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A method for faster application of Process Integration techniques in retrofit situations

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Abstract

Numerous process integration techniques were proved to be highly effective for identifying and estimating potential energy savings in the industry. However, they require high time and effort to collect and analyse process data. As a result, they do not constitute the common practice in the industry and opportunities for increasing the energy efficiency of industrial processes are missed.

The paper presents a method, termed the "*Energy-Saving Decomposition*", which is based on Process Integration techniques. It is intended for expeditiously outlining and promoting energy efficiency in the industry. Two screening tools, based on mathematical criteria and engineering experience, are employed for reducing the problem dimension before applying conventional design procedures. The first step disregards streams based on their contribution to the overall energy-saving potential, calculated utilising a novel energy-saving decomposition technique. The most promising network is then selected based on its energy-saving potential and size. The second step reduces the problem complexity further, employing economic considerations.

This novel method was exemplified by application to a dairy factory: the outcomes and the method itself were compared to conventional Pinch Analysis techniques. The results showed that the developed method can simplify and reduce the time consumption of conventional Process Integration methods significantly, while identifying the most encouraging saving opportunities. The automatic algorithm allowed for reducing the problem size from 62 process streams of the existing plant to 22 streams requiring a computational time of only 135 s. The final retrofit design proposed was the same obtained with conventional Pinch Analysis, achieving a 23 % reduction in the plant final energy consumption.

Keywords: dairy industry, energy efficiency, Energy-Saving Decomposition method, heat exchanger network, Process Integration, retrofit.

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1. Introduction

CO_2-reduction is paramount for tackling the issue of climate change. In this regard, the European Union has recently increased its efforts, aiming at 55 %, and 100 % reduction of CO_2 emissions compared to the 1990 level, by 2030 [1] and 2050 [2], respectively. However, despite the effort put in the last decade, the 2030 goals are not expected to be met at an European level following the current trends of development [1]. The industrial sector can play a major role in swinging this negative forecast, being responsible for roughly 25 % of the overall European final energy consumption [3] and embedding considerable energy-saving potential. In this context, Process Integration (PI)

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Nomenclature

A	area, m^2
E	Energy flow, W
N	Number of iterations, -
T	temperature, °C
U	overall heat transfer coefficient, W/m^2-K
$\dot{Q}$	heat flow rate, W
$\mathbf{u}$	Set of indices, -
TS	Total Solids content, %
c	Anchor value, -
j	Generic index, -
k	number of subsections, -
x	Generic variable, -
Abbreviations	
ESD	Energy-Saving Decomposition
HEN	Heat Exchanger Network
HEX	Heat Exchanger
PBT	Payback Time
PI	Process Integration
PTA	Problem Table Algorithm
RDRA	Required Data Reduction Analysis
Greek letters	
Δ	Perturbation
σ	Average energy-saving content, %
ς	Specific energy-saving potential, -
ξ	Energy-saving potential, W
Subscripts	
T	Total
lm	logarithmic mean
tot	Total

methods proved to be highly effective tools for detecting energy-saving opportunities and suggesting solutions for exploiting them. Reported case studies show consumption reduction possibilities in the range 10 % to 75 % [4].

Particular interest lies within the analysis and improvement of existing plants, a situation normally referred to by the term “retrofit”. In fact, it is far more common to face retrofit projects than newly designed plants [4]. Slightly more than 60 journal papers were published in this field [5], showing three main diverging family of methods:

(i) *User-driven methods based on Pinch Analysis*. Such methods build on the Pinch Point concept [6], making extensive use of basic thermodynamics, heuristics, and graphical representation tools to find appropriate energy-saving solutions, by constantly keeping the designer informed of the possible options. Examples are the “matrix method” of Carlsson et al. [7], the “advanced composite curves” of Nordman and Berntsson [8], the “retrofit thermodynamic diagram” of Lakshmanan [9] later modified by Yong et al. [10], the “path analysis” by Van Reisen et al. [11], the “heat loads plot” of Piacentino [12] and the “bridge analysis” of Bonhivers et al. [13]. They extensively rely on good engineering judgement for making design decisions, allowing the designer to handle process risk considerations difficult to convey to automatic software. The inherent drawback is that there is no guarantee that the “optimal” solution is detected, as the problem complexity, in terms of number of retrofit solutions, increases drastically with the number of process streams and it is not possible to extensively analyse the solution space relying on good engineering judgement alone.

(ii) *Mathematical-programming-based methods*. This family of methods, on the contrary, seeks to find the global optimum through mathematical optimization, see e.g. Silva and Zemp [14] and Pan et al. [15]. This approach may lead to infeasible or unpractical solutions, as the designer solely relies on model results and the usage of good engineering judgement is severely limited. Moreover, the heat exchanger retrofit design is generally a “Mixed Integer Non-Linear Programming” problem. The usually long computational time of the solvers and the non-determinism of the solutions challenge the practical use of these methods.

(iii) *Hybrid methods*. They aim at combining the strengths of the previous groups and limiting their respective weaknesses. Mathematical programming is used to assess combinatorial problems, and the designer is in charge of deciding the path to follow when investigating possible design alternatives. They are either based on the

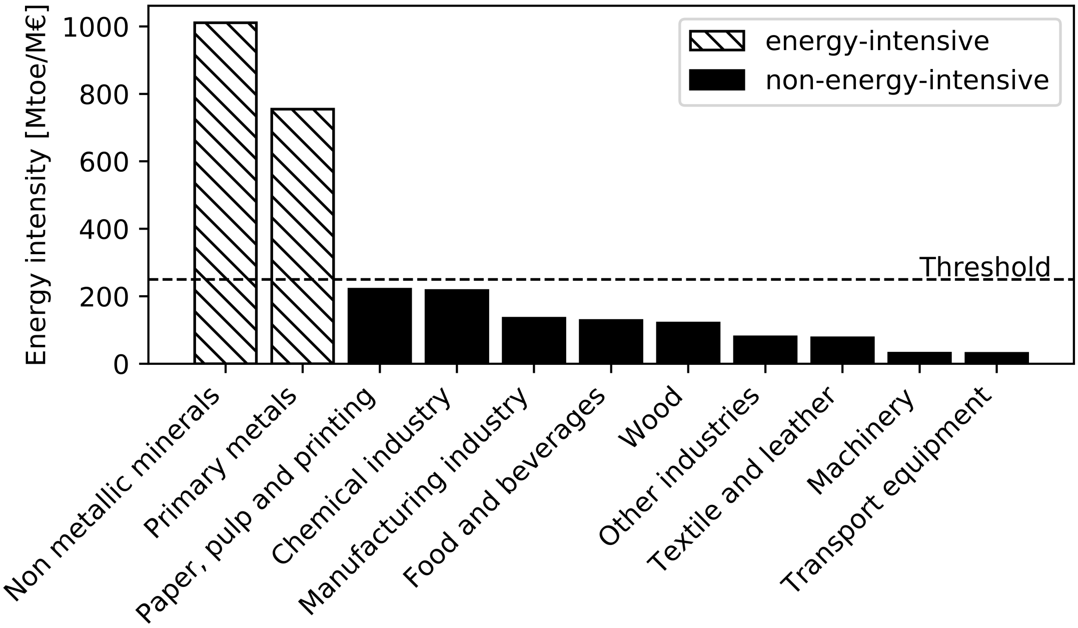

Figure 1: Energy intensity in EU28 divided into industrial sectors. Data referring to 2015 [18].

"network pinch" concept firstly presented by Asante and Zhu [16], or on the "bridge" concept as in Walmsley et al. [17]. However, they still present weaknesses proper to both groups of methods.

The aforementioned methods were applied effectively to identify energy-saving possibilities in energy-intensive industries (e.g. petrochemical). However, they were not often used for assessing non-energy intensive ones, which represent roughly 66 % of the EU industrial final energy consumption [18]. Although there is no one definition for "non-energy-intensive industries", they are hereby defined as processes with an energy intensity lower than 250 Mtoe/M€ of value-added, which corresponds to 1/4 of the most energy-intensive sector (i.e. non-metallic minerals). These processes are generally characterised by a low share of energy costs over the total cost of the final product, traditionally resulting in a lower interest in investing in energy-saving projects. This leaves a large aggregated energy-saving potential unexploited. Under this class of industries the (i) chemical, (ii) food, (iii) pulp and paper, and (iv) textile and leather can be generally found (Figure 1), even though some of their subcategories are in fact energy-intensive if the sectors are disaggregated. Considering their high demand for process heating and cooling, all such processes would strongly benefit from the application of Process Integration methods. A limiting factor for their application is a high cost of performing detailed Process Integration studies because of the need for extensive data and large time consumption. Some authors tried, therefore, to speed-up process integration techniques, acting on the two most time-consuming steps of a retrofit project, i.e. *Data acquisition* and *Conceptual design*. The former, which is the most time-consuming stage [19], has been broadly overlooked in the past years [20] and only recently it has been systematically addressed by Bergamini et al. [21], who proposed the *Required Data Reduction Analysis* (RDRA) method. A higher number of attempts were performed for speeding-up the *Conceptual design* stage by reducing the size of the design problem (e.g. number of streams). These novel methods were based on either graphical screening tools (e.g. the "advanced curves" of Nordman and Berntsson [8]), simple energetic or economic criteria (e.g. the "path analysis" of Van Reisen et al. [22] and the "Limiting match" concept of Dalsgård et al. [23]), or the use of different levels of details (Pouransari et al. [20]). However, none of them was accepted widely, as proven by their very limited development after their first proposal. A possible reason is that despite succeeding in reducing the problem size before the *Process synthesis* stage, they do not provide a "stop criterion" for spotting the optimum simplification for achieving a good retrofit.

This paper proposes a novel PI method for process retrofit, named the "*Energy-Saving Decomposition*" (ESD) after the core screening technique it employs. The method aims at reducing the size of the problem at the beginning of the *Conceptual design* step of PI retrofit projects (Figure 2). It successively employs two simplification steps,

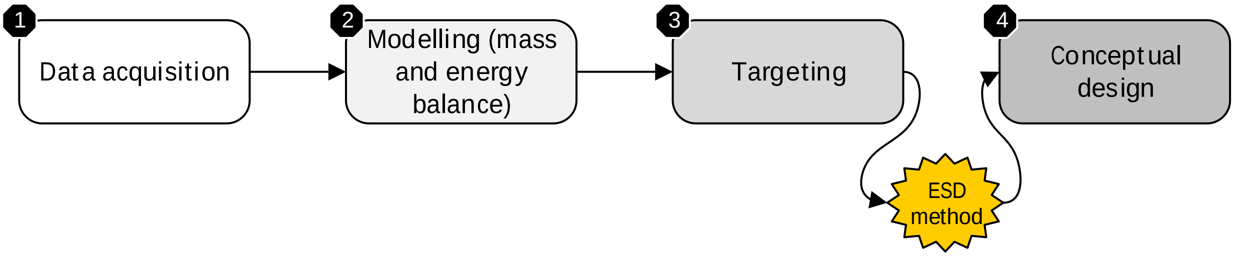

Figure 2: Activities in a PI retrofit project.

which build on simple thermodynamic and economic considerations. The first is applied right after performing the detailed data acquisition. The potential for energy savings proper of each subsection of the total plant is calculated, grounded on a novel decomposition of the total energy-saving potential of the plant. The subsections with the lowest potential for energy savings are progressively eliminated from the analysis. A stop criterion based on the maximization of an indicator σ and the energy-saving potential of the remaining network identifies a "good enough" network to be further analysed. The second simplification introduces economic considerations, reducing the search space for possible retrofit actions. The overall goal is to drastically reduce the cost of Process Integration studies for non-energy-intensive industries, assuming that the 80/20 principle [24] applies to the energy-saving potential of existing plants. An embryonic formulation of this method was presented in [25], out of which only the second simplification step has been retained in the present work. The paper follows this structure: Section 2 describes the novel energy-saving decomposition technique and provides an illustrative example of its application. Such decomposition is at the core of the proposed method, which is outlined in Section 3 together with an illustrative example of its application. Section 4 presents the cheese production process on which the method was tested as a case study and the obtained results. Section 5 discusses the merits and limitations of the presented approach, giving ideas for future work to be carried out. Finally, Section 6 summarises the main conclusions.

2. Decomposition of the energy-saving potential of existing plants

Pinch Analysis allows, among others, to calculate the minimum theoretical external heating and cooling requirement of a plant, through the Problem Table Algorithm (PTA) [4]. The difference between the actual energy consumption and the so-calculated theoretical minimum reveals the potential for energy saving of the plant. This is an inherent characteristic of the plant structure, and energy can be "saved" by connecting different subsections of the plant employing heat exchangers. Generally, not all combinations between subsections result in energy savings, meaning that not all subsections (or their combinations) inherently have a positive contribution to the overall energy-saving potential of the plant. The decomposition technique presented below aims to decompose the total energy-saving potential of the plant among its subsections and their combinations, quantifying their contribution to the total.

