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Development of a Simplified Process Integration Methodology for application in Medium-Size Industries

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Abstract:

Achieving significant energy savings is fundamental for reaching the ambitious EU 20-20-20 environmental targets. Several methodologies based on the Pinch concept have proved to be highly effective for identifying and assessing energy savings possibilities in the industrial sector. However, saving opportunities may be missed in the case of medium-size industries. Applying these methods may indeed be costly and time-consuming, as it can require large engineering efforts, e.g., for data acquisition.

This paper presents a methodology based on process integration techniques, termed "Specific Savings Potential method" (SSP), to depict and promote energy savings in intermediate-size industries for plant retrofit. It builds on the idea that only few of the process streams in a factory should be considered for efficiency measures implementation with regards to economic and operational aspects. Three screening tools are introduced. They are used to reduce the problem size before applying the traditional design procedure. They are based on engineering experience and simple mathematical criteria, including both thermodynamic and economic considerations. Moreover, possibility of using less accurate data or estimates is discussed, since data acquisition is a severely time-consuming task in retrofit projects.

This novel methodology is applied to a Danish dairy factory: the results and the method itself are compared with conventional pinch analysis. The findings show that the SSP method is a tool able to simplify and shorten the conventional pinch technique, while depicting the most promising savings opportunities: in the case study a reduction in energy use of 24% is achieved when only considering 24 process streams out of 62. In this sense, it has the potential of promoting the application of PI tools in the industry, especially in medium-size industries where budgets for external consultants are generally low.

Keywords:

Process Integration. Retrofit. Dairy industry. Simplification. Time consumption. Data accuracy.

1. Introduction

The European Union has set ambitious short- and medium-term targets of CO_2-reductions to tackle the issue of climate change, aiming at 20%, 40% and 80% decrease compared to the 1990's emissions level, by 2020, 2030 and 2050, respectively (EU framework [1]). Such goals can be met by (i) shifting to more sustainable energy sources, (ii) decreasing the energy intensity of human activities, and (iii) improving the efficiency of energy conversion processes.

Industrial processes may present significant potentials for energy savings, and process integration techniques, such as Pinch Analysis, are powerful tools for depicting them and suggesting economically-sound improvements. This method was developed by Linnhoff [2] in the 80's – 90's for designing heat exchanger networks in chemical processes and was extended to industrial sites and complexes by Dhole and Klemes [3] (total site analysis). Mathematical models were proposed in parallel, with the example of the transhipment model, and more complex strategies were developed since, such as the Mixed Integer Linear Programming formulation presented in Maréchal and Kalitventzeff [4]. These methods were at first developed for grassroot applications and research on retrofit cases is scarcer.

As discussed in the literature, a retrofit problem does not present a single solution but several ones, and is made complex by the high number of degrees of freedom when modifying the heat exchanger network (HEX). The retrofit solutions differ by the number of required modifications, which results in a clear trade-off between the additional investment costs and the reductions in operating costs (Hackl et al. [5]).

A complex retrofit problem can be formulated mathematically as non-linear and mixed-integer, as described in Kralj et al. [6] and in Mejia-Suarez et al. [7], but may be difficult to solve because of the large problem size. The interest for genetic algorithms to tackle such issue is discussed in Yu et al. [8], while possibilities for reducing the problem complexity by eliminating the non-linearity aspects are described in Pan et al. [9]. Graphical tools have been of interest, as demonstrated with the work of Nordman and Berntsson [10], as well as heuristic procedures, which include other insights such as the detailed design of the heat exchangers (Piacentino [11]) or alternative rules for path construction (Varbanov and Klemes [12]).

These methods are most often applied for retrofit of large-size systems, and they may not be relevant for small-scale processes, for which improvements may be obvious at a first glance. The case of intermediate-size systems is tricky. Such processes may be too complex to easily depict possible energy improvements that would be economically sound. However, the use of computationally-intensive or time-consuming tools, which require large engineering efforts with regards to data collection and problem solving, may not be justified. This may in turn discourage the application of process integration tools for these systems.

