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Analysis of energy integration opportunities in the retrofit of a milk powder production plant using the Bridge framework

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A B S T R A C T
The “bridge framework” is a systematic decision-making support tool for process integration retrofit of industrial plants, which proposes the use of “bridge analysis” in a structured fashion. Its potential of rigorously analysing industrial processes has been discussed, but no applications on actually operating plants considering process constraints have been presented to date.

The paper demonstrates the capabilities of the bridge framework in analysing an actually operating milk powder production plant. Its step-by-step application is thoroughly described and discussed, highlighting inherent strengths and weaknesses of the method. Moreover, a clarification of the “energy transfer diagram” is proposed, distinguishing avoidable and unavoidable heat degradation in the heat exchanger network by introducing the concept of “limit heat transfer interface”.

The results proved that the bridge framework is a rigorous tool, which provided valuable insight to the analyst aiding the open-ended decision-making activities related to the retrofit of both process operations and heat exchanger network. Seven design proposals were identified, out of which the best resulted in 54000 €/y of economic saving with an internal rate of return of 34% and a minimum risk level. The step-by-step application of the method demonstrated that good engineering judgement is critical for achieving beneficial solutions. Expertise on process operations as well as energy analytics is essential for completing the project. Finally, the concept of “limit heat transfer interface” allowed to completely link bridge analysis and pinch analysis and to clarify the meaning of the “grand composite curve”.

1. Introduction

Process Integration methods (Kemp, 2007) have proved to be highly effective tools for identifying opportunities for increasing energy efficiency of industrial processes. Reported case studies have demonstrated that significant reduction in energy demand can be achieved in various industrial sectors, such as the petrochemical industry (detected savings ranged from 10 % Bakhtiar and Bedard, 2013 up to 33% Nordman and Berntsson, 2009), the chemical industry (53% Yong et al., 2014 and 75% Pouransari et al., 2014), food industry (24% Bergamini et al., 2016 and 25% Muster-Slawitsch et al., 2011), pulp and paper (66% Ruohononen and Ahtila, 2010), and textile industry (51 % Dalsgaard et al., 2002), to cite a few. This often directly translates to emissions reduction, as these industrial processes are conventionally supplied by fossil fuel-driven utilities. However, most of the tools display limitations when retrofitting existing plants. The main limitations are: (i) visualisation tools providing only limited insight to the analyst (Lakshmanan, 1996) (e.g. the grand composite curve, which was developed for grassroots design), (ii) deficient evaluation of the multiple cost factors required for assessing cost-effective projects (Carlsson et al., 1993), and (iii) inefficient exploration of the retrofit solution space (Van Reisen et al., 1995). The “bridge method” (Bonhivers et al., 2017) was proposed as an improvement of existing process integration methods with regards to problem (i) and (iii). It is composed of two main tools: the Energy Transfer Diagram (ETD) and the list of bridges. The ETD (Bonhivers et al., 2014) is a map representing the flow rate

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of cascaded heat as a function of temperature through each utility component, process operation, and heat exchanger. In this way it can fully describe the empty regions at the right-hand side of the grand composite curve commonly used in pinch analysis, corresponding to process operations, and to the left-hand side, corresponding to the heat exchanger network. This diagram facilitates the identification of modifications that improve the overall energy efficiency of a plant (problem (i)), for the reason that reducing the heating utility use in a process implies reducing the flow rate of cascaded heat from the heating utility to the ambient through the operations or the heat exchanges. Any reduction in heating utility demand through a process implies a set of modifications, termed “bridge modifications”, that decreases the flow rate of cascaded heat through the HEN and process operations in the entire temperature interval from the heating utility to the ambient. A systematic method for listing the bridges was presented by Bonhivers et al. (2017), improving the analysis of the solution space when retrofitting heat exchanger networks (problem (iii)). More recently, the bridge method was included in an overarching framework for site-wide energy analytics able to retrofit both process operations and heat exchanger network (Moussavi and Stuart, 2020). However, both the bridge method and bridge framework have only been tested on illustrative examples to date and no detailed explanation of their use and benefits when considering practical process constraints have been presented.