2.1. The decomposition technique

The energy-saving potential of a plant (ξ) is a multivariate function depending on the process streams and their properties (temperatures and heat capacity rate) [4]. Once the properties of the streams are known, and the various streams are grouped in k disjoint sets, ξ depends solely on the considered sets of streams, which can be represented as a vector of variables x where $x \in [0,1]^k$. $x_j = 0$ means that the jth set is not included in the evaluated network, while $x_j = 1$ means that the jth set is included. Such a function can be decomposed in a sum of 2^k terms, with each term depending on a group of variables (in this case a group of sets of streams) indexed by a particular subset of $\{1, ..., k\}$ [26].

Let $[1..k] := \{1, ..., k\}$ be a shorthand notation for the set of indices from 1 to k and let $(\mathbf{1};\mathbf{0})_\mathbf{u}$ denote the k-dimensional vector whose jth component is $x_j = 1$ if $j \in \mathbf{u}$ (where $\mathbf{u}$ is a generic set of indices) and $x_j = 0$ if $j \notin \mathbf{u}$

(i.e. $(1_1, ..., 1_{j-1}, 0_j, 1_{j+1}, ..., 1_k)$ for $j \notin \mathbf{u}$). Then, according to the work of Kuo et al. [26], such a decomposition of ξ, which is proven to be *minimal*, meaning that it does never introduce unnecessary terms, is the following:

$$\xi = \sum_{u \subseteq [1..k]} \xi_{\mathbf{u}} \tag{1}$$

Where:

$$\xi_{\mathbf{u}} = \sum_{\mathbf{v} \subseteq \mathbf{u}} (-1)^{|\mathbf{u}|-|\mathbf{v}|} \xi((\mathbf{1};\mathbf{0})_{\mathbf{v}}) \tag{2}$$

This corresponds to the so-called *Anchored decomposition* [26] of the multivariate function ξ with respect to the anchor $c_j = [0]^k$. As an example, consider a plant divided into two subsections (i.e. $k = 2$). In this case the subsets $\mathbf{u}$ of $\{1, 2\}$ are $\emptyset$, $\{1\}$, $\{2\}$ and $\{1, 2\}$, and Equation 1 reduces to:

$$\begin{aligned} \xi &= \xi(1,1) && \text{(3a)} \\ &= \xi_{\emptyset} + \xi_1 + \xi_2 + \xi_{12} && \text{(3b)} \\ &= \xi(0,0) + [\xi(1,0) - \xi(0,0)] + [\xi(0,1) - \xi(0,0)] + [\xi(1,1) - \xi(1,0) - \xi(0,1) + \xi(0,0)] && \text{(3c)} \end{aligned}$$

Of the 2^k terms in Equation 1, one is always null ($\xi_{\emptyset}$), k are first-order terms (ξ_i), a total of $\binom{k}{2}$ are second-order terms (ξ_{ij}), and so on. All the terms $\in \mathbb{R}$ and they physically represent the portion of the total plant energy-saving potential which derives from integrating the sub-networks in their indices and that cannot be explained by lower-order terms of the same indices. It can be easily proven that they can be calculated in a univocal way as:

$$\begin{aligned} \xi_{\emptyset} &= \xi(0,0) && && \text{(4a)} \\ \xi_i &= \xi((\mathbf{x};\mathbf{c})_{\mathbf{u}}) - \xi_{\emptyset} && \mathbf{u} = \{i\} && \text{(4b)} \\ \xi_{ij} &= \xi((\mathbf{x};\mathbf{c})_{\mathbf{u}}) - \xi_i - \xi_j - \xi_{\emptyset} && \mathbf{u} = \{i, j\} && \text{(4c)} \end{aligned}$$

And so forth. Based on its value, $\xi_{\mathbf{u}}$ provides two possible indications:

- $\xi_{\mathbf{u}} > 0$. The integration of all the subsections in $\mathbf{u}$ *provides additional potential energy savings* compared to what could be achieved by considering smaller subsets of $\mathbf{u}$.
- $\xi_{\mathbf{u}} \leq 0$. The integration of all the subsections in $\mathbf{u}$ *does not provide additional potential energy savings* compared to what could be achieved by considering smaller subsets of $\mathbf{u}$. Furthermore, $\xi_{\mathbf{u}} < 0$ indicates that some of the subsets of $\mathbf{u}$ compete in attaining the same energy-saving potential. In other words, the attainment of the energy-saving potential of one subset forbids, partly or totally, the possibility to attain energy saving of the other.

2.2. The specific energy-saving indices

Equation 1 can be rewritten in a more useful way by dividing both sides of the equation by the energy-saving potential of the whole plant (ξ):

$$1 = \sum_{u \subseteq [1..k]} \varsigma_{\mathbf{u}} \tag{5}$$

where $\varsigma_{\mathbf{u}}$ is the *specific energy-saving potential* of the set of sub-networks $\mathbf{u}$, defined as:

$$\varsigma_{\mathbf{u}} = \frac{\xi_{\mathbf{u}}}{\xi} \tag{6}$$

Equation 5 is composed of 2^k terms. The computational burden for calculating all of them can easily become excessive when the number of sets of streams k increases. For this reason, instead of calculating the 2^k terms of Equation 5, it is recommended to only calculate the following two sets of k indices:

1. *First-order energy-saving index*. It expresses the portion of the total energy-saving potential caused by each subset of streams alone. For subsection j this is expressed as Equation 6, where $\mathbf{u} = \{j\}$. This index can be used for *sub-system prioritisation* purposes, i.e. for answering the question of which subset of streams, if disregarded, would reduce ξ the most.

2. *Total-effect energy-saving index*. It expresses the total portion of energy-saving potential caused by the presence of subsection j (and its associated streams). The total portion of energy-saving potential caused by all but subsection j can be calculated as $\xi((\mathbf{1};\mathbf{0})_{\sim\mathbf{u}})/\xi$, where $\sim\mathbf{u} := [1..k] \setminus j$ is a shorthand notation for the set of indices from 1 to k not including j. This encompasses all the terms of any order that do not include index j. As all the specific energy-saving terms add up to 1, it follows that the total portion of energy-saving potential caused by subset $\mathbf{u} = \{j\}$ is:

   $$\varsigma_{T_{\mathbf{u}}} = 1 - \frac{\xi((\mathbf{1};\mathbf{0})_{\sim\mathbf{u}})}{\xi} \tag{7}$$

   This is made up of all the terms of first and higher order which include subset $\mathbf{u}$. This index is used for *Factor Fixing* purposes, i.e. to answer the question of which subset of streams could be disregarded without appreciably lowering the energy-saving potential of the total system. This is useful for reducing the dimension of the retrofit problem, as whole sections of the plant could be disregarded if all subsets of streams of that section are not influential. It is clear that $\varsigma_{\mathbf{u}} = 0$ is a necessary, but insufficient condition for determining that a subsystem is non-influential, as it might have an influential effect as a result of interaction with others. It can be demonstrated that $\varsigma_{T_{\mathbf{u}}} = 0$ is a necessary and sufficient condition for subset $\mathbf{u}$ to be non-influential.

2.3. Illustrative example

Let us consider the simple system in Figure 3, composed of two cold streams and one hot stream whose heating and cooling requirement is fully supplied by external utility. It can be directly seen that the total potential for energy savings in this system is $\xi = 2$ kW (1 kW of hot utility and 1 kW of cold utility). This can be achieved by installing one heat exchanger (E1) recovering excess heat from stream 3 at the same time preheating either stream 1 or stream 2. The case of preheating stream 1 is depicted in Figure 4. In this case, it is possible to divide the total system into $k = 3$ subsets of streams, composed each of the individual streams. Equation 1 then becomes:

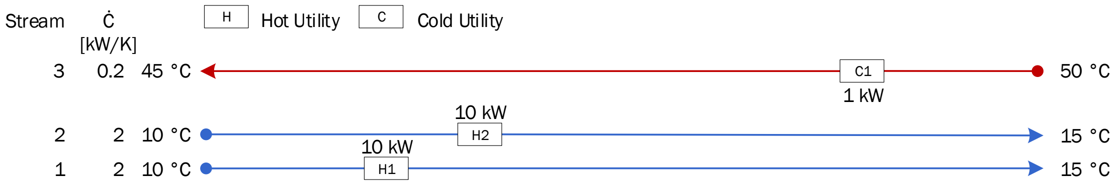

Figure 3: HEN representation of the initial network for example 1.

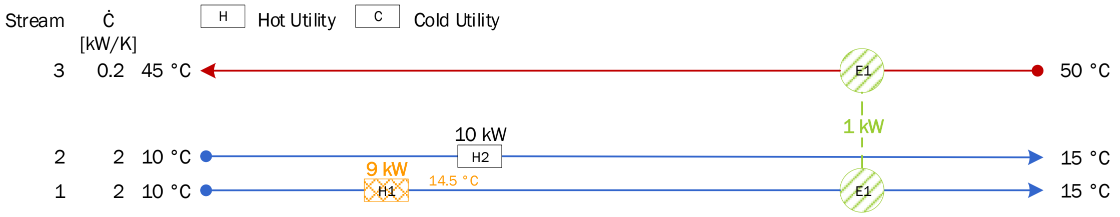

Figure 4: HEN representation of the modified network for example 1.

$$\xi = \xi_{\emptyset} + \xi_1 + \xi_2 + \xi_3 + \xi_{12} + \xi_{13} + \xi_{23} + \xi_{123} \tag{8}$$

Table 1: Energy-saving potential decomposition indices for example 1.

subset	ξ	ς	subset	ξ	ς
$\emptyset$	0 kW	0	$\{1, 2\}$	0 kW	0
$\{1\}$	0 kW	0	$\{1, 3\}$	2 kW	1
$\{2\}$	0 kW	0	$\{2, 3\}$	2 kW	1
$\{3\}$	0 kW	0	$\{1, 2, 3\}$	-2 kW	-1

Equation 5 assumes a similar form, substituting ξ with ς. The terms calculated by the two equations are reported in Table 1. Analysing the results, the first-order indices are all null as expected, as the selected subsets of streams are composed of single streams and it is not possible to achieve any energy savings with only one stream. The energy-saving potential indices are null also for the subset $\{1, 2\}$, as both Stream 1 and Stream 2 are cold streams. On the contrary, the indices for subsets $\{1, 3\}$ and $\{2, 3\}$ are positive and $\varsigma_{13} = \varsigma_{23} = 1$. In fact, as already stated, it is possible to achieve the maximum energy saving for the plant by direct heat exchange between Stream 3 and either Stream 1 or 2. It should be noted that the indices for the subset $\{1, 2, 3\}$ are negative. This indicates that the integration of all the sub-networks in the subset does not provide additional potential energy savings compared to what could be achieved by considering subsets of it. Indeed, considering all the streams together does not increase the attainable energy savings, which is still 2 kW, with respect to what can be achieved by considering smaller sets, e.g. $\{1, 3\}$ or $\{2, 3\}$. The negative value of this indicator effectively spots that there is no benefit in increasing the problem size, concerning attainable energy savings.

Finally, the total-effect specific energy-saving indices are $\varsigma_{T_1} = \varsigma_{T_2} = 0$ and $\varsigma_{T_3} = 1$. They effectively indicate that there is no harm in removing either Stream 1 or Stream 2 (not both together) from the retrofit problem, as this would not jeopardise the possibility to attain the total energy-saving potential. On the contrary, by removing Stream 3, 100 % of the overall energy-saving potential would be lost and impossible to be attained.

3. The Energy-Saving Decomposition Method

Industrial production plants are often characterised by high complexity, a significant number of process and utility streams, and scarcity of structured process data records. A thorough process evaluation seeking the maximum energy saving in retrofit projects is time-demanding and requires a remarkable engineering effort. In practice, several streams prove to be irrelevant when economic, thermodynamic and operational constraints are considered, for many have a limited energy demand or the involved heat exchangers cannot be easily redesigned.

The novel method aims to reduce the time consumption in retrofit projects, by decreasing the problem dimension in the early stages of the *Process analysis* step, identifying and dismissing irrelevant streams. The procedure requires the typical data needed in Process Integration studies, such as: (i) a process flowsheet comprehensive of the existing heat exchanger network connections, (ii) temperatures and heat capacity rates of the streams entering and exiting the system and each heat exchanger, (iii) cost functions for the relevant types of heat exchangers employable in the plant, and (iv) price of the energy carriers used in the plant. The procedure then applies two simplification steps, which should be used alongside any well-established Process Integration tool the analyst is familiar with. In the following, Section 3.1 defines the concept of *Elementary subsection*, which is preparatory for the use of the method. Section 3 describes the method itself. The method framework is summarised in Figure 5.

3.1. Elementary subsections of a plant

The identification of "irrelevant" streams grounds on the novel decomposition technique introduced in Section 2. The key to using it is to group the streams in relevant subsections of the plant, incorporating the existing network structure as the basis of their differentiation. Such relevant subsections are hereby named *Elementary subsections*, and have the following properties:

1. They are heat-balanced parts of the original network. Hence, the streams fractions covered by individual process-to-process or process-to-utility heat exchangers are part of individual elementary sub-networks.