As discussed in Dalsgård et al. [13], it is therefore relevant to look for possible problem and procedure simplifications. Pouransari et al. [14] proposed an approach based on the representation of energy requirements at different levels of details to address the retrofit problem, while Dalsgård et al. [13] developed a heuristic procedure in four steps to actually simplify the process integration problem before using conventional analysis tools. Though relevant, these retrofit methods have not been used widely, and the proposed paper aims at developing an efficient screening tool, by which irrelevant streams are disregarded, based on thermodynamic, operability, and economic aspects. The main effort was on completing the conventional retrofit methodologies with heuristic and mathematical simplification criteria, in order to reduce the problem size and propose a feasible and reasonable retrofit.

The present paper is structured as follows. Section 2 consists of the description of the proposed methodology, together with a description of the case study on which it is applied. Section 3 presents the associated results, with a comparison of the outcomes obtained by the traditional method. Section 4 discusses benefits, limitations and possible improvements of the proposed approach, and Section 5 summarises the main conclusions and describes possibilities for future works.

2. Methodology

2.1. The “Specific Savings Potential Method”

Industrial processes are often characterised by a high complexity and present a remarkable number of process and utility streams. A complete system evaluation for retrofit projects, which aims at the maximum energy savings, is time-consuming and requires significant engineering efforts. In practice, including all streams in the analysis is not relevant from an economic and operational perspective, because most have a small energy demand or the corresponding heat exchangers cannot be easily re-designed.

The novel methodology presented hereby, named “Specific Savings Potential method” (SSP), aims to cut the time spent in the retrofit projects, by reducing the problem size as soon as possible along the design procedure and by disregarding irrelevant streams. The method includes three simplification steps, which have to be used alongside with the traditional Pinch Analysis. They are presented in the following subsections.

2.1.1. First simplification

The first simplification step is performed before the thorough data collection. At this stage no detailed data regarding the processes is readily available, but eventually information about the utility consumption associated with the heating and cooling demands of each stream. However, based on just these few data, a first simplification can be made grounded on an analytical criterion and engineering experience.

1. *Simplification based on external utility consumption.* The percentage of utility consumption caused by each stream with respect to the entire plant is calculated. A threshold value is set by the method practitioner and all the streams with a smaller energy demand are disregarded. The aggregated consumption of the remaining streams should preferably not be lower than 85% of the whole plant. If two streams are connected in the existing process, through, e.g., a heat exchanger or a heat recovery loop, they are both considered in the reduced sub-network, even though one of them has a utility consumption lower than the threshold.
2. *Simplification based on experience.* The selected streams are screened another time and another selection is made on timing, safety concerns or other criteria derived by experience.

2.1.2. Second simplification

3. *Data collection.* A full data collection is performed on the previously selected streams, as done in the traditional Pinch Analysis procedure [15]. Particular attention should be paid on retrieving data related to temperatures of streams with high heat capacity rate.

At this point an iterative procedure is performed to detect the most important streams from an energy recovery perspective. This is the core of the whole methodology and includes the following three steps:

4. *Targeting procedure.* The targeting procedure of the Pinch Analysis [15] is performed on the previously selected sub-network.
5. *Specific Savings Content calculation.* From the results of the targeting procedure, the *Specific Savings Content* (σ) of the sub-network is calculated. It is defined as:

$$\sigma = \frac{Percentage\, utility\, savings}{Number\, of\, streams} \qquad (1)$$

Where

$$Percentage\, utility\, savings = \frac{Utility\, savings\, target}{Existing\, utility\, consumption} \cdot 100 \qquad (2)$$

σ represents the average savings potential of the considered streams. The higher its value, the higher the benefit prospective of a retrofit conducted on the selected sub-network.

6. *Optimisation.* Raise the threshold and disregard the streams responsible for a lower utility consumption. Then, repeat the procedure from step 4 until σ reaches a maximum.

2.1.3. Third simplification

At this point, the retrofit procedure is simplified to include fewer streams in the analysis, which are responsible for a significant external utility demand. However, this does not imply that the retrofit project is economically feasible, and a last simplification is therefore performed based on an economic criterion:

7. *Identification of the "Pinch violations"*. The pinch violations present in the selected sub-network are calculated, exactly as performed in the traditional Pinch Analysis procedure [15]. They represent the process inefficiencies with regards to energy consumption.
8. *Economic evaluation.* This step connects the savings potential of the streams with economic feasibility criteria. By fixing a maximum acceptable *payback time* (PBT) and a maximum acceptable *minimum logarithmic mean temperature difference* (ΔT_{lm}) for a heat exchanger, a threshold for the heat exchanger duty is set by means of the following equations:

$$PBT = \frac{Investment}{Savings} \tag{3}$$

$$A = \frac{H}{U \cdot \Delta T_{lm}} \tag{4}$$

$$Investment\,cost = f(A) \tag{5}$$

$$H = \dot{m}c_p(\Delta T) \tag{6}$$

   Where A is the heat exchanger area, H is the heat flow rate, U is the overall heat transfer coefficient, $\dot{m}$ is the stream mass flow rate, c_p is the average specific heat capacity of the used medium and ΔT is the temperature difference between heat exchanger inlet and outlet.