This paper aims at filling the gap in the literature regarding the application of the bridge framework on real process plants with known practical constraints. More specifically it aims at:

- Thoroughly demonstrate how to apply the bridge framework on an actually operating process plant.
- Discuss benefits and weaknesses of the bridge framework in guiding engineering judgement in the open-ended decision-making activities of a retrofit project.
- Describe a modified version of the energy transfer diagram and composite curves distinguishing avoidable and unavoidable heat degradation through the Heat Exchanger Network.

These goals are achieved by means of a step-by-step application of the bridge framework to the retrofit of a process plant for the production of milk powder. The paper has the following structure: Section 2 presents a detailed literature review of the application of process integration methods in the dairy industry, justifying the relevance of the chosen case study. Section 3 describes the case study and the method followed for applying the bridge framework. Section 4 introduces the theoretical concepts at the basis of the modified ETD, illustrates its application with an example and describes a simple calculation strategy. Section 5 presents the results of the step-by-step application of the bridge framework to the case study. Section 6 discusses strengths and weaknesses of the bridge framework and the modified ETD. Finally, Section 7 highlights the main conclusions of the study.

2. Process integration in the dairy industry subsection

Global milk output is steadily growing and was estimated to be 843 million tonnes in 2018 (FAO, 2019). Fresh milk is processed and transformed into several final products (e.g. liquid milk, butter, cream, cheese, condensed milk, milk powder). Energy plays a critical role in the dairy industry, especially for performing heat treatments aimed at controlling bacteria growth. Nonetheless, energy accounts for only 1% to 3% of the total production cost and the dairy industry is classified among the non-energy-intensive sectors (Ramírez and M.Patel, 2006). As generally experienced in this category of industries, high potential for energy efficiency improvement is expected, as energy-related projects are often neglected due to the relatively low economic importance of energy consumption (Ramírez et al., 2005). This large potential, together with the low process and pinch temperatures and the non-continuous nature of the production, established the dairy industry as an excellent sector for applying and developing process integration tools (Atkins et al., 2013). The non-continuous nature of dairy processes allowed testing a modified version of the composite curves, which is useful for estimating the optimal temperature and size of stratified tanks for heat recovery in non-continuous processes (Atkins et al., 2010a) and a method for designing heat recovery loops while accounting for process variability (Atkins et al., 2012). Moreover, thanks to the low pinch temperature, dairy plants were proven to be suitable for integration of solar heating. Atkins et al. (2010b) proved that a combination of pinch analysis and solar information can be used to develop an operating strategy for solar collectors in a milk powder production plant. Quijera and Labidi (2013) used pinch analysis to show that solar energy could completely replace boilers in a Spanish multi-purpose dairy plant with payback period as low as 8.3 years. Waller et al. (2018) proved that solar heating can be cost-effective in dairy processes only in combination with optimised heat recovery and heat pumps. Integration of heat pumps has been extensively analysed thanks to the low process temperatures of dairy processes, in an attempt to increase their degree of electrification in an energy-efficient way.
Optimal vapour recompression in milk evaporation trains has been studied by Walmsley et al. (2016) proving that process integration techniques could lead to substantial economic savings in this process. The work was later expanded (Walmsley, 2016) proposing a total-site integration method for evaporation trains, considering both vapour recompression and integration with other processes (e.g. spray drying) and an “ultra-low energy” milk powder production process was finally proposed (Walmsley et al., 2018). Becker et al. (2012) tested a method for selecting the optimal integration of heat pumps in a cheese production plant, showing that cost savings up to 50% could be achieved with such a project. Stampfli et al. (2019) recently proposed a hybrid insight-based/mathematical-programming method for integration of heat pumps in non-continuous processes proving that up to 73% of energy use could be avoided in a cost-effective way in a butter production plant. Bühler et al. (2019) compared different strategies to fully electrify a milk powder production plant, proving that an ad-hoc centralised heat pump system could solve the task reducing the total energy consumption by 65%. Finally, the generally large potential for energy saving of existing dairy plants established them as good case studies for proving the effectiveness of new process integration methods. Tarighaneslam et al. (2017) used a multi-purpose dairy site for testing a modified total site heat integration method. Dalsgaard (2001) and Bergamini et al. (2020a) tested two methods for faster heat integration studies, named “Limited match” method and “Energy-saving decomposition” method, on cheese factories. Finally a method for a more rational and expeditious data acquisition in process integration studies, named “Required data reduction analysis”, was proposed and tested for a cheese production plant (Bergamini et al., 2019) and four milk powder production plants (Bergamini et al., 2020b).