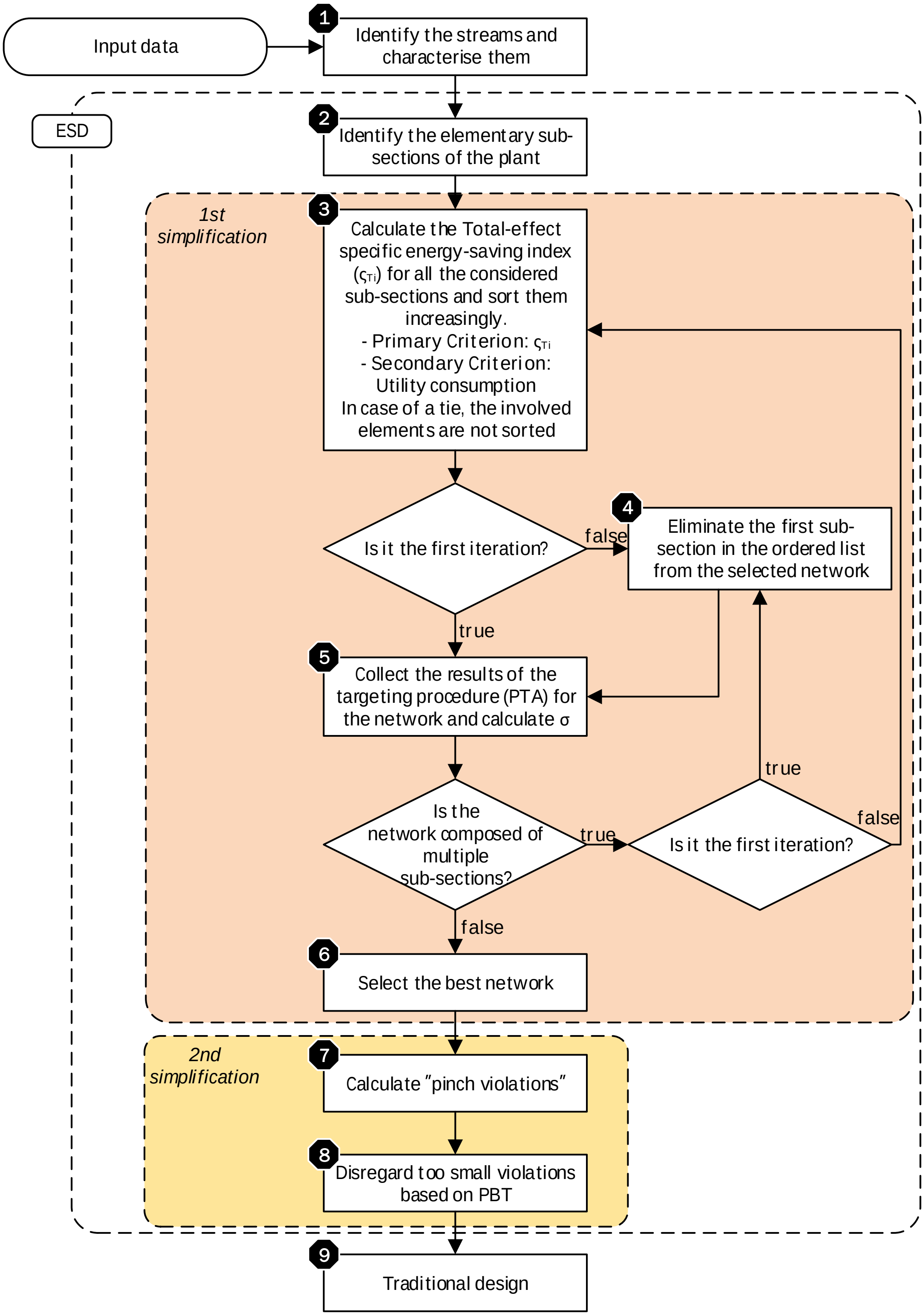

Figure 5: Energy-Saving Decomposition method process scheme.

2. They comprehend the totality of one or multiple process streams.
3. No one process stream is a member of multiple elementary sub-networks.
4. It is not possible to identify any subset of process streams member of an elementary sub-network which respects properties 1-3.

These properties ensure that the plant can be divided into the smallest sets of independent streams, allowing application of independent changes to one or multiple elementary subsections without incurring the risk of affecting other sections remaining outside the scope of this analysis. A graphical example of separation of a plant in elementary subsections is provided in Figure 6. In the displayed case the plant can be divided into 4 elementary subsections. They can be easily identified by considering whole streams connected by means of process/process heat exchangers (represented by pairs of circles connected by a dotted line). This ensures that the identified subsections respect the aforementioned properties. For example, subsection 1 comprises streams 1 and 7, as they are connected by a process/process heat exchanger (HEX). Subsection 4 includes only Stream 6, for it is only supplied by a process/utility HEX and by no process/process HEX.

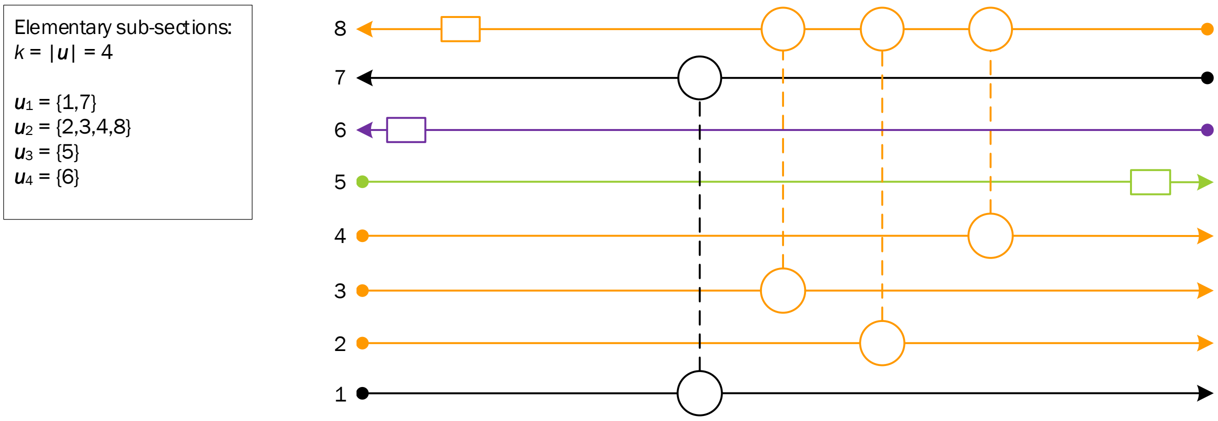

Figure 6: Example of separation of a plant in its elementary subsections. Circles represent process/process HEXs, while rectangles represent process/utility HEXs.

3.2. *The method*

The method can be divided into 9 steps as displayed in Figure 5.

3.2.1. *Initialisation*

1. *Stream characterisation.* The algorithm is initialised by retrieving the required input data, and by identifying and characterising the streams. These activities are performed as it is traditionally recommended in Process Integration retrofit studies and their description is outside the scope of this work. For a detailed explanation the reader can refer to Kemp [4], while a method for performing a faster data acquisition is presented in Bergamini et al. [21] and Bergamini et al. [27]. The minimum temperature difference (ΔT_{min}) is chosen based on engineering experience, considering the type of heat exchangers and the fluids involved. It is recommended to use individual ΔT_{min} contributions for the streams if fluids with significant differences in thermo-physical properties (e.g. state, viscosity) are involved [4].

2. *Identification of the elementary subsections.* The k elementary subsections of the total plant are identified based on the structure of the existing network, as described in Section 3.1. The identification of the elementary subsections can be easily automated in a computer-based software by following the aforementioned definition or can be performed manually, at need.

3.2.2. *First simplification: Average energy-saving potential*

The first simplification is based on the decomposition of the energy-saving potential of the total plant. It aims at identifying a sub-network of reduced size, by disregarding subsections of the plant which do not significantly contribute to the total energy-saving potential. The following iterative procedure is employed, which constitutes the core of the method. It can be easily automated in a computer-based software for fast computation.

3. *Energy-saving potential decomposition*. The total-effect specific energy-saving indices (ς_{T_u}) are calculated for the elementary subsections composing the considered network. This is performed based on the energy-saving potential decomposition theory described in Section 2. In the first iteration, this results in k indices. The subsections are then sorted in increasing order based on two criteria:

    - *Primary criterion*: Total-effect specific energy-saving index.
    - *Secondary criterion*: Overall utility consumption (E_tot) in the process-to-utility heat exchangers part of the subsection.

    The primary criterion is used first on all elements. In case of a tie between multiple elements, the secondary criterion is used to sort them. In case of tie also using the secondary criterion, no sorting is performed on these elements.

    Then, if it is the first iteration of the procedure, skip Step 4 and proceed to Step 5. Else proceed to Step 4.

4. *Reduction of the network size*. Remove the first subsection in the ordered list with all its process streams, reducing the size of the considered network.

5. *Targeting procedure*. The results of the PTA [6] for the selected network (already calculated in Step 3) is collected. From the outcomes of the targeting procedure, a novel indicator named *Average energy-saving content* (σ) of the considered network is calculated. It is defined as:

    $$\sigma = \frac{\xi_{\%}}{n} \tag{9}$$

    where n is the number of process streams in the network and $\xi_{\%}$ is the percentage energy-saving target defined as:

    $$\xi_{\%} = \frac{\xi}{E_\mathrm{tot}}\% \tag{10}$$

    where E_tot is the overall utility consumption of the existing plant, while ξ is the energy-saving potential of the considered network. σ represents the average percentage of energy-saving potential embedded in each process stream of the evaluated network. The higher the value of σ, the higher the prospective benefit of a retrofit performed on the considered sub-network, as the average process stream has a higher contribution to the overall energy-saving potential of the plant.

    The information retrieved on the network is recorded. Then, if the evaluated network is composed of multiple subsections, if it is the first iteration the procedure is repeated from Step 4, else from step 3. When the network cannot be divided into elementary subsections any further this loop is stopped and the algorithm proceeds with Step 6. The loop can be fully automated and is fast to compute. The number of computations of the PTA required (N_PTA) can be expressed by the following relation:

    $$N_\mathrm{PTA} = \frac{k(k+1)}{2} + 1 \tag{11}$$

6. *Selection of the best network*. The results obtained on the previously considered networks are evaluated and the most beneficial network is selected among them. This decision is based on thermodynamics and requires Good Engineering Judgement. As the goal of the current method is to identify a sub-network of reduced size without overlooking the biggest opportunities for achieving energy savings, two indicators are particularly relevant: (i) the Average energy-savings content (σ) and (ii) the total energy-saving potential (ξ). The best network

concerning the aforementioned goal is one which shows maximum (or near-maximum) σ and that does not pay a high loss in energy-saving potential compared to the total plant. Once the most beneficial network is selected, the engineer can evaluate the streams included and disregarded. Based on their experience and judgement, if they believe that it would be beneficial to consider some disregarded streams in order to achieve cost-effective and low-risk retrofits, such streams could be reintroduced.

3.2.3. Second simplification: economic potential

At this stage, the retrofit procedure has successfully reduced the problem size, by neglecting streams which would not provide a significant contribution to the total attainable energy savings. However, this does not ensure that a retrofit project conducted on the sub-network would be economically feasible. The goal of this simplification step is to evaluate the economic feasibility of a potential retrofit design conducted on the network, before investing time in the actual design, possibly embarking on a time-consuming trial-and-error procedure. Depending on the PI method chosen for conducting the detailed PI analysis, different strategies can be used at this point. For instance, one such a method based on "bridge analysis" [13] was recently presented by Walmsley et al. [17]. It can be employed at this point jumping to Step 9 after its completion. In case that the traditional retrofit method based on Pinch Analysis presented by Tjoe and Linnhoff [28] was employed, Step 7-8 can be used to achieve similar results:

7. *Identification of the Pinch violations*. The heat exchangers transferring heat across the pinch in the selected sub-network are identified and the amount of heat they transfer across the pinch is calculated as described by Tjoe and Linnhoff [28]. These heat transfers are traditionally named "pinch violations" as they "violate" the three rules of pinch analysis: (i) do not use external heating below the pinch, (ii) do not use external cooling above the pinch, and (iii) do not transfer heat across the pinch [6]. The heat transferred through processes violating these three principles quantifies all the inefficiencies in the heat exchanger network concerning energy consumption. Actions aiming at their reduction or complete elimination result in an energy consumption decrease.

8. *Economic evaluation*. This step links economic feasibility criteria to the potential energy savings embedded in the individual pinch violations. Through the definition of a maximum acceptable payback time (PBT) and a maximum allowable logarithmic-mean temperature difference (ΔT_{lm}) of a heat exchanger, a lower bound for the duty of a heat exchanger is defined (Figure 7a) utilising equations 12 - 13.

$$\mathrm{PBT} = \frac{\text{Investment cost}}{\text{Yearly monetary savings}} \tag{12}$$

$$A = \frac{\dot{Q}}{U \cdot \Delta T_{\mathrm{lm}}} \tag{13}$$

Where A is the heat exchanger area, $\dot{Q}$ is the heat flow rate, and U is the overall heat transfer coefficient.