   All the violations lower than this threshold are not considered for the final retrofit. In a similar way the duty threshold could be set fixing a maximum acceptable PBT and UA-value, in place of the ΔT_{lm}.
9. *Traditional retrofit.* The usual procedure is performed.

The presented methodology is summarised in Figure 1.

2.2 Data accuracy

Data collection and acquisition is a crucial task in PI projects, as results depend largely on the quality of the input data when a real project is performed. However, this task is often overlooked due to the harsh time requirement with which it is associated (up to 80% of the entire project time [16]), resulting in high uncertainties in the project outcomes. This is especially caused by process parameters (e.g. temperatures, mass flow rates), which are accompanied by many sources of uncertainties, such as (i) parametric variability and (ii) residual variability [17]. The former is related to measurement errors, while the latter to the unpredictability of the process, which shows a time variation of parameters around their set-points. It is therefore essential to understand the uncertainties influence on the project outcomes, to avoid mistakes able to undermine the success of the study. The influence of uncertainties related to temperatures and mass flow rates was therefore analysed by means of Monte-Carlo analysis [18]. A model accounting for all the process interrelations of such factors was developed by means of *Simulink*® [19].

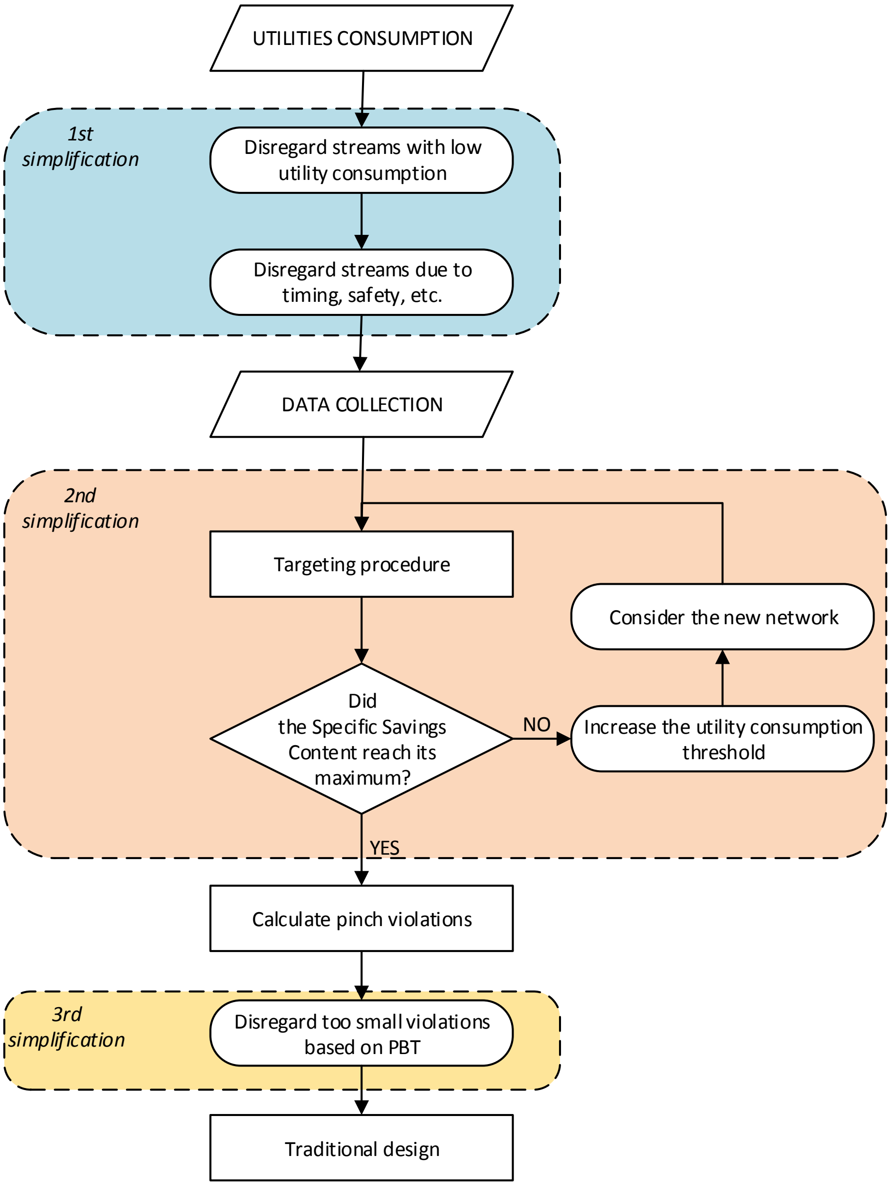

Fig. 1. Specific Savings Potential method process scheme.

2.3 The case study

The SSP method has been applied on a dairy factory currently operating in Denmark to test and validate its usefulness and benefits. Almost 75,000 tons per year of cheese are produced, together with by-products such as *cream* and *whey cream*, while around 750,000 tons of raw milk are processed. The plant includes 62 process streams, which require many thermal treatments such as pasteurisation, sterilisation and thermalisation. These operations are all characterised by the need of heating a liquid stream and then cooling it down, and these features suggest that there is a high potential for implementing heat recovery measures. The actual plant utility demand is 8546.4 kW, while the overall pinch target is calculated to be 3792.5 kW. This shows a heat recovery potential of 4753.9 kW (56% of the actual consumption), even though the existing processes are already highly integrated by means of regenerative heat exchangers. The plant operates for 7,800 hours per year.

3. Results

3.1 Traditional pinch analysis