3. Method

The case study was analysed by means of the bridge framework proposed by Moussavi and Stuart (2020) (in the following simply called “bridge framework”). A step-by-step description of its application is provided. This section introduces the case study and describes the method followed in applying the bridge framework. The assumptions for performing the techno-economic analysis are described in Appendix A.

3.1. Case study: milk powder production

A currently operating process plant for the production of milk powder from fresh milk was studied. It was able to process 26 m³/h of fresh milk at full capacity, requiring 4528 kW of heat supplied by steam (produced by a centralised natural gas boiler), natural gas and electricity. The plant operated for 7350 h/y, while for the remaining hours it was shut down or undergoing cleaning. The plant was assumed to run at steady conditions during this production period. The required data for formulating a thermodynamic process model were retrieved by SCADA logs, screenshots of the SCADA system and assumptions based on experience of the plant production manager and process experts of GEA Process Engineering A/S (GEA Process Engineering A/S, 2020). The thermophysical properties of liquid milk were modelled according to Munir et al. (2016).

The plant (Fig. 1) could be divided in four main sections:

1. **Milk pasteurisation.** Raw milk with Total Solids content (TS) of 13% was preheated by means of a recuperative plate heat exchanger recovering heat from the condensate extracted from the evaporation train. It was then pasteurised by means of a regenerative-flash pasteuriser and sent to the evaporation section.

2. **Evaporation.** The evaporation section contained a multi-stage evaporation train composed of three effects and equipped with mechanical vapour recompression in Effect 1 and thermal vapour recompression compressing vapour from Effect 3 to Effect 2. The condensate was cascaded through the effects incurring a flash process (Flash 1 and Flash 2) and was ultimately extracted from Effect 3. It was then mixed with the condensate extracted from the condenser and the heat contained in it was recovered by means of the aforementioned preheater in the Milk pasteurisation section. The cooled condensate was employed for driving the condenser and the heat recovered in this way was further used in the Drying section. The concentrated milk at 50% TS extracted from Effect 3 was sent to the Concentrate heating section.

3. **Concentrate heating.** The concentrate was preheated by means of a steam heater, pressurised to high pressure and sent to the Drying section.

4. **Drying.** The pressurised concentrate was dried to 97.5% of TS by means of a spray dryer equipped with a static fluid bed and a vibrating fluid bed. The ambient air entering the dryer was firstly preheated by recuperating part of the heat contained in the condensate with an indirect heat recovery loop. The air flow was then split into five air streams: the main air was heated by means of an indirect-fired natural gas heater equipped with economiser, the air flow driving the static fluid bed was heated by means of the warm condensate and steam, while the remaining three air flows were heated by steam and sent to the vibrating fluid bed. The condensate was finally cooled with a cooling tower and the exhaust air from the dryer was rejected in the ambient. The possibility to recover the sensible heat contained in it was accounted for, while the latent heat was considered an unavoidable loss both for the exhaust air and the flue gas from the burner.

Further details of the mentioned equipment can be found in Westergaard (2010). The grid diagram of the full plant is shown in Fig. 2. The figure displays cold streams in blue lines, hot streams in red lines and intermediary heat recovery (IHR) loops in green lines. The streams composing it are not process streams, but rather features of the existing HEN. Finally, utilities are represented in dotted coloured lines.

3.2. Bridge framework application

The bridge framework was formulated as an overarching step-wise procedure guiding the analyst in using the full capabilities of the bridge method (Bonhivers et al., 2017). As such, it aims at analysing industrial plants as thoroughly and rigorously as possible, while keeping the user in charge of the decision-making process. A summary of the main steps of the decision-making procedure is presented in Fig. 3. A more detailed description is provided in Moussavi and Stuart (2020). The decision-making procedure is divided in four main groups of activities: Computerised calculation engines where computer-based software performs automatic calculations, Dashboard graphically representing the results of the calculations, Open-ended decision-making activities where good engineering judgement is employed based on the obtained results and Decision where a final decision is made. As it can be noted, the method is employed after a thorough data acquisition is performed and a process simulation is available. Eight main phases where followed:

1. **Problem definition.** Based on the process simulation, the Process Operations (POs) and the heat exchangers belonging to the HEN were identified, as displayed in Fig. 1. This decision-making step is subjective and highly important for the sake of the analysis, as it greatly influences the results and insights achievable. General recommendations for performing this task can be found in Kemp (2007).
2. \( \Delta T_{\text{min-cont.}} \) definition. The process streams where identified and the grid diagram was produced (Fig. 2). The minimum individual temperature difference contribution \( \Delta T_{\text{min-cont.}} \) was defined for all the process streams. Based on experience, \( \Delta T_{\text{min-cont.}} = 1 \) K was assumed for phase-changing streams, \( \Delta T_{\text{min-cont.}} = 2 \) K for liquid streams and \( \Delta T_{\text{min-cont.}} = 10 \) K for gaseous streams. \( \Delta T_{\text{min-cont.}} = 0 \) K was assumed for streams belonging to the intermediary heat recovery loop as they were not necessary for the POs, but rather present due to design choices in the existing HEN. As such, they could potentially be removed as part of a HEN retrofit.

3. Process Operation modification. The energy transfer diagram for the process operations and the energy transfer curves (Bonhivers et al., 2014) of individual POs were produced. Possibilities for PO modification were evaluated, but they were not finally implemented as deemed not economically interesting for the current case study.

4. Potential energy savings. The enthalpy cascaded through PO and HEN was calculated by means of the Problem Table Algorithm (PTA) (Linnhoff and Flower, 1978) and the site-wide ETD was produced, introducing a novel representation of the avoidable and unavoidable flow rate of the heat cascaded through the HEN (described in detail in Section 4). The minimum hot utility and cold utility consumption (HU\(_{\text{min}}\), CU\(_{\text{min}}\)) were calculated by means of this. The potential for energy savings (\( \zeta \)) was then evaluated for accepting or rejecting the project.

5. Risk level definition. The connection table indicating all the possible connections between hot and cold streams was displayed and the risk level associated to each connection was evaluated. This included risk related to (i) Controllability, i.e. the ability to reach steady state in all the required operating conditions, (ii) Complexity, i.e. the difficulty in controlling the plant to maintain steady state operation, and (iii) Economics, related to loss of profit if the plant needs to be shut-down due to increased maintenance requirements. The risk level was qualitatively assigned based on the 5-level scale displayed in Table 1. This required high process expertise and close communication with the plant process manager, involving subjective decisions.

6. Analysis of the solution space. The list of possible bridges was calculated following the automatic procedure presented by Bonhivers et al. (2017). They are defined as sets of modifications to the existing HEN, composed of matches connecting suppliers of coolers to receptors of heaters. Only the bridges composed of up to 5 matches were calculated, assuming that bridges formed of a higher number of matches would not be interesting in a practical retrofit (Bonhivers et al., 2017). The potential energy saving of each bridge and the maximum risk level in their matches was calculated and a subset of bridges was selected for further investigation, considering a threshold hurdle rate of 200 kW of energy savings for screening them. The hurdle rate was set in accordance with the plant process manager. A novel approach was formulated for calculating the energy saving potential of each bridge. Unlike the linear programming method proposed by Bonhivers et al. (2017), the proposed procedure evaluates the heat cascaded between individual matches sequentially using the problem table algorithm. It is conceptually exemplified in Fig. 4.
Fig. 2. Existing heat exchanger network configuration and stream data of the case study.
Let us consider an hypothetical bridge C1-E1-H1 between a cooler (C1) and a heater (H1) passing a process/process heat exchanger (E1). The procedure starts by considering the first match (C1-E1): at first the cumulative surplus and deficit of heat flow rate in the match between the supplier of C1 and the receptor of E1 is evaluated by means of the PTA (the corresponding grand composite curve is displayed in panel a). The "heat pockets" (green areas in the figure) are removed and the net deficit heat flow rate (panel b) is extracted, corresponding to the energy need of the receptor of E1 that cannot be satisfied by the supplier of C1. Next, the procedure is repeated considering this net deficit heat flow rate and the supplier of E1 (panel c). After removing the heat pockets, the net surplus heat flow rate is extracted (panel d), corresponding to the heat "freed" from the supplier of E1 after satisfying the remaining heat demand of its receptor, and available for preheating the receptor of H1. Finally, the PTA is calculated considering the net surplus heat flow rate and the receptor of H1 (panel e). The difference between the actual duty of H1 and the minimum hot utility requirement calculated with the PTA corresponds to the energy-saving potential of the bridge C1-E1-H1. A numerical example is provided in Appendix B. This same procedure can be applied to bridges of any length.