According to its definition, any heat exchanger of duty smaller than the so-calculated threshold $\dot{Q}$ (Equation 13) would be economically infeasible. Considering that, to eliminate a pinch violation, at least a heat exchanger of the size of the violation itself is needed, this information can be used for further reducing the problem size. All the violations smaller than this threshold (i.e. lower than the calculated $\dot{Q}$) are ignored for the retrofit and the focus is then kept only on the remaining ones (Figure 7b). Similarly, the duty threshold could be defined by setting a maximum acceptable PBT and UA-value, instead of the ΔT_{lm}.

9. *Traditional retrofit*. At this point the size of the problem has been reduced, focusing the attention of the analyst on a limited solution space. Any PI method for process retrofit proposed in the literature can be used now for guiding the engineer in making Good Engineering Judgement (GEJ) in the retrofit design, aiming at reducing the external energy requirement of the process based on the conducted analysis. In the presented case, in which the method proposed by Tjoe and Linnhoff [28] is employed, this means reducing (or completely eliminating) the selected pinch violations present in the reduced sub-network. The design is then finalised.

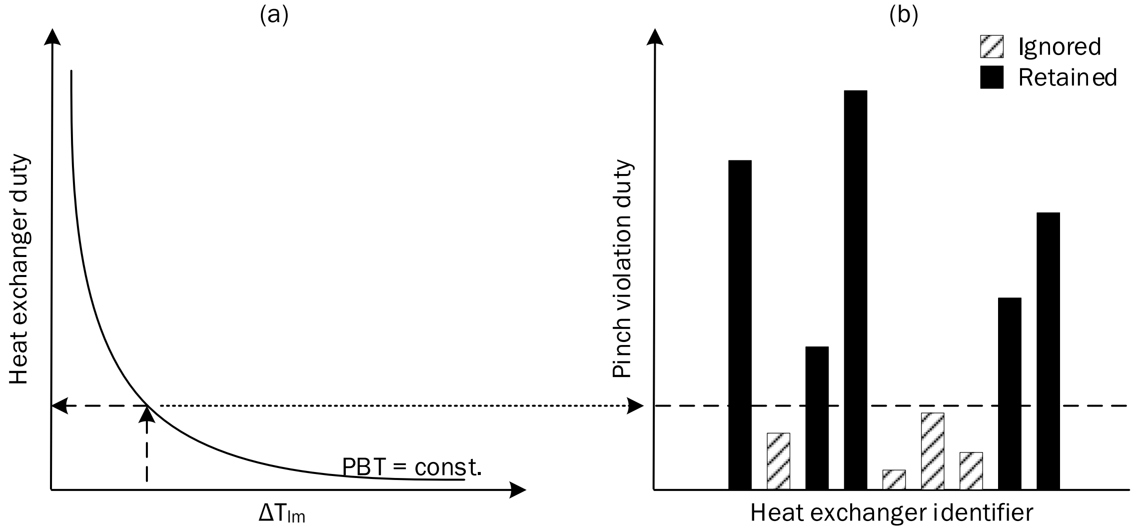

Figure 7: Exemplification of the 2nd simplification step of the ESD method. (a) Heat exchanger duty ($\dot{Q}$) selection based on ΔT_{lm} and PBT, (b) Selection of pinch violations to be corrected.

3.3. Illustrative example

As an example of the application of the first simplification step, the ESD method from Step 2 to Step 6 was applied on the previously introduced simple system, depicted in Figure 3.

In Step 2 of the procedure three elementary subsections were identified, each one composed of one stream: $\mathbf{u}_1 = \{1\}$, $\mathbf{u}_2 = \{2\}$, $\mathbf{u}_3 = \{3\}$. The loop composed of Step 3-5 was then performed for a total of three iterations. The results are reported in Table 2 and Figure 8. As can be noted from Table 2, in the first iteration both $\mathbf{u}_1$ and $\mathbf{u}_2$ had equal ς_T and E_{tot}. According to the subsection elimination criterion (Step 4), they had equal ranking, so the elimination of one or the other made no difference. $\mathbf{u}_2$ was eliminated in Iteration 2, leaving a network where $\varsigma_{T_1} = 1$ unlike calculated for network $\{1,2,3\}$. This is expected, as eliminating $\mathbf{u}_1$ from network $\{1,3\}$ would eliminate any possibility of attaining energy savings. Finally, $\mathbf{u}_3$ was eliminated in Iteration 3, as $E_{\text{tot}_3} < E_{\text{tot}_1}$.

Table 2: Results of the 1st Simplification loop on example 1.

Iteration	Network	Subsections	Eliminated	ς_{T_i}	E_{tot}
1	$\{1,2,3\}$	$\mathbf{u}_1 = \{1\}$ $\mathbf{u}_2 = \{2\}$ $\mathbf{u}_3 = \{3\}$	-	$\varsigma_{T_1} = 0$ $\varsigma_{T_2} = 0$ $\varsigma_{T_3} = 1$	$E_{\text{tot}_1} = 10$ kW $E_{\text{tot}_2} = 10$ kW $E_{\text{tot}_3} = 1$ kW
2	$\{1,3\}$	$\mathbf{u}_1 = \{1\}$ $\mathbf{u}_3 = \{3\}$	$\mathbf{u}_2$	$\varsigma_{T_1} = 1$ $\varsigma_{T_3} = 1$	$E_{\text{tot}_1} = 10$ kW $E_{\text{tot}_3} = 1$ kW
3	$\{1\}$	$\mathbf{u}_1 = \{1\}$	$\mathbf{u}_3$	$\varsigma_{T_1} = 0$	$E_{\text{tot}_1} = 10$ kW

The examination of the results performed in Step 6 of the ESD procedure suggested the selection of the network $\{1,3\}$ used in Iteration 2 as the best network. As depicted in Figure 8, this network has the highest σ (Panel d) and it does not pay high loss in energy-saving potential compared to the total plant (Panel b). As a matter of fact, in this case, it does not pay any loss. All in all, in this case, the method successfully selected a network of reduced size, which would allow reaching the full energy-saving potential if a retrofit was conducted on it, as demonstrated in Figure 4.

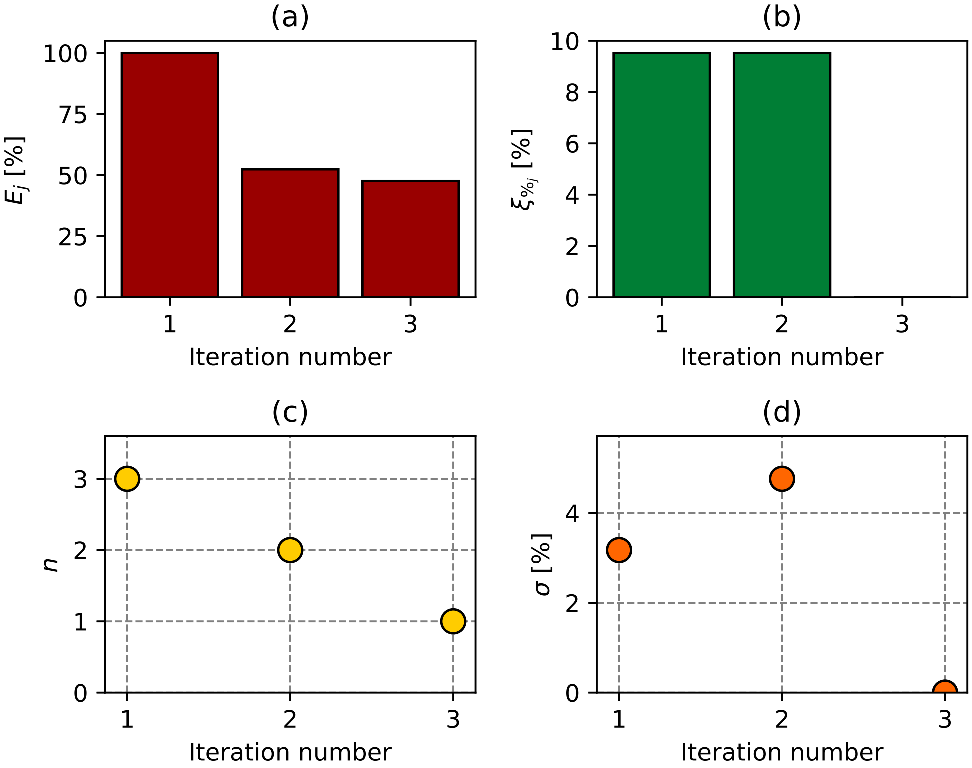

Figure 8: ESD 1st simplification step results on the illustrative example. (a) Percentage utility consumption compared to the total system, (b) Percentage energy-saving potential, (c) Number of streams and (d) Average energy-saving content.

4. Case study: retrofit of the HEN of a cheese-production plant

The ESD method was applied to a dairy factory producing cheese and several other by-products, to verify its use and benefits. The results were compared to the retrofit obtained by applying the traditional Pinch Analysis retrofit method proposed by Tjoe and Linnhoff [28]. This section describes the case study, the assumptions for applying the retrofit methods to it, and the obtained results.

4.1. Case study description

The dairy plant included 62 process streams, which required various thermal treatments such as pasteurisation, sterilisation, and thermalisation. These operations are all characterised by the requirement of heating a liquid stream and then cooling it down, representing favourable conditions for the implementation of heat recovery measures. Other studies have shown heat pump integration in cheese factories can reduce energy use [29] and that an indirect integration of large dairy sites, with low pinch temperatures, can be done through heat recovery loops [30]. The existing plant showed a high integration employing 38 regenerative plate heat exchangers. As shown in Figure 9, the plant could be divided into six different sections:

(a) *Weigh-in*: milk is collected and filtrated from impurities. These are pasteurized for further processing, while the treated milk is sent to the next section.

(b) *Milk handling*: the milk is skimmed, and its fat content is standardized. The cream in excess is pasteurized and sent to packaging, while the standardized milk proceeds in the plant. Two lines in parallel ensure continuity of operation also during cleaning periods.

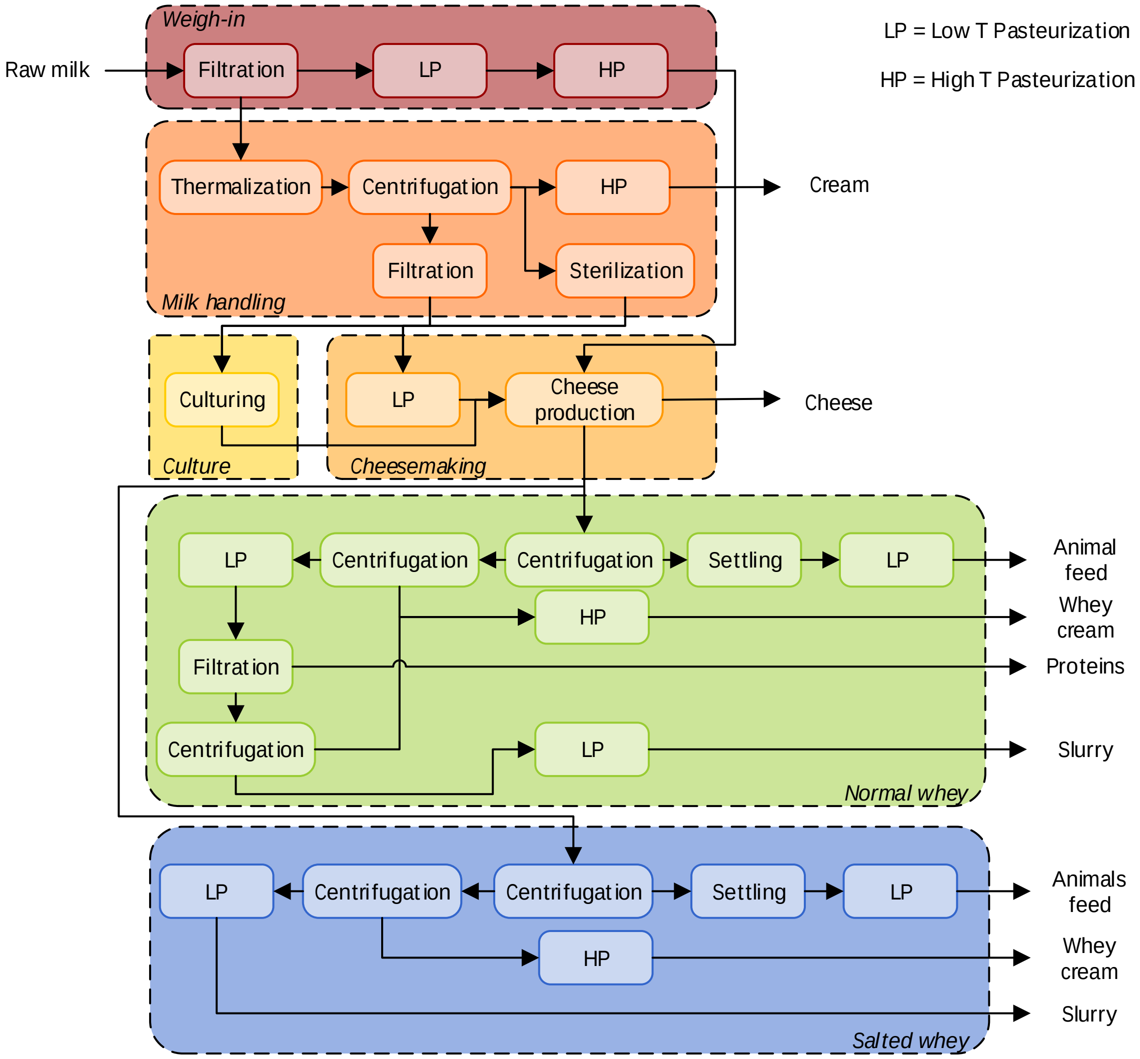

Figure 9: Conceptual process flow sheet of the dairy processing plant for the production of cheese.

