger (see section 2.1). For the network depicted in Fig. 2, the following location matrix for the heat exchangers can be derived (see Table 1).

Table 1. Exchanger location matrix of the example HEN for defining the position of all process-to-process (P2P) and utility exchangers and the target temperatures of streams with utility exchangers.

		Hot streams		Cold streams			Only for Type "utility"
Exchanger	UA	Stream-number	HEX number on stream	Stream-number	HEX number on stream	Type (P2P or utility)	Target temperature (after exchanger)
1	UA1	5	1	10	2	P2P	
2	UA2	2	1	10	3	P2P	
3	UA3	3	1	7	1	P2P	
4	UA4	5	2	8	2	P2P	
5	UA5	4	1	10	4	P2P	
6		5	3			utility	$T_{target,5}$
7				8	1	utility	$T_{target,8}$
8				10	1	utility	$T_{target,10}$

In Table 1 and Fig. 2, all heat exchangers are counted from left to right which in this case is the grid flow direction of the hot streams. In general, different directions of counting are possible and can be implemented in the tool.

A similar positioning system is used to describe the location of stream splits and mixing of streams. It is also based on the introduced stream numbering system. Table 2 presents the location matrix for the stream splits and mixes for the example network in Fig. 2.

Table 2. Split/mix location matrix describing the position of all stream splits and mixes of the example network.

	Split streams			Mix streams		
Index	In	Out1	Out2	In1	In2	Out
1	1	2	3	2	3	4
2	6	7	8	7	8	9

For describing the location of switches, it is required to specify the ingoing and the outgoing stream, and a similar location matrix can be derived.

Input data and limitations of the computational tool

In accordance for the analysis tool to be applied to a given HEN design, input data needs to be provided. The necessary input data is summarised in Table 3.

Table 3. Necessary input data for applying the computational analysis tool to a HEN.

<table>
<tr><td colspan="3">For each process-to-process heat exchanger:
▪ UA-value.
▪ Type of heat exchanger.
▪ Hot and cold stream which are connected by the exchanger.
▪ Position of heat exchanger on hot and cold stream.
▪ Individual heat transfer coefficients and CP values for the design case to calculate corrected UA-values by means of the chosen correction factor.</td></tr>
<tr><td>For each hot and cold stream:
▪ CP value.
▪ Supply temperature.</td><td>For each split/mix
▪ Inlet and outlet stream(s).
▪ Split ratio to maintain linearity of the problem.</td><td>For each switch (two switches for a circulation loop)
▪ Inlet and outlet stream.</td></tr>
</table>

Based on this input data, the proposed tool enables the design engineer to calculate all network temperatures and duties of process-to-process and utility exchangers. As the above listed input data already implies, there are limitations for application of the tool, as listed below:

- Temperature dependency of UA- and CP-values is not respected.
- The analysis tool does not explicitly provide suggestions regarding specific design changes.
- The tool is limited to give the network response to variations in network supply temperatures, heat capacity flowrates and UA-values.
- Operational parameters which can be adjusted and represented by the analysis tool are heat exchanger bypass ratios, split ratios and flow rates of utility streams (loads of utility exchangers).
- The tool supports trial and error and partial trial and error adjustment of operational parameters; optimization algorithms are not incorporated.

3. Case study

This section illustrates usage of the proposed analysis tool for screening different retrofit design proposals to utilize more waste heat in the secondary heating system of one of the largest Kraft pulp mills in Sweden. The tool was used in accordance with the procedure presented in Section 2. In a first step, historical data was screened to identify four different operational data sets representing typical operating conditions for each of the four annual seasons. In practice, spring and autumn operational conditions are sufficiently similar to consider the same data set for both seasons. More operational data sets may be necessary to guarantee the previously defined aims of sufficient flexibility while maintaining a high degree of energy recovery over the entire operating period.