In order to set a benchmark for evaluating the benefits of the SSP method, the traditional Pinch Analysis procedure was firstly applied on the case study, looking for PI potentials. This was done by applying the procedure presented by Linnhoff [15]. The design results showed that a 24% reduction in energy consumption could be achieved with a 4.1 years payback time and a Net Present Value (NPV) of 66 MDKK in a 20-years life span. This proves that it is possible to significantly cut the process utility consumption in an economically feasible way. Moreover, such a beneficial retrofit was achieved by modifying the heat exchanger network of just 24 of the 62 streams, which illustrates that only a limited number of streams is interesting when implementing feasible energy conservation measures.

3.2 SSP method

The following illustrates the application of the SSP method, altogether with the obtained results, following step-by-step the procedure presented in Section 2.1.

3.2.1. First simplification

A percentage utility consumption threshold of 3% was set at first. In this way, 43 process streams were selected out of the 62 composing the whole plant, achieving a remarkable reduction in the number of streams. Despite this simplification, the utility consumption of the selected sub-network is equal to 93.8% of the existing plant consumption, making it very unlikely that interesting streams are ignored. Even if possible according to the procedure, the threshold was not hereby risen any further and the "*simplification based on experience*" was not applied, in order to study the second simplification step more in detail.

3.2.2. Second simplification

The second simplification tool was then utilised on the selected sub-network, starting from the detailed data acquisition and applying the aforementioned iterative procedure. The results are presented in Figure 2.

As it is shown, by increasing the utility consumption threshold, the aggregated utility consumption of the selected sub-network decreases (Figure a), as well as the number of streams (Figure c). However, the most interesting result is presented in Figure d, which depicts the trend of σ raising the threshold. It can be seen that an optimum is detected for a threshold of 8%. Based on the SSP method, the sub-network corresponding to that case is the chosen one for the retrofit. It was found that it is composed by all the streams that were considered when using the traditional methodology. Increasing the threshold up to 14% one important stream would have been disregarded, lowering significantly the savings potential (18% decrease in absolute terms). Therefore, the SSP method proved to be efficient in detecting the most promising sub-network based on savings potential. In reality, the selected network comprises one stream in surplus, which is a stream related to space heating. This is caused by the fact that this stream was not considered as feasible using the traditional methodology while during this calculation it was retained valid, because step 2 of the SSP method was not performed. However, an expert designer would have disregarded it, achieving the optimum simplification during the present step.