(c) *Culture*: the starter for the cheese manufacturing is produced in a batch process, by using a small portion of milk, heated at high temperature.

(d) *Cheesemaking*: the milk is pasteurized, and cheese is produced in several parallel tanks, making this batch process a semi-continuous one. Whey is separated from the curd and sent to storage tanks for further processing.

(e) *Normal whey*: whey is treated to produce whey cream, whey proteins and purify the rest before disposal. This comprehends several centrifugation, filtration and pasteurisation processes conducted in parallel lines.

(f) *Salted whey*: Similar to the previous section, excluding the production of whey proteins.

The detailed stream data and actual heat exchanger network are presented in Figure 10. The existing utility system comprised three hot utility levels (water at 90 °C, pressurized water at 112 °C and steam at 3 barg), and a cold utility level supplied by a glycol-water mixture at -2 °C. Moreover, the plant was equipped with an energy recovery loop (termed as E in Figure 10) running between 22 °C and 40 °C. It absorbed 571 kW of heat in excess from hot streams, compared to the one delivered to cold streams, which was rejected to the ambient by means of a radiator not reported in Figure 10. Finally, the plant followed an operation schedule with 20 hours of continuous production followed by 4 hours of cleaning, justifying the assumption of continuous operation in the performed PI analysis.

4.2. Method

The traditional Pinch Analysis procedure was first applied to the case study to set a benchmark for assessing the advantages of the SSP method, seeking for PI opportunities. This was performed by applying the method presented by Tjoe and Linnhoff [28], which consists of identifying and reducing (or completely eliminating) pinch violations by considering the whole plant. Individual stream minimum temperature differences were considered to account for the different types of fluids and heat exchangers. A minimum individual temperature difference contribution of 1 K was assumed for low viscosity liquids (i.e. having Total Solids content $TS \leq 9$ %), 2 K for medium viscosity ones (i.e. having 9 % $<$ TS $\leq$ 20 %) and 5 K for highly viscous liquids (i.e. having TS $>$ 20 %). Once the design was completed, an economic analysis was conducted on it by assessing the economic feasibility of conducting such retrofit on the existing plant. The correlations used for the investment cost and yearly energy savings calculations are detailed in the appendix.

Finally, the ESD was applied to the original data by following the procedure described in Section 3. The results were compared to what previously obtained, and an assessment of the benefits and weaknesses of the ESD method was conducted.

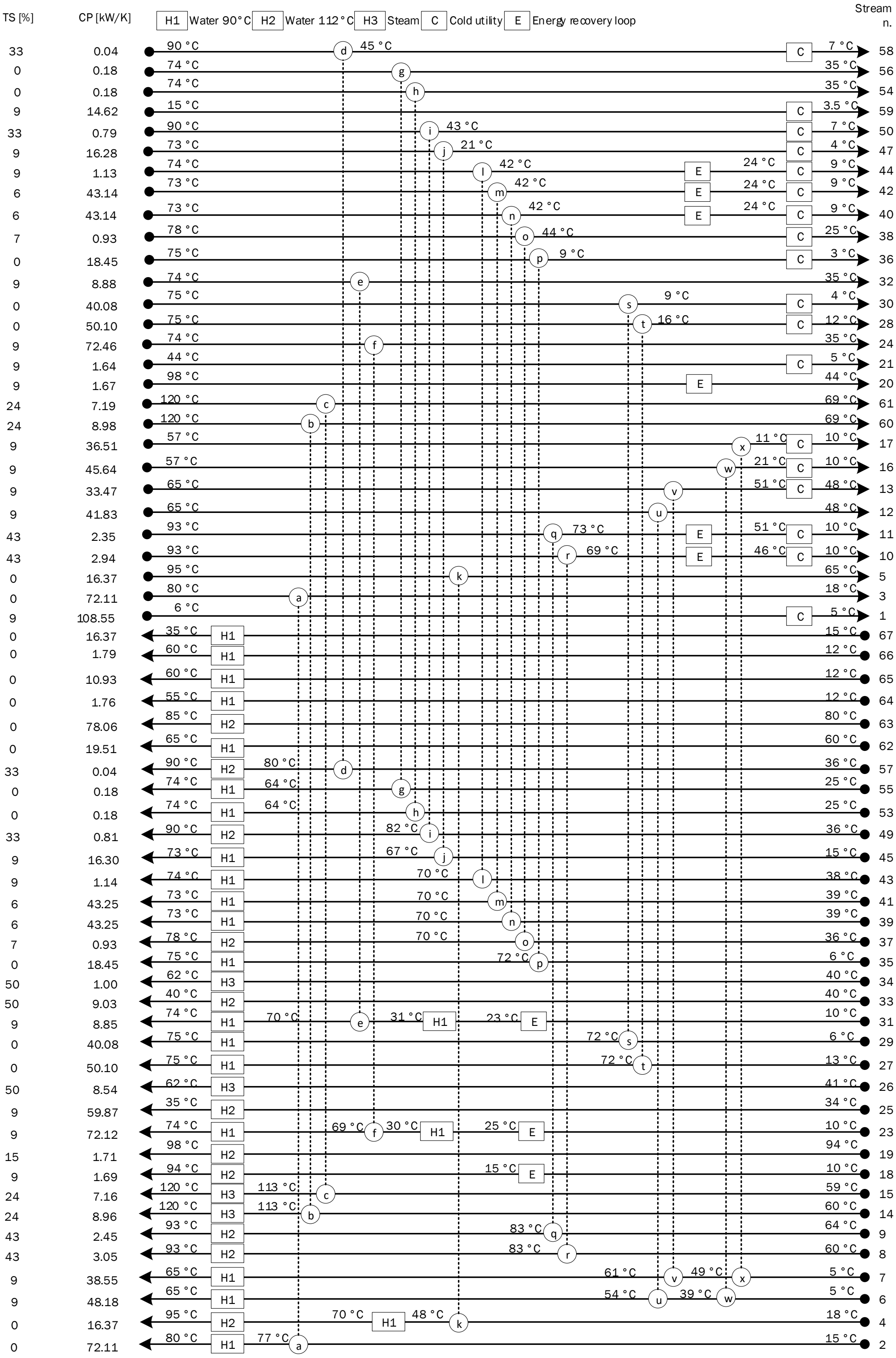

Figure 10: Existing heat exchanger network configuration and stream data of the case study.

4.3. Results

4.3.1. Traditional Pinch Analysis

Based on the extracted data, the Pinch energy targeting procedure (PTA) was conducted. The actual plant utility demand was $E_{\text{tot}} = 9164$ kW, of which 5271 kW for heating and 3893 kW for cooling. The overall energy target was calculated to be 3240 kW (2309 kW for heating and 931 kW for cooling). The total energy-saving potential was $\xi = 5924$ kW (65 % of the actual consumption), despite the high integration of the existing processes which was achieved by employing several regenerative heat exchangers.

After identifying the pinch violations, the retrofit analysis was carried out and the retrofitted network is shown in Figure 11. The design outcomes proved that a 23 % reduction in thermal energy consumption could be achieved by accepting a 4.1 years payback time. This showed that the utility consumption could be significantly decreased in an economically viable manner. Furthermore, only 21 of the 62 streams were considered for HEN modification in the proposed retrofit, which proved that only a reduced number of process streams was needed for implementing feasible energy-saving measures. No optimisation was involved in finding this solution, which should be regarded as one "viable" solution rather than "the optimal" one.

4.3.2. ESD method

Based on the configuration of the existing network (Figure 10), the plant was decomposed in its elementary subsections, identifying the $k = 30$ subsets of process streams depicted in Table 3.

Table 3: Results of the 1st Simplification loop on the case study.

j	$\mathbf{u}_j$	j	$\mathbf{u}_j$	j	$\mathbf{u}_j$	j	$\mathbf{u}_j$
1	$\{2, 3\}$	9	$\{25\}$	17	$\{45, 47\}$	25	$\{65\}$
2	$\{4, 5\}$	10	$\{26\}$	18	$\{49, 50\}$	26	$\{66\}$
3	$\{6, 12, 16\}$	11	$\{27, 28\}$	19	$\{53, 54\}$	27	$\{67\}$
4	$\{7, 13, 17\}$	12	$\{29, 30\}$	20	$\{55, 56\}$	28	$\{1\}$
5	$\{8, 9, 10, 11, 18, 20, 23, 24, 31, 32, 39, 40, 41, 42, 43, 44\}$	13	$\{33\}$	21	$\{57, 58\}$	29	$\{21\}$
6	$\{14, 60\}$	14	$\{34\}$	22	$\{62\}$	30	$\{59\}$
7	$\{15, 61\}$	15	$\{35, 36\}$	23	$\{63\}$		
8	$\{19\}$	16	$\{37, 38\}$	24	$\{64\}$		

The decomposition in elementary subsections reveals that the plant was not as highly integrated as apparent at a first sight, despite the high number of heat exchangers employed. The number of elementary subsections is considerable and they are composed on average of 2 streams each. Only subsection 5 comprises more than 3 streams, due to the presence of a heat-recovery energy loop that enlarges the number of process streams that contribute to the energy balance of it.

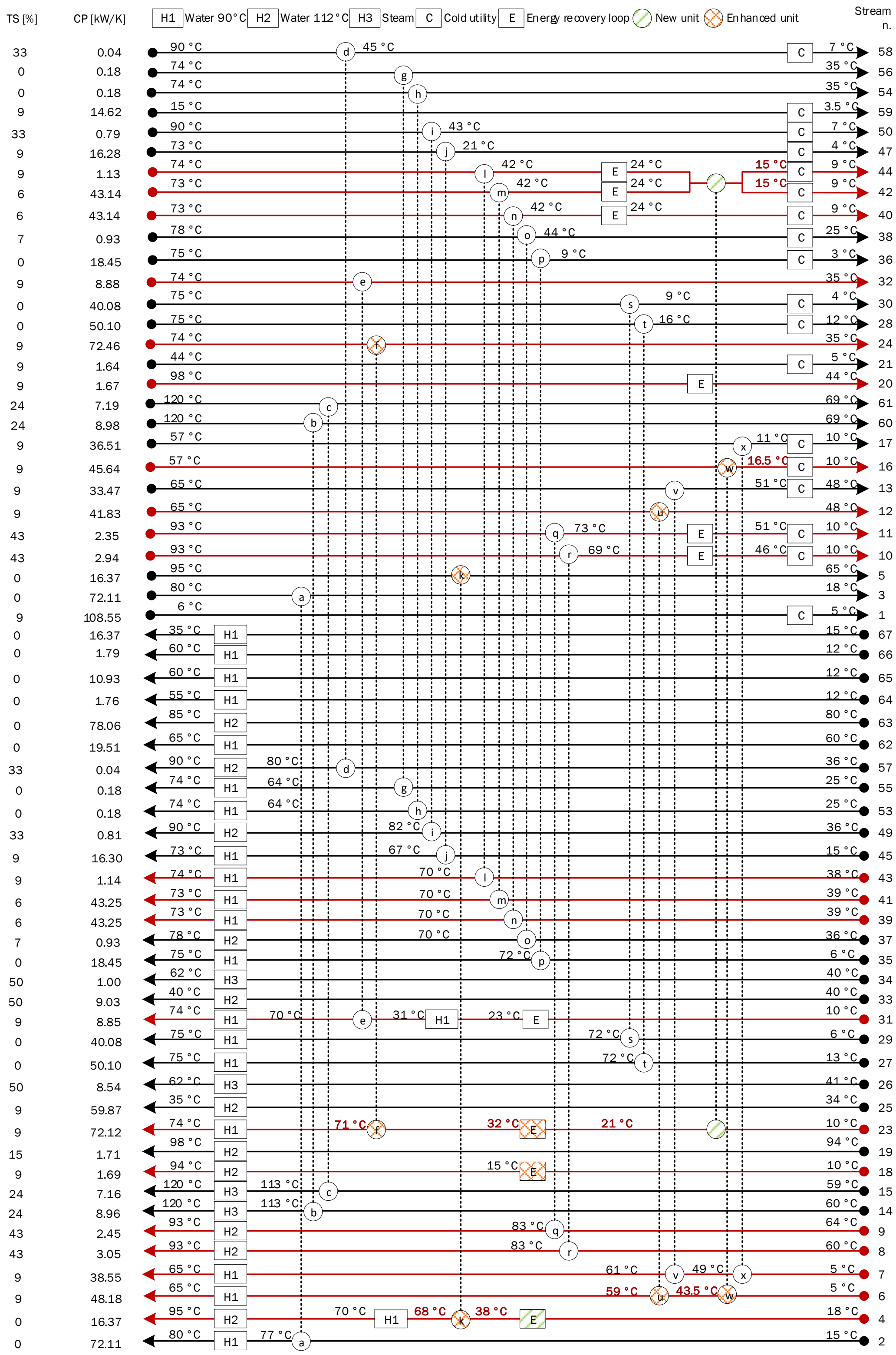

Figure 11: Improved heat exchanger network configuration and stream data. Red lines indicate streams to be considered for designing the proposed modifications.