After identification of the operational data sets, pinch analysis was performed with the operational data for spring/autumn conditions and the magnitude of possible savings was quantified (27.7 MW) as well as the magnitude of major pinch rule violations. Spring conditions were chosen to avoid over- or underestimation of the potential savings which may occur when using more extreme Summer or Winter conditions. The two largest pinch rule violations identified involved steam heating below the pinch in the primary air heating (6 MW) and the feed-water heating (4.1 MW), representing 36.5 % of the total identified pinch violations. The two corresponding process streams (heating of primary air and feed-water) are found in the same independent subsystem within the secondary heating system of the pulp mill, which is shown in Fig. 3. In this subsystem, a third process stream (internal heating network) is also present.

The three process streams are connected through the secondary heating system which is fed by cold water from the corresponding tank and by a small amount of blowdown steam which is released from a boiler. The cold water is heated by hot effluent from the recovery boiler system in heat exchanger HEX 2. The heat is then distributed through a closed circulation loop to the primary air heating (HEX 1 and 3) and over a series of stream splits to the feed water heating (HEX 6 and 7) and the internal heating network (HEX 4 and 5). Additionally, a small amount of hot water is extracted from the secondary heating system to the hot water tank (stream split 2) from where it is later distributed to several processes, e.g. to the washing and dilution steps in the bleaching section of the pulp mill. By means of the historical data screening, seasonal variations which affect temperatures and mass flows were identified at five different locations (marked by circled numbers in Fig. 3). The variations are presented in Table 4.