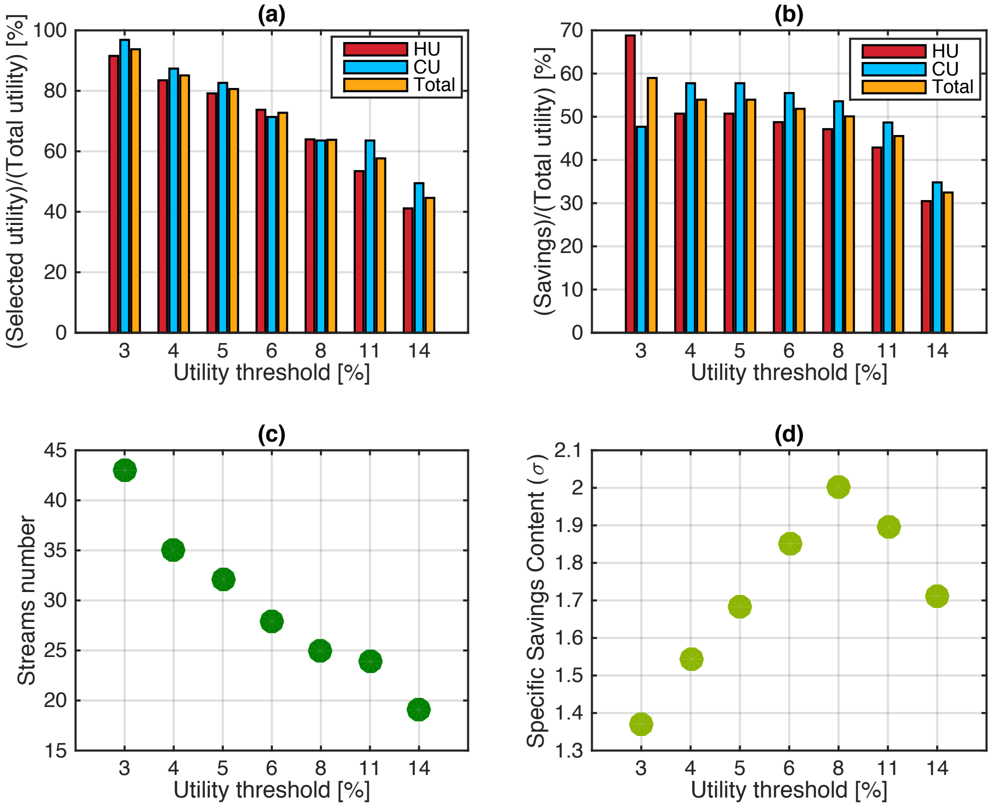

Fig. 2. SSP second simplification step results. (a) Total utility, (b) Utility savings, (c) Number of streams and (d) Specific Savings content.

Finally, Figure 7.2b shows the potential savings variation. By looking at the total utility savings, it can be seen that the biggest drops are experienced when σ decreases. This proves that in those situations streams that could achieve high savings have been missing. This effect is particularly pronounced by comparing the results for a utility consumption threshold of 8% and 14%. In between the two a large drop in both savings potential and σ is detected. This is caused by the loss of a heat exchanger responsible for a significant pinch violation.

3.2.3. Third simplification

The third simplification step was applied considering a maximum PBT=5 years and a maximum acceptable ΔT_{lm} =5K. Based on this, a minimum Pinch violation threshold of 100kW was calculated (Figure 3b).