First simplification

The first-order and total-effect energy-saving indices were calculated for the 30 subsections (Figure 12) of the plant and sorted in increasing order. It can be noted that most of the subsections have a negligible ς_T. As previously discussed, removing them from the retrofit problem would cause no (or little) reduction in the potential energy-saving attainable in the remaining network. This shows that there is a high potential for reducing the size of the retrofit problem.

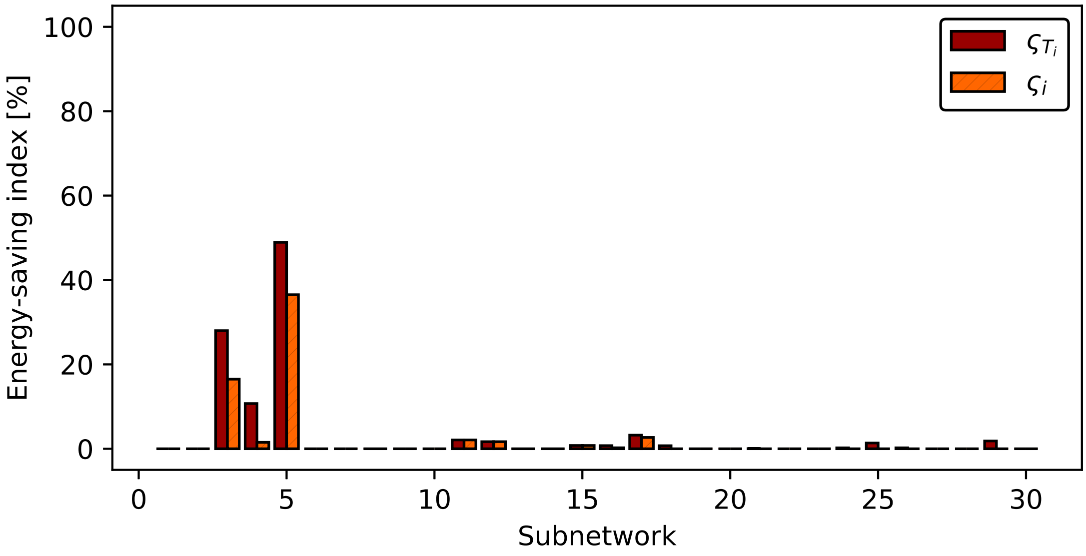

Figure 12: First-order (ς_i) and Total-effect (ς_{T_i}) energy-saving indices for the elementary subsections of the dairy plant.

The iterative procedure composed of Step 3-5 of the ESD method was then performed for a total of $k = 30$ iterations, sequentially removing subsections in the following order:

$$\mathbf{u}_{13}, \mathbf{u}_{19}, \mathbf{u}_{20}, \mathbf{u}_{8}, \mathbf{u}_{14},\mathbf{u}_{7},\mathbf{u}_{9},\mathbf{u}_{6},\mathbf{u}_{22},\mathbf{u}_{28},\mathbf{u}_{30},\mathbf{u}_{10},\mathbf{u}_{1},\mathbf{u}_{23},\mathbf{u}_{21},\mathbf{u}_{24},\mathbf{u}_{26},\mathbf{u}_{18},\mathbf{u}_{16},\mathbf{u}_{15},\mathbf{u}_{12},\mathbf{u}_{29},\mathbf{u}_{11},\mathbf{u}_{17},\mathbf{u}_{27},\mathbf{u}_{4},\mathbf{u}_{25},\mathbf{u}_{3},\mathbf{u}_{2}$$

According to Equation 11, this required $N_{\text{PTA}} = 466$ computations of the PTA, which could be executed in just 135 s with a laptop equipped with a 2.5 GHz CPU. The results of each iteration are summarised in Figure 13. As expected, removing subsections from the network causes the percentage of utility consumption embedded in the remaining network to decrease (Panel a), as well as the percentage energy-saving potential $\xi_{\%}$ (Panel b) and the number of streams (Panel c). Focusing on Panel b, it can be seen that $\xi_{\%}$ remains constant for the first 17 iterations and it decreases very slowly until Iteration 25. In the following iterations, a rapid decrease is spotted. This is the intended behaviour when using ς_T as primary sorting criterion for removing subsections from the network. It proves that it is effectively able to identify subsections with low (or no) contribution to the total energy-saving potential and to remove them first from the problem. Finally, the progressive removal of subsections resulted in a trend showing a maximum for the Specific saving content (Panel d). By comparing Panel d and Panel c it can be noted that decreases in σ correspond to significant drops in $\xi_{\%}$, indicating that streams responsible for a high energy-saving potential were removed from the network. Focusing on Panel d, an optimum of σ was identified for the network evaluated in Iteration 27 ($\sigma = 2.36$). According to Step 6 of the ESD method, this network was selected for the retrofit project, as it had the highest σ and it did not pay a high loss in energy-saving potential compared to the total plant. Such a network could potentially attain an energy saving of 52 % compared to the actual plant consumption. The selected network is presented in Figure 14. It was found that it is composed of all the streams that were considered during the final design when using the traditional Pinch Analysis method (red lines), plus one extra stream (Stream 65). This proves the usefulness of σ as a screening indicator and of the ESD method in general for reducing the problem size. In fact, by using it, only 22 streams were considered instead of the original 62 and the same final retrofit could be reached.

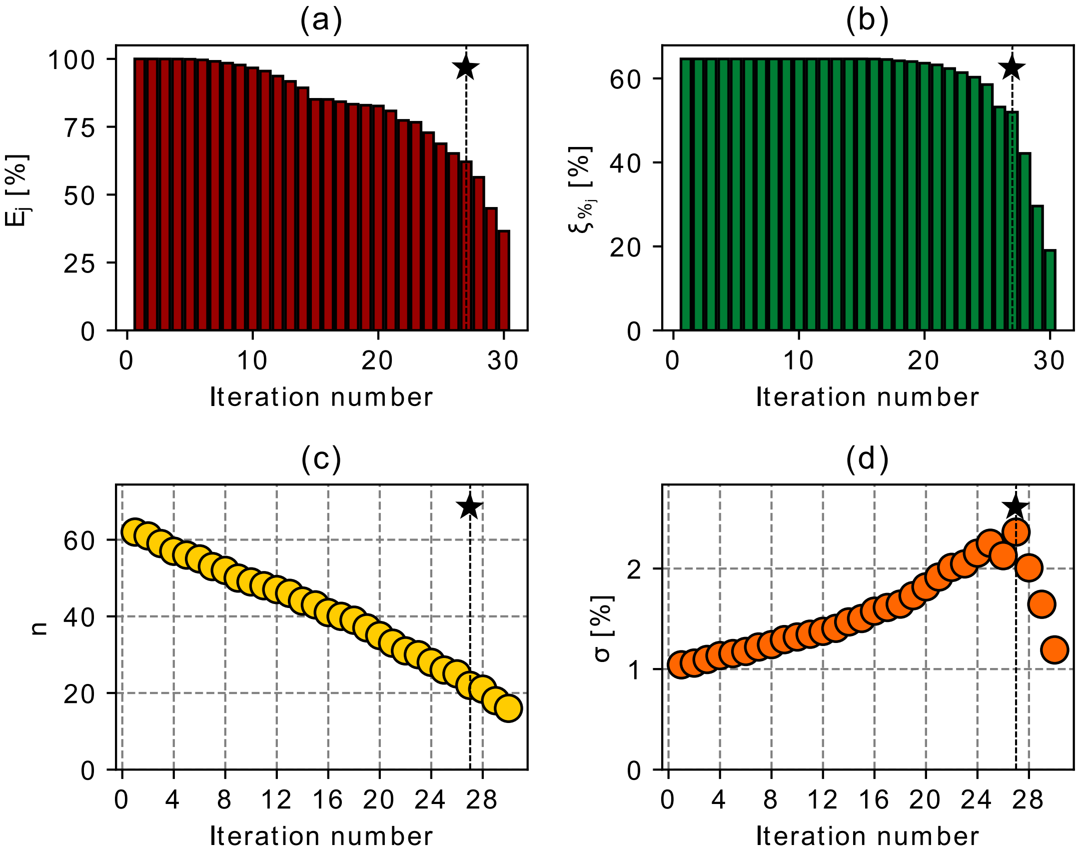

Figure 13: ESD 1st simplification step results. (a) Percentage utility consumption compared to the total system, (b) Percentage energy-saving potential, (c) Number of streams and (d) Average energy-saving content. The star indicates the selected iteration.

Another worthwhile elucidation regards the role of the "extra stream" selected by the ESD method (i.e Stream 65). From an energy-saving perspective, this is an important stream, contributing much to the total energy-saving potential. Proof of this is that, if the network evaluated in the successive iteration (Iteration 28) was selected, Stream 65 would have been removed, causing σ to drop to 2.00 and the potential for energy savings to $\xi_{\%} = 42\%$, with a total loss of 10 % of the energy-saving potential. However, the reason for not considering Stream 65 in the final retrofit design falls outside considerations based on the energy targets. It concerns the assumption of continuous operation of the plant. Stream 65 is in reality associated with space heating needs, making it a seasonal stream. Hence, it was disregarded during the design stage, despite the potential energy savings achievable in the winter season. The fact that the ESD did not screen out Stream 65 left the analyst in charge for making this decision using good engineering judgement, concomitantly aiding them with information on the thermodynamic importance of such stream.

Finally, Figure 15 compares the grand composite curve (Figure 15a) and composite curves (Figure 15b) of the complete plant and of the selected sub-network after the first simplification step. As can be seen, both composite curves and grand composite curve are similar in shape in the two cases. In particular, the grand composite curve after simplification presents "pockets" similar to the ones spotted in the complete plant. Nevertheless, after the application of the ESD the energy targets are lower, the highest temperature reached in the analysed process is lower and the minimum one is higher. This is a direct result of the elimination of streams from the retrofit problem. Moreover, the pinch point location is different in the two cases. It is important to note that such differences, and in particular the variation in the pinch point location, do not impede the analyst in achieving the same retrofit solutions designed by considering the entire plant. This points out that precise knowledge of the global pinch point location is not essential

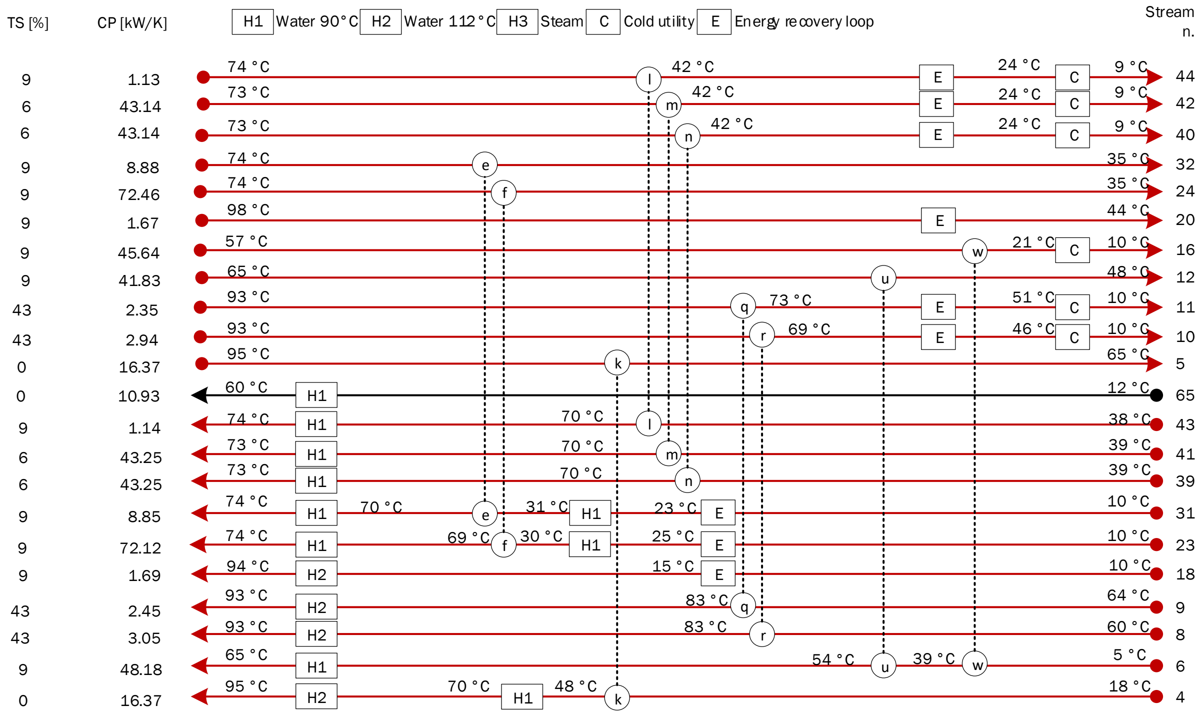

Figure 14: Existing heat exchanger network configuration and stream data after applying the first simplification step of the ESD method. Red lines indicate streams to consider for designing the proposed modifications (Figure 11).

for reducing the utility consumption and performing effective retrofit designs.