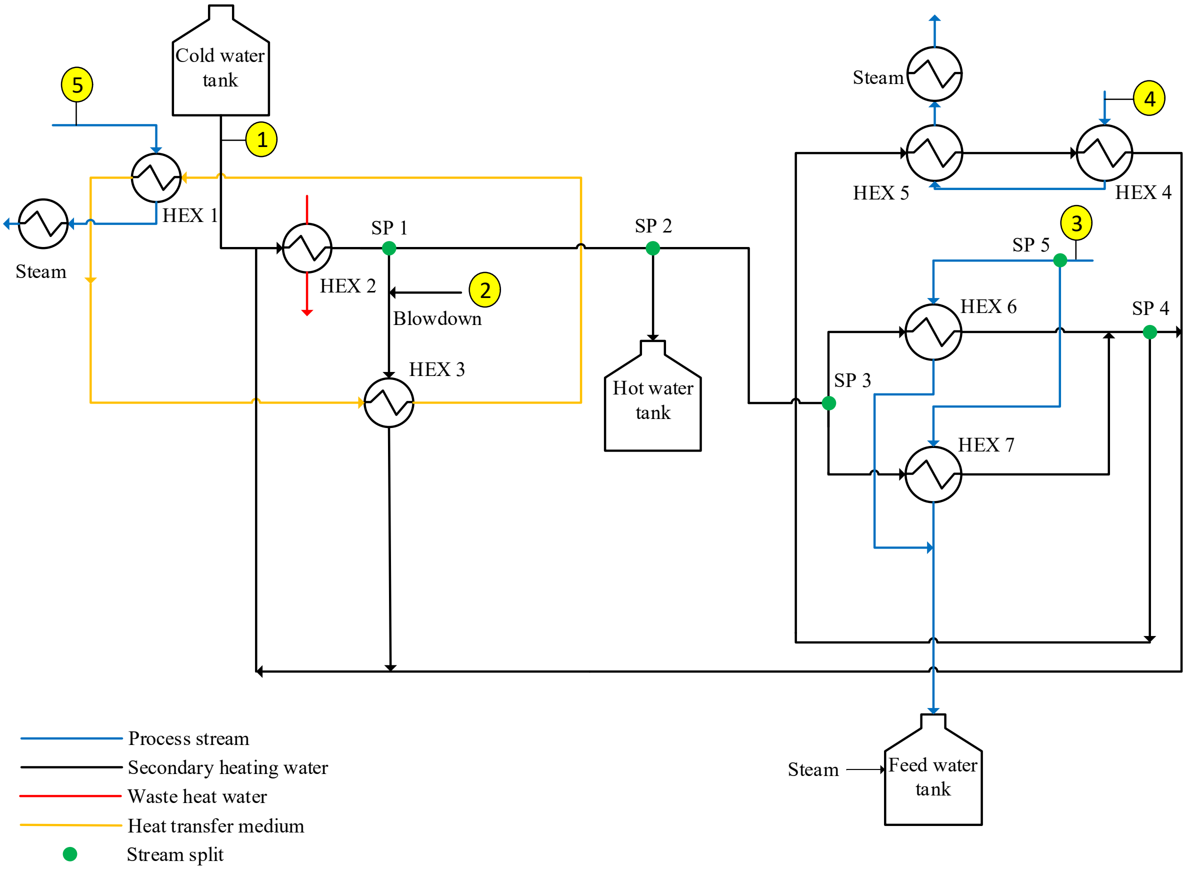

Figure 3. Network structure of the studied subsystem of the pulp mill's secondary heating system, including the locations where disturbances in temperature and heat capacity flow are introduced.

Table 4. Location and description of the disturbances in the studied subsystem of the pulp mill's secondary heating system.

Location	Description	Spring/Autumn	Summer	Winter
1	Temperature of cold-water tank [°C]	16.8	19.4	12.3
	Flowrate from cold-water tank [kg/s]	-	-	-
2	Temperature blowdown [°C]	92.5	93.6	92.1
	Flowrate blowdown [kg/s]	8.9	9.5	9.4
3	Feed water temperature to HEX 6 & 7 [°C]	82.5	86.6	80.3
	Feed water flowrate to HEX 6 & 7 [kg/s]	53.9	47.5	62.0
4	Temperature internal heating network [°C]	51.4	62.9	49.4
	Flow internal heating network [kg/s]	29.5	28.7	32.2
5	Temperature of air to boiler [°C]	32.7	36.9	31.4
	Flowrate of air to boiler [kg/s]	154.9	153.4	156.9

In order to reduce the pinch violations, different retrofit proposals were formulated. One interesting option is to implement two new heat exchangers (New1 and New2) which utilize waste heat from the digester section of the pulp mill. Pressurized secondary heating water is heat exchanged in the digester section of the mill to generate “very hot water” (VHM) which is then heat exchanged with the process streams in the studied subsystem. Two locations in the studied subsystem were identified for the new heat exchangers New1 and New2. With respect to the flow arrangement of the pressurized VHM, this resulted in two different design alternatives (design 1 and 2), as shown in Fig. 4.

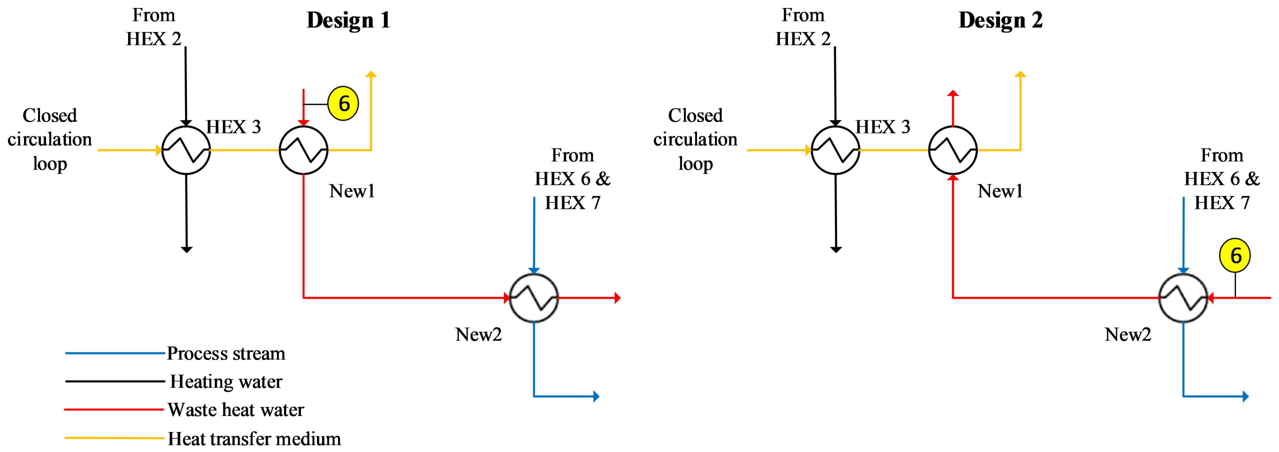

Figure 4. First retrofit proposal and the resulting two design alternatives (design 1 and 2) of the studied subsystem of the pulp mill’s secondary heating system.