7. **Topology selection.** A promising modified HEN topology was identified for each selected bridge, forming the new matches between HX suppliers and receptors indicated in the bridge. This step generally involved the replacement of existing HXs, the reduction in heat exchange area of existing HXs or the placement of new HXs and was performed based on good engineering judgement. As a result, a list of promising HEN topologies was formulated.

8. **Design proposals.** A techno-economic analysis was performed on each topology and the non-linear programming (NLP) problem constituting the retrofit of a HEN with fixed topology was manually optimised by tuning the decision variables in a recursive procedure. A list of design proposals was formulated and sorted based on economic and risk-based considerations.

4. **Developments of the energy transfer diagram**

4.1. **Concepts**

Energy is transferred from the heating utilities to the heat exchanger network and process operations, gradually degrading (i.e. reducing its thermal exergy content) until it is rejected to the ambient. The energy transfer diagram (Bonhivers et al., 2014) provides a graphical representation of this phenomenon, describing how energy is degraded through an industrial site. However, the HEN representation provided by the commonly used ETD does not account for the necessity of allowing a minimum temperature difference ($\Delta T_{\text{min}}$) when heat exchangers are employed. As a consequence, the ETD cannot represent the GCC and the energy targets calculated through the problem table algorithm of pinch analysis and an important link between bridge analysis and pinch analysis is missing. Moreover, bridges cannot be easily identified in the ETD when $\Delta T_{\text{min}} > 0$ is required for HXs. The following clarifies an evolution of the ETD, where the effect of $\Delta T_{\text{min}}$-cont. is accounted for. The possibility to consider this effect was conceptually mentioned in Bonhivers (2013), but it was never clarified in detail and used afterwards.

Process operations require energy for performing their production activities, mainly in the forms of mechanical, chemical and thermal energy. Thermal energy is supplied by utilities and can be delivered in various forms under the restrictions of the first and second laws of thermodynamics. The most common means for delivering thermal
energy to POs is by employing heat exchangers. The choice of this equipment introduces an additional constraint to heat transfer, besides the laws of thermodynamics. While the second law of thermodynamics determines that heat can be transferred between two bodies as long as the temperature difference between them is greater than zero ($\Delta T > 0$), when economic constraints are taken into consideration a minimum temperature difference ($\Delta T_{\text{min}}$) can be identified. The investment in a heat exchanger with $\Delta T < \Delta T_{\text{min}}$ would result in a too large heat exchanger area and the investment would not be economically feasible. In practice, all the HXs in a process plant transfer heat with $\Delta T \geq \Delta T_{\text{min}}$.

The higher $\Delta T$, the higher the heat degradation (i.e. exergy destruction) in the heat exchanger. Considering this, the heat degraded in a HX can be divided in two components: an avoidable and an unavoidable part (Fig. 5a). The unavoidable heat degradation corresponds to the heat transferred within $\Delta T_{\text{min}}$. According to the definition of $\Delta T_{\text{min}}$, it is not possible to design a heat exchanger able to avoid this exergy destruction in an economically feasible way. Conversely, the avoidable heat degradation results from the heat transferred with $\Delta T > \Delta T_{\text{min}}$ and could be avoided by modifying the heat exchanger network. For each process stream exchanging heat with the HEN it is possible to define a Limit heat transfer interface representing the extreme temperature at which heat should be supplied (in case of a cold stream) or absorbed (in case of a hot stream) without incurring in avoidable exergy destruction (as above defined). This concept is intrinsically considered in the PTA by means of the procedure named “Temperature shifting” and influences the pinch point, energy targets and shape of the GCC (the validity of this term is discussed in Section 6). The avoidable and unavoidable heat degradation through each HX constituting the HEN can be represented in the ETD by identifying the limit heat transfer interface of each process stream and the heat degraded within and outside of it (Fig. 5b). The unavoidable heat degraded through the HEN is of scarce interest in a retrofit project, as no retrofit action could reduce it. For this reason only the cumulative enthalpy flow rate cascaded within $\Delta T_{\text{min}}$ as function of temperature in all HXs is represented in the figure (grey region). Conversely, the avoidable heat degradation through the HEN is of high interest as energy savings would result from its reduction and the Energy Transfer Curves (ETCs) (Bonhivers et al., 2015) corresponding to the individual HXs contributions are represented in the ETD (green region). The limit separating the unavoidable and avoidable heat degradation through the HEN (blue line) corresponds to the GCC when $\Delta T_{\text{min}} > 0$ is assumed. This allows the graphical identification of the pinch point, energy targets and “pinch violations” (PVs) on the ETD, providing a complete link between bridge analysis and pinch analysis, as illustrated in Fig. 5b. Moreover, bridges can easily be identified in the green region: heat could be transferred between supplier and receptor of two HXs without violating the $\Delta T_{\text{min}}$ requirement as long as their ETCs are positive at the same temperature (i.e. as long as they are vertically aligned).