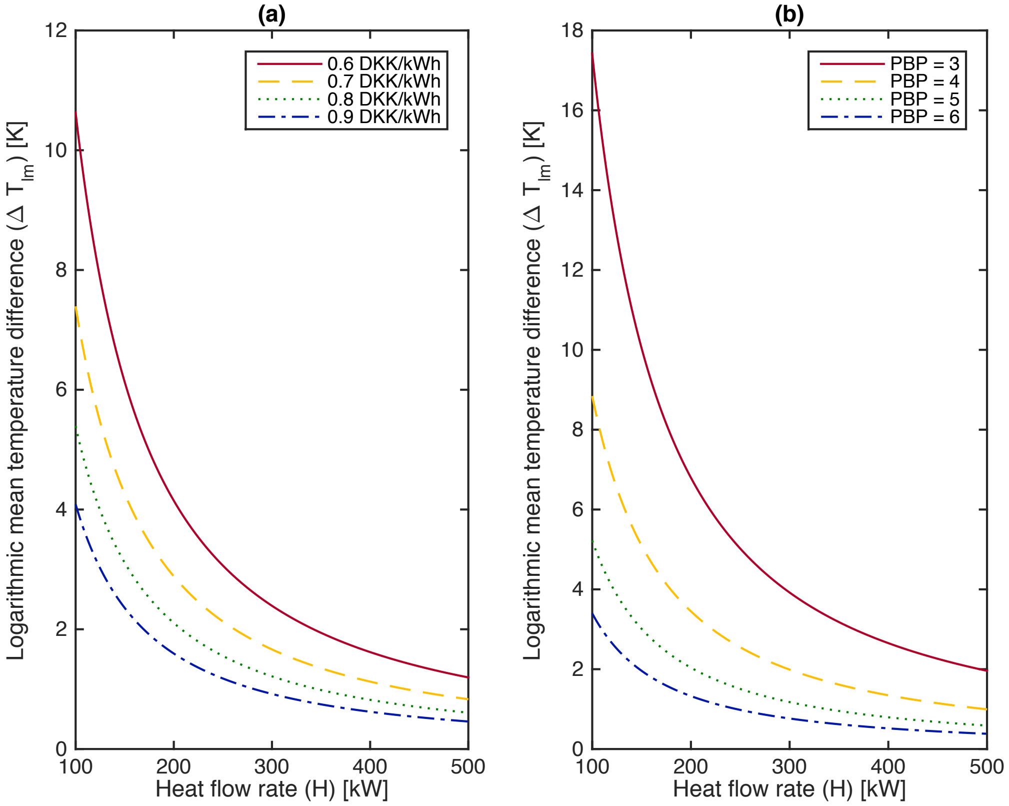

Fig. 3. ΔT_{lm} *requirement varying: (a) Energy price (b) Payback Times.*

By applying the simplification, three violations were not considered for possible modifications. However, all the violations taken into account by using the traditional procedure were regarded also by the SSP method for the final sub-network retrofit. This confirms the validity of the SSP methodology, because a retrofit of that sub-network proved to be possible accepting a PBT=4.1 years, thus lower than the threshold. Moreover, after the simplifications, the same design achieved when conducting the traditional retrofit methodology could be deduced, because the same streams were also considered in the SSP method.

3.3 Data accuracy

The Monte-Carlo analysis conducted on mass flow rates and temperatures shows different trends with these two parameters. Uncertainties of the former have a low influence, resulting in standard deviations of the utility targets of up to 6% with respect to the nominal values, and no variation of the pinch point location. On the contrary, temperature uncertainties prove to have a remarkable impact on the results. The HU and CU targets show a standard deviation of 13% and 36% of the targets when varying the inlet and outlet stream temperatures by just ±2°C, considering a normal distribution function, as presented in Table 1. Furthermore, these uncertainties affect the pinch point location, which shows a standard deviation of 7.2 °C. The high impact on the energy recovery targets is graphically shown by the composite curves (Figure 4b). As it can be seen, they are not lines, but rather areas. Their thickness proves a high variability of the utility targets, while the several intersections of the Grand Composite Curve with the y-axis of Figure 4a graphically shows the variability of the Pinch point location.

Another interesting result is obtained by analysing the streams with the highest impact on the targets. Such an analysis proves that (i) only uncertainties related to streams with high heat capacity