Additionally, it was considered to reduce the investment cost by investing in only one new heat exchanger New1 but use the pressurized VHM in the existing heat exchangers HEX 6 and HEX 7 instead of the hot secondary heating water generated by HEX 2. With respect to the flow arrangement of New1 and HEX 6/7, two additional design alternatives (design 3 and 4) were identified which are shown in Fig. 5. In these two design alternatives the hot secondary heating water, which was originally split in stream split 3 (see Fig. 3) to feed the hot sides of HEX 6 and HEX 7, bypasses the feed water heating (HEX 6 and HEX 7) completely and flows directly to stream split 4. This is not shown in Fig. 5.

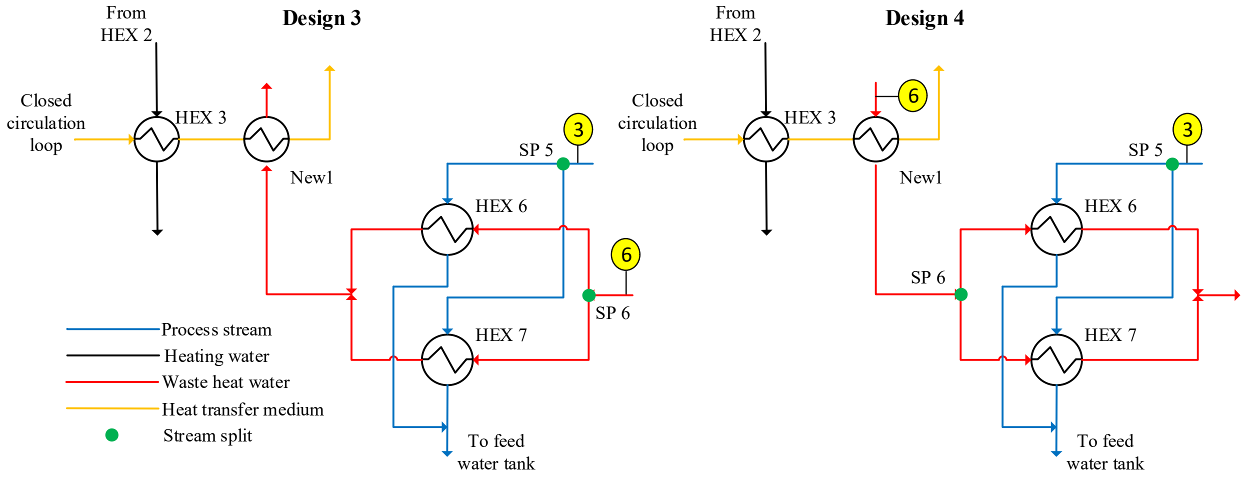

Figure 5. Second retrofit proposal and the resulting two design alternatives (design 3 and 4) of the studied subsystem of the pulp mill’s secondary heating system.

Since the utilizable waste heat is also affected by seasonal variations, a sixth location at which seasonal variations influence the system was introduced. These variations are presented in Table 5.

Table 5. Location and description of the disturbances introduced to the studied subsystem of the pulp mill's secondary heating system by the two retrofit proposals.

Location	Description	Spring/Autumn	Summer	Winter
6	Temperature of very hot water [°C]	113.7	103.6	113.2
	Flowrate of very hot water [kg/s]	81.8	81.8	88.7

The analysis tool was used to test the different design alternatives for the identified operational data sets. Seven operational constraints were defined in cooperation with mill engineers in order to guarantee the operability of the studied subsystem and to some extent also of other processes such as the washing and dilution steps which use hot water produced in the subsystem. The operational constraints are listed below, and the corresponding numerical values are presented in Table 6:

1. The heat transferred in HEX 2 is limited by the available heat and the heat exchanger size. This can be expressed by two constraints:
    a. Maximum duty of HEX 2.
    b. Specified outlet temperature of the secondary heating water from HEX 2.
2. The return temperature of the pressurized VHM has a lower limit since it is also fed to the hot water tank.
3. The flowrate through HEX 3 is limited to ensure that no increase in size of HEX 3 is necessary.
4. The flowrates on the hot sides of HEX 7 (a) and HEX 6 (b) are limited.
5. The flowrate of hot secondary heating water to the hot water tank is specified (stream split 2).