### 4.2. Illustrative example

The following exemplifies how avoidable and unavoidable enthalpy flow rate cascaded through a heat exchanger can be represented in the ETD for a HEN composed of only one HX. A more complex example of a site-wide ETD is provided in Section 5 for the analysed case study.

Consider a heat exchanger network composed of only one heat exchanger, as illustrated in Fig. 6. It transfers 20 kW of heat between stream PS1 and stream PD1. They both have an individual minimum temperature difference contribution of 2 K. However, the traditional ETD does not consider this information and displays the flow rate of cascaded heat as a function of temperature with no distinction between avoidable and unavoidable part (Fig. 6b). As a consequence, the ETC
of this HX corresponds to the PO curve of a plant whose HEN is formed of only this HX, but it would not display the GCC.

The separation between avoidable and unavoidable enthalpy flow rate cascaded through the heat exchanger network can be displayed by identifying the limit heat transfer interfaces for the two streams (Fig. 7a). The heat exchanger is divided in three fictitious units: $EU_h$ transferring heat within $\Delta T_{\text{min-cont.}}$ of the hot stream, $EU_c$ transferring heat within $\Delta T_{\text{min-cont.}}$ of the cold stream and $EA$ transferring heat outside $\Delta T_{\text{min}}$. All the avoidable heat degradation through the heat exchanger happens in $EA$, as this heat could potentially be transferred to other processes (e.g. a heat engine) and be degraded through them.

The remaining units transfer heat with unavoidable degradation. Representing the ETCs of these three units in the ETD allows effective decomposition of the ETC of the heat exchanger in its avoidable and unavoidable contributions (Fig. 7b). This allows identification of both the PO curve (red line) and the GCC (blue line), providing a complete link between the ETD and pinch analysis.

4.3. Computational strategy

The proposed ETD can easily be calculated without additional procedures compared to the traditional one. As aforementioned, there is little merit in distinguishing the individual contributions of the

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**Fig. 5.** Illustrative example of the novel Energy Transfer Diagram. (a) concept of avoidable and unavoidable heat degradation in a HX. (b) link between ETD and pinch analysis.

**Fig. 6.** (a) Grid diagram and (b) traditional ETD for example 1.
individual HXs to the unavoidable heat degradation (grey region) and this activity is not recommended. The previous example displays such distinction for demonstrating the theoretical validity of the proposed concept. As such, the ETD can easily be calculated using geometrical considerations: the PO region (displayed in yellow in Fig. 5) can be calculated as traditionally proposed (Bonhivers et al., 2014). The region of avoidable heat degradation through the HEN (displayed in green in Fig. 5) can be calculated by considering the flow rate of cascaded heat between the limiting heat transfer interfaces of the streams involved in the HEN. This corresponds to considering the so called “shifted streams” (using the terminology traditionally used in pinch analysis). Finally, as the ETD should result in a rectangular shape (Bonhivers et al., 2014) with height equal to the total utility consumption in the existing plant, the ETC corresponding to the unavoidable heat degradation through the HEN can be calculated as difference between the rectangle and the previously calculated ETCs.

5. Results

The case study was analysed by means of the bridge framework. Phase 1 and Phase 2 of the framework (Fig. 3) were applied as described in Section 3. Their results are displayed in Figs. 1 and 2, respectively. The results of the other phases are reported in the following.