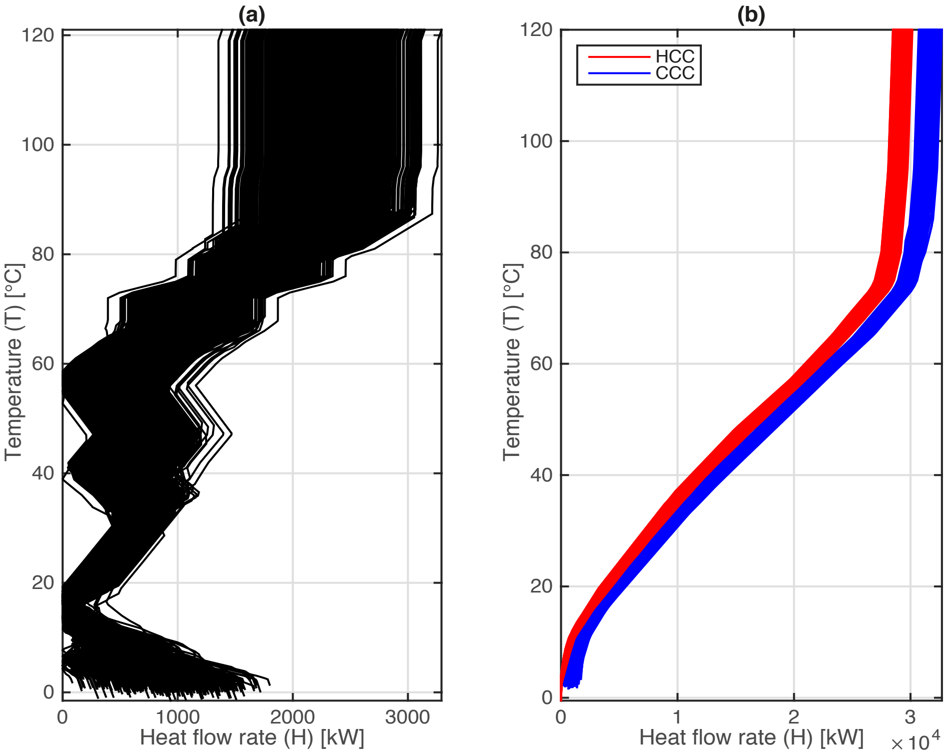

Fig. 4. Temperature uncertainties influence on: (a) Grand Composite Curve, (b) Composite Curves.

rate have a high effect on the results, and (ii) the temperature levels at which the streams are operated have an impact on the pinch point location.

All in all, it is essential that the data on the streams with high heat capacity rate is accurate enough, especially if they are operating around the pinch point. This lesson has to be kept in mind when performing step 3 of the SSP method (Section 2.1): time can be used more wisely by conducting a less accurate analysis over streams with low data accuracy impact, while performing a better investigation on the others.

Table 1 – Standard deviation of the studied uncertainties.

	Standard deviation				
	HU target		CU target		PP location
	kW	*%*	*kW*	*%*	*°C*
Mass flow rate	25.58	1	55.82	6	0
Temperature	294.98	13	322.55	36	7.2

4. Discussion

The Specific Savings Potential method proved to be beneficial in simplifying and shortening the PI retrofit project when applied on the case study. This success is imputable to the wise choice of the three simplification criteria constituting the core of the methodology:

1. *First simplification*. The first simplification has the merit of reducing the size of the problem at the very beginning of the project, even before the detailed data acquisition step. This can significantly cut the time requirement associated to data acquisition, which is estimated to be

responsible of up to 80% of the overall project time [16]. Moreover, analysing the simplification criterion, it appears logical to utilise the percentage utility consumption to detect uninteresting streams at this stage. In fact, a small utility consumption can have two causes: (i) the stream has a small heat requirement compared to the rest or (ii) the stream is already highly integrated in the existing network. In either case, it does not make sense to consider it for retrofit purposes. Overall, this is an important tool for a simplified methodology, which is missing in all the methods present in the literature and mentioned in Section 1.1.

The limitation of this criterion resides in the availability of data related to utility consumption of the process streams. Such information could be missing in some industries, especially where the energy cost constitutes a little share of the overall product cost. In such cases a limited version of the first simplification can be applied: an evaluation based on the mass flow rates of the streams, which should be available based on raw material input and product output can be performed. Very small mass flow quantities can then be neglected.

2. *Second simplification*. This step has the advantage of providing an analytical indicator able to detect when to stop the simplification based on savings potential. This tool is grounded on the Specific Savings Content (Eq.1), whose maximisation appears to be a logical optimisation criterion. In fact, representing the average savings potential of the network streams, it is able to link energy performance of the sub-network to its complexity in performing the final design. A higher value of this indicator shows that a retrofit performed on the selected sub-network has a higher efficiency prospective. This is because a high savings potential is embedded in a reduced number of streams and, therefore, a retrofit conducted on it is expected to require less time to be performed. Moreover, as proved by the results, it is able to spot the losses of important streams, which are highlighted by significant drops of σ. This novel feature solves the lack of analytical simplification stop criteria in most of the PI methodologies present in the literature.
3. *Third simplification*. The last step has the merit of connecting the sub-network characteristics to economic considerations. Once the maximum acceptable payback time and ΔT_{lm} are set, the minimum profitable heat exchanger size threshold is univocally defined. This analytically sets a lower limit to the profitability of fixing pinch violations. In fact, in order to eliminate a violation, at least one heat exchanger with the same duty of the violation itself is needed. If the heat exchanger duty is lower than the so defined threshold, the designer is certain that the investment is not profitable. Hence it is reasonable to disregard such violation from the design.