Table 6. Numerical values for the identified operational constraints.

	1 a [MW]	1 b [°C]	2 [°C]	3 [kg/s]	4 a [kg/s]	4 b [kg/s]	5 [kg/s]
Spring/Autumn	≤ 15	86.2	95.8	≤ 50	≤ 28	≤ 70	12.9
Summer	≤ 15	86.9	87.0	≤ 50	≤ 28	≤ 70	21.2
Winter	≤ 15	86.7	95.1	≤ 50	≤ 28	≤ 70	13.6

To apply the proposed tool to the design problem, UA-values for all heat exchangers including the new heat exchangers New1 and New2 are required. These values were calculated using a simplified model of the studied subsystem. Additionally, the analysis of the simplified model revealed that doubling the area of heat exchanger HEX 1 is an interesting option to better utilize the waste heat transferred in heat exchanger HEX 2. The increased area of HEX 1 and the preliminary area values for New1 and New2 can be adjusted in the analysis step to find a good trade-off between operating and investment costs.

In order to ensure that the identified operational constraints are not violated when the subsystem is exposed to variations, the following adjustable operational parameters were identified:

- Split ratios (SR) 1-5 (6 for designs 3 and 4).
- Flow rate in closed circulation loop.
- Bypass ratio of heat exchanger New1 or New2 (only one of the heat exchangers needs to be bypassed to control the return temperature of the VHM to the hot water tank).

With the above stated information, the different design proposals can be evaluated using the analysis tool. The main objective is to satisfy all operational constraints while reducing the steam demand in the steam heaters of the three process streams. This can be achieved by adjusting the operational parameters. In this context, the analysis tool enables different strategies to find feasible solutions, e.g. trial and error adjustment. In this paper, a partial trial and error procedure was adopted. Additional constraints were defined to avoid a full trial and error procedure, e.g. SR 4 was set so as to avoid any steam demand in the internal heating network (if possible: SR 4 <= 1). Similar additional constraints were formulated for SR 1, 2, 3 and 5. The remaining adjustable operational parameters (SR 6 for design 3 and 4, flow rate in closed circulation loop and bypass ratio of New1/New2) were subject to trial and error adjustments to find feasible operating points with decreased steam demand. The analysis tool revealed that it is possible to satisfy the operational constraints for all four design proposals. Furthermore, all design proposals achieve steam savings, as shown in Fig. 6. These steam savings were achieved with the preliminary area values for New1 and New2 and with an increased area of HEX 1 (increased by 100 %).

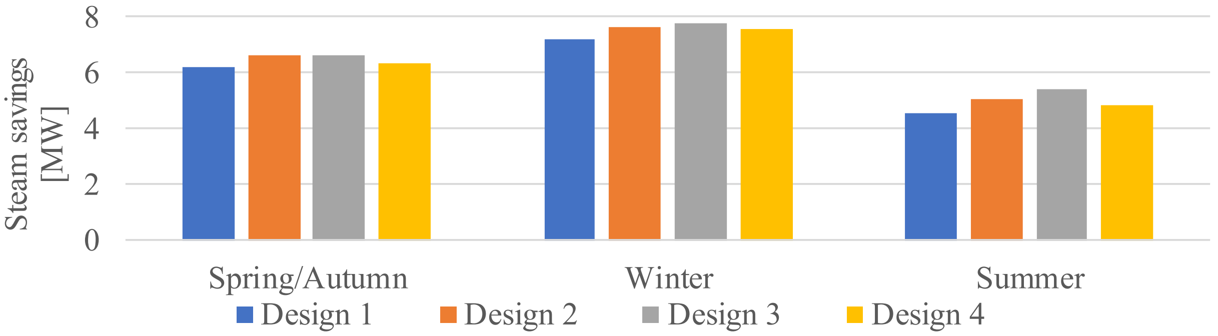

Figure 6. Steam savings of designs 1-4 for typical spring/autumn, winter and summer operating conditions.