Second simplification

The second simplification procedure was employed setting a maximum PBT of 5 years and a maximum acceptable ΔT_{lm} of 5 K. This resulted in a minimum Pinch violation threshold of 100 kW, as shown in Figure 16a for different combinations of PBT and ΔT_{lm}. These assumptions were based on engineering experience and aimed to set a loose cut-off criterion for the present analysis. In practice, the normally acceptable payback period in the industry can be as low as 2 to 3 years, while the logarithmic mean temperature difference in the dairy industry can be as low as 1 K to 2 K.

The application of the second simplification step suggested neglecting 10 cross-pinch heat transfers in the final design (Figure 16b) over the total 15. As sought, they were not considered for modification when applying the traditional pinch procedure, which proved that the ESD method was able to further reduce the problem size without missing any feasible opportunity. All the streams and the pinch violations considered in the traditional retrofit were considered also by the ESD method, achieving the same retrofit by successfully reducing the time consumption and engineering effort required. Moreover, such investment resulted in a PBT of 4.1 years, which is lower than the threshold previously set.

As a final remark, analogous thresholds could be set assuming other values of PBT and ΔT_{lm}, based on specific economic constraints and technical considerations related to the heat exchange in the specific process. For example, a PBT=3 year and ΔT_{lm}=2 K would set a threshold of $\dot{Q}$=490 kW. This would suggest disregarding all the violations except for the one caused by heat exchanger “w” between Stream 6 and Stream 16. Consequently, no further time would be wasted in screening various possible design solutions not including this HEX, which would not satisfy the economic constraints of the project, considerably restricting the solution space.

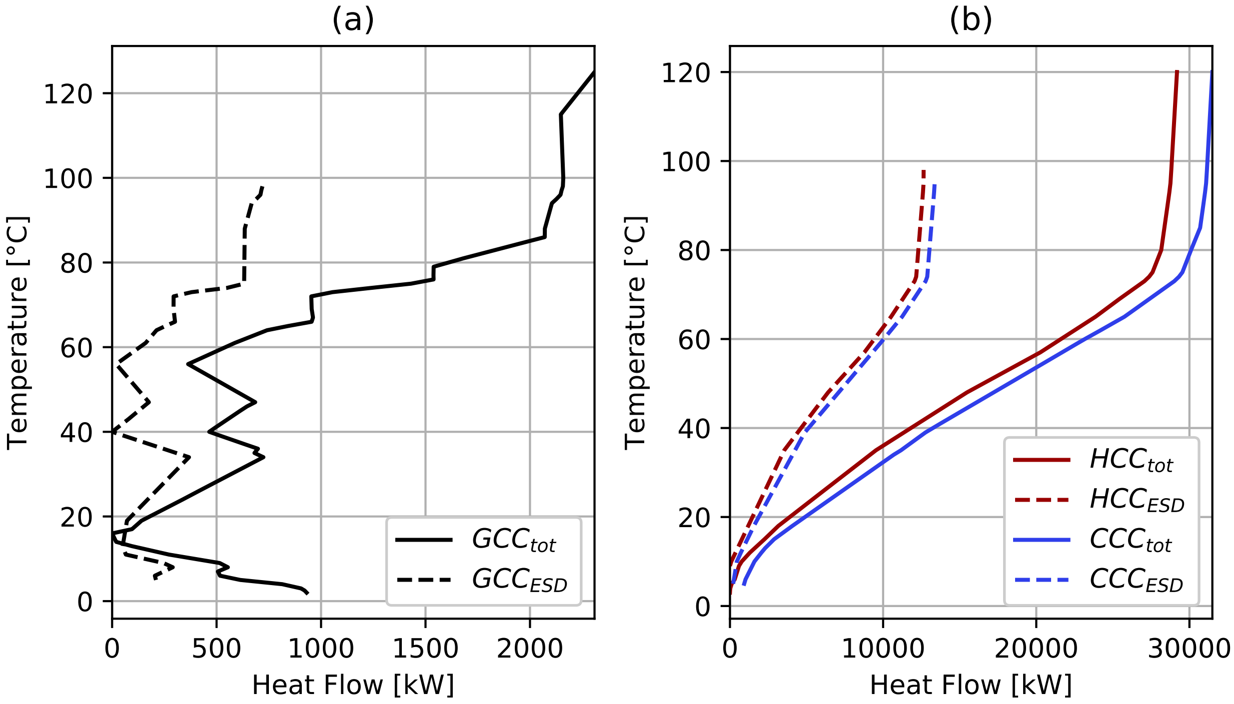

Figure 15: (a) Grand Composite Curve and (b) Composite Curves, for the complete process (tot) and the sub-network selected after the first simplification (ESD).

5. Discussion

5.1. Merits

The ESD method demonstrated its effectiveness in simplifying the PI retrofit study, potentially resulting in a conspicuous reduction in the time spent in the *Conceptual design* stage of the project. This success is ascribable to the novel decomposition technique introduced and to the definition of the two screening criteria, addressing multiple design necessities, ranging from operability concerns to thermodynamic and economic constraints.

5.1.1. Energy-saving decomposition technique

The novel decomposition technique proposed in this work demonstrated its ability to decompose the energy-saving potential of a system in a sum of terms depending on the subsections of the system and their interactions. Moreover, two summary indicators have been introduced. They can be used to systematically rank the importance of subsections based on their contribution to the energy-saving potential of the complete system. No published Process Integration method makes use of such a feature, which proved to be very effective when applied in the framework of the ESD method. In its formulation and usage, this function-decomposition technique is analogous to the ANalysis Of VAriance (ANOVA) [31] employed for decomposing the total variance of a model output between its input variables, and its application to sensitivity analysis [32]. All in all, it might prove very helpful for providing a rational basis to problem-simplification techniques in PI retrofit methods. Its application might not only relate to identifying subsections that can be disregarded (as applied in this work), but also to identifying the most promising subsection integrations after reducing the size of the problem, based on the individual terms on the right-hand side of Equation 1. Such a feature is not included in the ESD as described, and it will be part of future work.

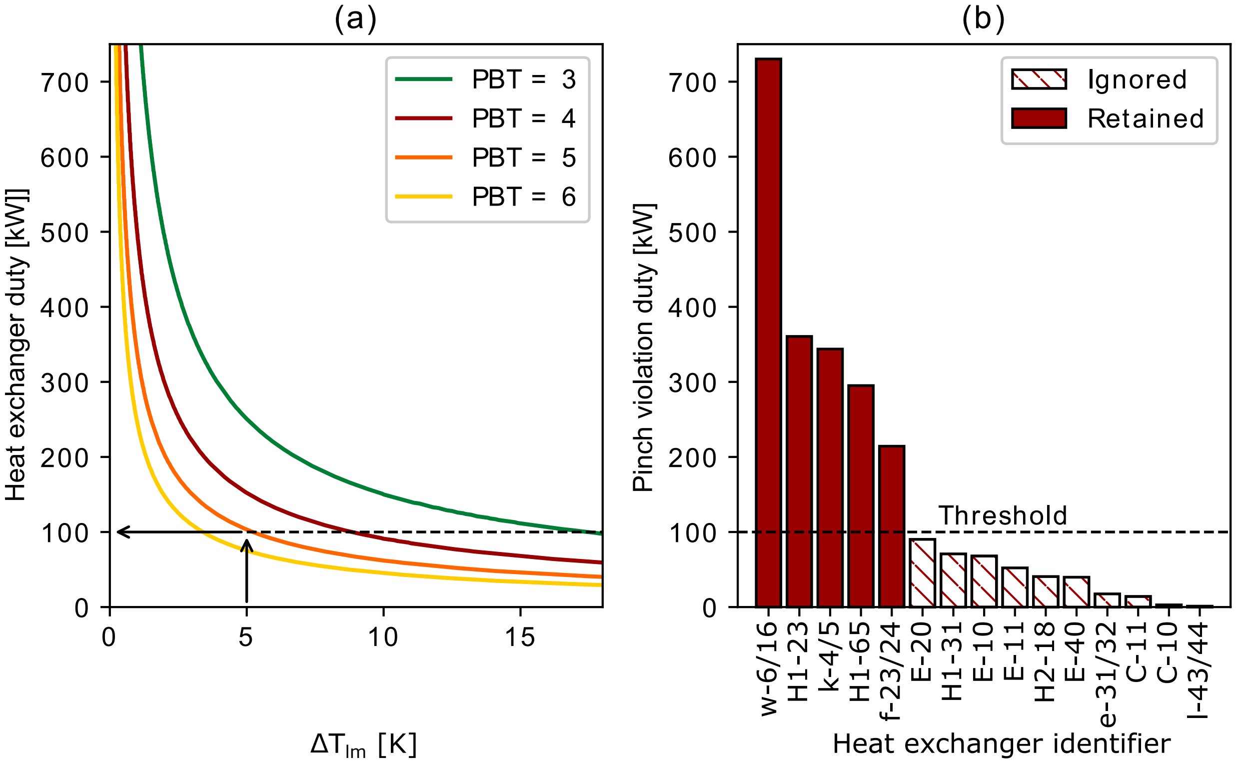

Figure 16: ESD 2nd simplification step results. (a) Heat exchanger duty requirement varying PBT, (b) Pinch violations selection based on the duty threshold. HEX identifiers indicate the label of the HEX (as in Figure 10) followed by the number of the streams involved.

5.1.2. *First simplification: Average energy-saving potential*

The merit of this simplification lies in: (i) the employment of the novel energy-saving decomposition technique for prioritising the elimination of subsections from the problem and (ii) the definition of a performance indicator able to systematically identify when it is most advantageous to stop the simplification, grounded on the energy-saving potential of the remaining problem. They are discussed in the following:

(i) The energy-saving decomposition employed in the ESD provided a solid rational basis for reducing the size of the problem before making design decisions. When applied to the case study, the size of the problem was significantly decreased, from 62 to 22 process streams, without incurring in the risk of disregarding subsections important for proposing practical energy-saving solutions. Previously proposed methods, having a similar feature, based the screening of process streams on criteria presenting different drawbacks. Dalsgård et al. [23] proposed a screening based on the concept of “limiting match”. This grounded only on economic considerations, not accounting for the potential for heat integration of the various streams. This leaves a risk of removing streams with a high contribution to the total energy-saving potential, resulting in a network with streams considered beneficial under an economic point of view, but which could not be integrated according to the thermodynamic laws. Van Reisen et al. [22] proposed a screening based on “Path analysis” and on the concept of “Zoning”. However, the method is reportedly sensitive to the division of the plant in sub-sectors (called “zones”), which is a rather subjective task, and handles with difficulty plants with more than 10 subsections. This is caused by the fact that the method always evaluates the 2^k possible combinations of k subsections, lacking summary indicators which can reduce the computational effort (similar to ς_T used in this work).

(ii) The maximization of the *Average energy-saving content* (Equation 9), together with the consideration of the energy-saving potential of the remaining network, appear to be a logical stop-criterion for a problem-size reduction technique. By representing the average energy-saving potential embedded in the considered streams, σ

links their thermodynamic performance to the complexity in retrofitting the selected sub-network. A higher *Average energy-saving content* reveals that a higher energy-saving potential lies in a reduced number of streams, suggesting that a retrofit conducted on the selected sub-network has a higher probability to be less time-consuming and thus has a higher chance of success, due to its reduced complexity and cost for the analysis. Furthermore, this indicator proved to be able to detect the detrimental overlooking of streams responsible for high thermodynamic inefficiencies, testified by consistent drops of σ. This novel feature provides a solution to the lack of stop criteria based on analytical indicators, encountered in the PI methodologies aiming at simplifying the problem, present in the literature.