   As aforementioned, the UA-value can be fixed in place of the ΔT_{lm}. This could be helpful in order to control (and eventually constraint) the overall network size and the total capital investment of the retrofit. Moreover, it can be argued that the UA-value is more relevant than ΔT_{lm}, because it is able to address phase-change heat exchangers (e.g. condensers and reboilers), which are frequently encountered in the industry. On the other hand, the concept of ΔT_{lm} is more easily understandable by consultants and plant technicians, thus more suitable for setting a rough threshold grounded on experience. Based on the specific case, the analyst can choose which parameter is more beneficial.

   A final important feature of this step is the great freedom in setting the economic parameters, such as: (i) payback time, (ii) ΔT_{lm}, (iii) heat exchangers cost and (iv) energy cost. In fact, on the basis of the specific process, one could vary them depending on sub-processes characteristics, setting different duty thresholds for different plant areas. This could be beneficial in many occasions, such as for processes requiring utilities at different temperature levels (e.g. hot water and steam at different pressures). Different energy prices could be allocated to different utility levels, resulting in multiple thresholds for this step (Figure 3a) and a better estimation of the individual pinch violations economic importance.

Despite the aforementioned benefits, the proposed methodology presents some limitations and potential for improvements. Firstly, it builds on heuristic considerations rather than analytical demonstrations. Its validity cannot be claimed "a priori" and the method should be tested and validated on a broader number of cases, besides the two dairy factories analysed in this work and in [20]. However, the simplicity and generic formulation of the simplification criteria suggest that this method would be applicable and beneficial on other case studies. Secondly, the SSP method has been developed for continuous processes only, while many industrial processes operate in semi-continuous or batch mode. However, the suggestions provided by the SSP method may also be useful in the first stages of a batch process retrofit to detect the most promising measures. Lastly, the proposed method is not applicable on grassroot designs. Its extension to other type of processes and problems, such as batch processes and grassroot designs, would make it a more general and powerful tool, and future work could lead towards this goal.

These points suggest that there is a great potential for improving this method. The authors believe that the general strategy behind the methodology should not be changed, because the SSP method addresses the most critical nodes of the traditional pinch method and provides valuable suggestions, while building extensively on the engineers' experience.

5. Conclusions

A simplified process retrofit methodology, termed *Specific Savings Potential method* (SSP) is presented in this paper. It completes the conventional methodology by introducing three screening criteria able to reduce the engineering effort in performing the retrofit. They are based on simple heuristic, thermodynamic and economic considerations. This method is applied on a Danish dairy factory: it highlights the most promising energy conservation opportunities and ends up with the same retrofit than in the traditional Pinch Analysis, by considering only 24 of the total 62 process streams.

The importance of data accuracy is evaluated: a temperature variability of ±2°C results in a standard deviation of up to 36% on the utility targets, and 7°C on the pinch point location. Streams with high heat capacity rates operating around the pinch point have a higher influence on the results, which suggests that particular care should be exercised when acquiring data on these streams.

All in all, the proposed methodology is promising for obtaining wider acceptance of pinch-based tools in the industry, especially in intermediate-size ones. The simplified approach is in fact able to reduce the engineering effort in performing retrofit designs based on process integration concepts, making them affordable also for industries of this size. This would promote the exploitation of a large energy savings potential that is nowadays overlooked, as proved by the savings achieved on the case study (24% compared to the existing process). However, future work will need to test the method on different industries, in order to validate its usefulness on a broader range of processes and refine the simplification criteria it builds on.

Acknowledgments

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Nomenclature

A	area, m^2
c_p	specific heat capacity at constant pressure, J/(kg K)
H	heat flow rate, W

$\dot{m}$	mass flow rate, kg/s
T	temperature, °C
U	overall heat transfer coefficient, W/(m^2 K)

Greek symbols

Δ	absolute difference
σ	specific savings content, -

Subscripts and superscripts

lm	logarithmic mean

Abbreviations

CU	Cold Utility
HEX	Heat EXchangers network
HU	Hot Utility
NPV	Net Present Value
PBT	Payback time
PI	Process Integration
PP	Pinch Point
SSP	Specific Savings Potential

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