From Fig. 6 it can be concluded that design proposal 3 achieves the highest steam savings for all seasons. Compared to the existing network, the achieved steam savings are 6.6 MW for spring/autumn, 7.8 MW for winter, and 5.4 MW for summer operating conditions.

Comparing the achieved steam savings with the identified pinch violations in the subsystem of interest (10.1 MW for spring/autumn operating conditions) reveals that pinch violations could be decreased by 65.7 % for spring/autumn operating conditions.

In a final step, the tool was used to further analyse the preliminary designed area for the new heat exchanger New1 in design proposal 3. The UA-value of New1 was decreased iteratively until either the steam consumption increased, or an operational constraint was violated. For spring/autumn and winter conditions, the UA-value can be decreased to 32.7 % and 28.5 % of the preliminary designed value, respectively. For summer conditions, any decrease in UA is penalized by an increased steam demand. Nevertheless, with a decrease of the UA-value to 32.7 % of its initial preliminary value, the steam savings during summer operation are decreased only by 10 % (see Fig. 7). It is therefore an interesting optimization option and should be considered in a further cost analysis. A decrease of the area of HEX 1, which was preliminarily designed to be the double of the current area value, was discarded since steam savings would decrease for all seasons. Based on the achieved results, rigorous cost calculations can be performed to make a final investment decision.

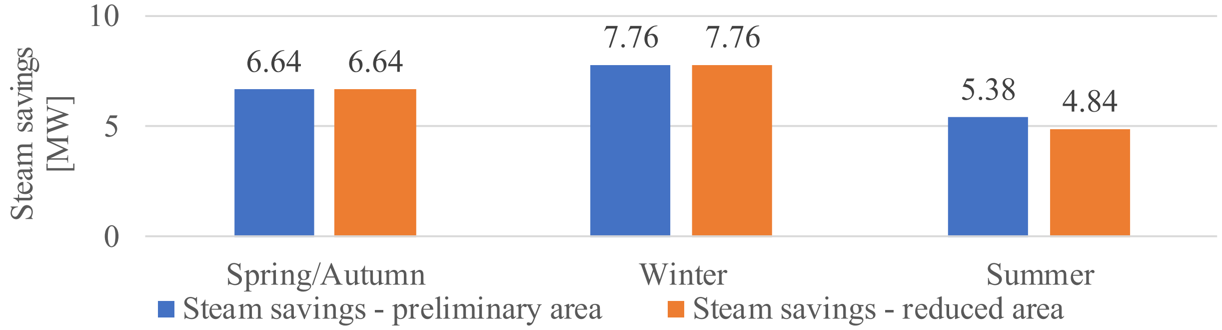

Figure 7. Steam savings of design 3 for typical spring/autumn, winter and summer operating conditions for the preliminary area and the reduced area of the new HEX New1.

4. Conclusion

Depending on the complexity of the process, the design of a HEN exposed to variations can be a cumbersome problem to solve if state-of-the-art methods are applied (pinch-based or optimization-based approaches). For pinch-based approaches, full simulation and/or analytical calculations are necessary to evaluate the network response when operational data changes. This applies also for the evaluation of adjustable operational parameters and (minor) design changes. The computational analysis tool proposed in this paper overcomes these difficulties. The successful implementation of the proposed tool was demonstrated in a case study on the HENs of a state-of-the-art Kraft pulp mill. The overall energy efficiency could be increased effectively while investment costs are maintained on a moderate level (one additional heat exchanger, increase of one existing heat exchanger and repiping of the feed water heating system). The results provided by the analysis tool allows for rigorous cost calculations and investment evaluations that require these values as inputs. To avoid an iterative procedure, future work will focus on implementing optimization algorithms to determine the adjustable operational settings.

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