5.1.3. Second simplification: economic potential

The second simplification has the value of introducing economic considerations before conducting the final design. The minimum feasible heat exchanger duty threshold sets a lower bound to profitable pinch violations to be fixed, providing an analytical tool able to reduce the number of possible design combinations. To remove a pinch violation, the investment in at least a heat exchanger of the same duty of the violation itself is needed. Whenever the violation size is lower than the so defined threshold, a possible retrofit aiming at eliminating this inefficiency would surely be economically infeasible, resulting in a waste of time.

The threshold definition can be grounded on either the ΔT_{lm} or the UA-value. The latter could be beneficial for controlling (and potentially constraining) the overall network size and capital investment of the project. The UA-value is also preferable from a thermodynamic perspective for addressing phase-change streams (processed by e.g. condensers and evaporators) which are frequently present in industrial processes. Conversely, plant technicians and consultants are more familiar with the concept of ΔT_{lm}, which is more easily understandable and is more suitable for defining rough thresholds based on experience. This leaves the choice of the parameter to the analyst, allowing considerations based on the characteristics of the investigated case.

A final remark is worth on the flexibility in setting important parameters, such as (i) target payback time, (ii) ΔT_{lm}, (iii) heat exchangers cost and (iv) energy cost. The analyst could easily vary them based on specific characteristics of the various sub-processes, allowing different thresholds for different sections of the plant. This permits evaluating single pinch violations based on the characteristics of the process involved, which could be helpful in many occasions, such as for processes requiring utilities at different temperature levels (e.g. hot water and steam at different pressures). In this case, different prices could be allocated to different utilities, resulting in multiple duty thresholds (Figure 7a) and refining the estimation of the economic importance of individual pinch violations. Moreover, parametric analysis on such assumptions could allow the refinement of rules of thumb widely used in the industry, such as in the definition of allowed ΔT_{lm} for heat exchangers, based on different media.

Overall, a similar feature has been proposed by Dalsgård et al. [23] and Walmsley et al. [17]. The application proposed by the former leaves some doubts, as it applies the cut-off criterion on the total stream duties instead of the pinch violations, using it for excluding unimportant streams. In this way, it disregards the actual network configuration by assuming a viewpoint more suitable for grassroots design projects rather than retrofit ones. The latter applies it to “Bridge analysis” [33] and appears to be a valuable tool coupled to such PI method. In case that “Bridge analysis” is used as an analysis tool in place of the method used in this study [28], its usage is recommended in place of the second simplification, stopping the ESD method after Step 6.

5.2. Limitations

The proposed method, despite presenting several strengths, embeds some limitations and needs further work to be fully validated. (i) Firstly, despite grounding on an analytically-solid decomposition technique, it relies on heuristic considerations for selecting the most promising network (Step 6 in the ESD method), forbidding to claim its validity “a priori” and requiring to test and validate it on a larger number of cases. To this end, its benefits have been recently proven on the retrofit of a simplified HEN in a pulp and paper mill [34] previously studied by Ruohonen and Ahtila [35], and further studies will be part of future work. (ii) Secondly, the ESD method as presented in this paper can only address continuous processes, being unable to punctually analyse the industrial processes operating in semi-continuous or batch mode. The results of the ESD can be used, in any case, for setting an upper bound to the potential savings by employing a Time Average Model approach [4]. (iii) Thirdly, the problem-size reduction in simplification 1 is solely based on thermodynamic considerations. While from the one side this ensures that no stream carrying high energy-saving potential is overlooked, it opens-up to the risk of overlooking streams which could lead to more cost-effective retrofit solutions. The likelihood of incurring in such a situation needs further evaluation. An experienced engineer could reduce this risk by evaluating the disregarded streams based on Good Engineering Judgement as allowed in Step 6 of the ESD. Fourthly, despite drastically speeding-up the Process analysis step, the ESD method introduces some complexity to the PI project, requiring the analyst to get familiar to some new concepts (e.g. the definition of elementary subsections). This might constitute a barrier to its widespread use in the industry. Lastly, the ESD does not address the data acquisition step of PI retrofit projects, which is likely to be the most time-consuming task of the whole project [19]. To achieve a significant reduction in the time required for performing the overall project, this method needs to be integrated into tools able to reduce the time-consumption of such step, such as the "Required Data Reduction Analysis" (RDRA) [21]. The proposal of an overall framework will be subject of future work.

6. Conclusion

A novel Process Integration retrofit method termed the *Energy-Saving Decomposition method* (ESD) was presented. It aims at reducing the complexity and time-consumption of the *Conceptual design* stage of conventional PI-based retrofit methods, and to them, it should be used as addition. It introduces two screening criteria, the first grounding on thermodynamics, making use of a novel decomposition technique for the energy-saving potential of the system, the second grounding on economics. The usage of the decomposition technique was illustrated on a simple example, while the overall method was applied to a dairy factory. It proved able to highlight the most promising energy conservation opportunities and resulted in the same retrofit performed by using the traditional Pinch Analysis procedure, by considering only 22 of the total 62 process streams and focusing the attention on reducing only 5 of the total 15 pinch violations. Moreover, the proposed algorithm could be automated and proved to be fast in reducing the problem size: only 466 computations of the Problem Table Algorithm were necessary on the case study, which could be executed in just 135 s with a commercial laptop.

Overall, the presented method appears encouraging for achieving a broader acceptance of Process Integration tools in the industry, especially in non-energy-intensive ones. The simplified approach is effective in decreasing the engineering effort in suggesting retrofit designs based on PI concepts, making such analyses also affordable for this type of industries. This is expected to foster the exploitation of a large potential for energy savings that is, as today, untapped, as proven by the savings achieved on the case study (23% compared to the existing process).

Appendix A. Economic analysis

The appendix provides a deeper insight into the economic analysis employed in the aforementioned calculations.

Investment cost

The heat exchanger investment cost was calculated to uniquely set a heat exchanger duty threshold in the second simplification step (Section 3.2.3). Many cost entries are relevant for the calculation of this parameter and it is not trivial to obtain sufficient information regarding all of them. A simplified approach was employed, as suggested by Bejan et al. [36]. The total investment cost was calculated by scaling the Purchased Equipment Cost (PEC) by a factor (γ) derived by experience and equal to 6.32 [36] (Equation Appendix A.1). This accounts for the fixed capital investment, startup costs, working capital, costs of licensing, research and development, and allowance for funds used during construction.

$$\text{Investment cost} = \gamma \cdot (\text{PEC}_{\text{HEX}} + \text{PEC}_{\text{pipes}}) - \varepsilon \tag{Appendix A.1}$$

The subscript "HEX" relates to heat exchangers, while "pipes" relates to piping. ε represents the energy efficiency incentive in the framework of the Danish white certificate scheme for energy savings. Its average value was considered as 0.06 \$ per kWh of delivered energy saved in the first year.

Purchased equipment cost

Heat exchangers were considered of the plate type and the PEC was calculated as a function of (i) heat exchange area, (ii) material, and (iii) operating pressure as it was in 1998 according to Turton [37]. This value was then rescaled utilising the CEPCI index, to estimate the 2018 price from 1998 one. Considering the purpose of the heat exchanging units in dairy processes, the material was considered carbon steel and the pressure was set to 1 bar for all the heat exchangers. The final cost correlation is:

$$\mathrm{PEC}_{\mathrm{HEX}} = 10^{k_1 + k_2 \cdot \log_{10} A + k_3 \cdot (\log_{10} A)^2} \cdot (B_1 + B_2 + f_m + f_p) \cdot f_a \qquad \text{(Appendix A.2)}$$

Where:
k_1 = model constant 1 $[\$]$
k_2 = model constant 2 $[\$/\mathrm{m}^2]$
k_3 = model constant 3 $[\$/\mathrm{m}^4]$
A = heat exchanger area $[\mathrm{m}^2]$
B_1 = bare module constant 1 [-]
B_2 = bare module constant 2 [-]
f_m = material factor [-]
f_p = pressure factor [-]
f_a = actualization factor [-]

The actualization factor was calculated as:

$$f_a = \frac{\mathrm{CEPCI}_{2018}}{\mathrm{CEPCI}_{1998}} \qquad \text{(Appendix A.3)}$$

The constants utilized in the previous calculations are presented in Table Appendix A.1.

Table Appendix A.1: Flat plate heat exchanger PEC calculation constants.

k_1	3.8528	$\$$	f_m	1	-
k_2	0.4242	$\$/\mathrm{m}^2$	f_p	1	-
k_3	0	$\$/\mathrm{m}^4$	CEPCI_{2018}	581 [38]	-
B_1	1.53	-	CEPCI_{1998}	382 [38]	-
B_2	1.27	-			

The piping cost was calculated as a function of (i) mass flow rate, (ii) Total Solid content, (iii) stream average temperature, and (iv) covered distance, as it was in 2003 according to Hackl and Harvey [39]. Again, this value was rescaled according to the CEPCI index and converted to Danish crowns. The material of construction was assumed to be carbon steel. The utilized cost correlation is:

$$\mathrm{PEC}_{\mathrm{pipes}} = (f_{\mathrm{BM}} \cdot C_{p,\mathrm{CS}} + C_{\mathrm{BM,ins}}) \cdot (1 + f_{\mathrm{CO}} + f_f) \cdot (1 + f_{\mathrm{SD}} + f_{\mathrm{OS}}) \cdot f_a \qquad \text{(Appendix A.4)}$$

Where:

f_{BM} = installation factor [-] $C_{p,\mathrm{CS}}$ = piping base cost $[\$/\mathrm{m}]$ $C_{\mathrm{BM,ins}}$ = cost for purchasing and installation of insulation $[\$/\mathrm{m}]$ f_{CO} = contingency factor [-] f_f = fee factor [-] f_{SD} = site development cost factor [-] f_{OS} = off-site factor [-] f_a = actualization factor [-]

The installation factor was calculated as:

$$f_{\mathrm{BM}} = 11.6 \cdot D_{\mathrm{nom}}^{-0.84} + 1.13 \cdot f_m \cdot f_p \qquad \text{(Appendix A.5)}$$

Where D_{nom} is the nominal pipe diameter in cm, f_m is the material factor, and f_p is the pressure factor. The theoretical pipe diameter was calculated assuming a maximum flow velocity of 2.5 m/s inside the pipes. The nominal value was then taken as the closest standardized pipe diameter higher than the calculated one, assuming a standard schedule (SCH40) [36]. The pipe thickness was fixed according to the same standard.

The piping base cost was interpolated from a cost chart [36], resulting in Equation Appendix A.6.

$$C_{p,\mathrm{CS}} = 0.0002303 \cdot D_{\mathrm{nom}}^{5} - 0.00829 \cdot D_{\mathrm{nom}}^{4} + 0.1137 \cdot D_{\mathrm{nom}}^{3} - 0.371 \cdot D_{\mathrm{nom}}^{2} + 0.5436 \cdot D_{\mathrm{nom}} + 9.702 \tag{Appendix A.6}$$

Finally, the cost of purchasing and installing pipe insulation was calculated as:

$$C_{\mathrm{BM,ins}} = 1.13 \cdot s_{\mathrm{opt}} \cdot (D_{\mathrm{out}} + s_{\mathrm{opt}}) \tag{Appendix A.7}$$

D_{out} is the external pipe diameter in m, and s_{opt} is the insulation thickness, calculated as:

$$s_{\mathrm{opt}} = 0.255 \cdot D_{\mathrm{nom}}^{0.20} \cdot \Delta T^{0.65} \tag{Appendix A.8}$$

ΔT is the absolute temperature difference between the bulk fluid temperature and the ambient one. The used constants are presented in Table Appendix A.2.

Table Appendix A.2: Pipes PEC calculation constants.

f_c	3.8528	-	f_m	1	-
f_f	0.4242	-	f_p	1	-
f_{SD}	0	-	CEPCI_{2003}	400 [38]	-
f_{OS}	1.53	-			

Revenues

The benefit of a process integration project is manifested in a reduction of energy and/or raw material consumption. In the conducted retrofit, just energy consumption reduction was attained. An artificial Cash Flow (CF) equal to the achieved energy cost savings was therefore calculated for conducting the economic analysis (Equation Appendix A.9). The heating demand was considered entirely supplied by gas boilers, while the cooling demand was satisfied employing vapour compression chillers.

$$\mathrm{CF} = c_{\mathrm{gas}} \cdot Q_{\mathrm{gas,savings}} + c_{\mathrm{el}} \cdot Q_{\mathrm{elec,savings}} \tag{Appendix A.9}$$

c_{gas} and c_{el} are respectively the specific cost of natural gas and electricity per unit of energy, while $Q_{\mathrm{gas,savings}}$ and $Q_{\mathrm{elec,savings}}$ are the saved energy embedded in natural gas and electricity, respectively. They were calculated from the final energy savings, considering the gas boiler thermal efficiency and chiller COP. The energy prices were assumed to be $c_{\mathrm{gas}} = 0.087$ \$/kWh and $c_{\mathrm{el}} = 0.143$ \$/kWh, while the final energy production performance was assumed to be $\eta_{\mathrm{th}} = 0.83$ and COP = 3.0.

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