5.1. Phase 3: Process operation modification

Possibilities for PO modification were evaluated by means of the ETD (Fig. 8). The ETD of the POs displays the enthalpy flow rate cascaded through the process operations as a function of temperature. It is drawn by summation of the enthalpy flow cascaded through each process operation, represented by the energy transfer curves (displayed in black lines). In the ETCs, segments with negative slope indicate that the process in that temperature range is a net heat sink, while the contrary indicates that the process is a net heat source. The upper curve (highlighted in red) is called the Process Operation curve and its maximum (the blue star) indicates the minimum enthalpy flow rate that should be provided by external utilities and that would be cascaded to the ambient through the process operations. To save energy, the maximum of this curve must be reduced by modifying individual POs (i.e. modifying the shape of ETCs) and their interaction (i.e. shifting the ETCs). Fig. 8 shows three sections in different shades of yellow: drying, evaporation and pasteurisation. As can be noted, the drying section is composed of the spray dryer and various energy losses, while no heat losses were accounted for in the other two sections. The losses of the drying section were deemed to be part of the process operations as they were considered unavoidable due to design constraints and heat could not be recovered in the existing plant by means of HXs without accounting for modifications to the POs. For example, the main heat loss was in the exhaust air from the dryer. Heat recovery from this air stream at temperatures lower than its dew point (55 °C) was deemed to be infeasible due to plant-specific configuration in the studied factory. To allow this opportunity, modification to the process operations would be required. Similarly, it was deemed infeasible to recover heat from the flue gases of the gas burner below the dew point. High process expertise and a high degree of engineering judgement was required at this stage.

As the overall objective of this phase was to reduce the maximum of the process operation curve, the main contributors to it were identified. The PO curve showed a global maximum at 60.1 °C accounting for 3733 kW and a local maximum at 6 °C accounting for 3655 kW. As the two maximum points were close in value, the proposed modifications should focus in reducing both of them. To do so, it is recommended to identify the main POs contributing to both maxima and identify directions of development for them. These aim at two possible goals: (i) reduce the maximum of the ETCs of the identified POs, resulting in an overall energy saving in the individual POs, or (ii) modify the POs to shift their ETCs to different temperature level, breaking their actual alignment. This would create possibilities for heat integration between them, allowing to transfer heat between net heat sources in one PO (segments with positive slope) and net heat sinks of another PO (segments with negative slope). For example, the local maximum was mostly caused by the energy losses in the drying section, in particular the ones related to the exhaust air from the dryer (2846 kW). Examining Fig. 8, it can be noted that it would be possible to recover part of the heat content of the exhaust air in the dryer itself. In fact, the ETC of the dryer has a positive slope in the temperature range from 6 °C to 55 °C, indicating that this is a net heat source region and excess

![Fig. 7.](image-url)
heat should be discharged. However, if heat is not recovered from the exhaust air as in the actual situation, the resulting ETC has a negative slope (graphically shown by adding the ETC of the dryer and of the exhaust air losses) indicating that roughly 1000 kW of heat should be provided to the dryer in this temperature range. However, recovering heat from this air stream was considered infeasible in the existing process as aforementioned, so no obvious modification direction could be identified.

Following this logic, specific directions for dryer, evaporation train, and pasteuriser contributing to the global maximum could be formulated. They are not reported, as no final PO modifications were proposed in the specific case. Nonetheless, it is clear that the formulation of suggestions requires deep knowledge in the physical phenomena determining the shape of the individual ETCs as well as the mutual interaction between them.

5.2. Phase 4: Targeting

The energy targets were calculated by means of the Problem Table Algorithm (PTA) and can be graphically shown in the sitewide ETD (Fig. 9). The link between the ETD and the Grand Composite Curve (GCC) traditionally employed in PI studies is highlighted in the figure. The process operation curve represents the enthalpy flow rate cascaded through the POs as a function of temperature. Its shape corresponds to the shape of the GCC when a global $\Delta T_{\text{min}} = 0 \degree C$ is assumed. The region below it is composed of the ETCs of the POs as described in the previous section. The region above the PO curve represents the enthalpy flow rate cascaded through the existing HEN as a function of temperature. An innovative representation of this region is proposed in Fig. 9, by dividing the enthalpy cascaded through each HX in an unavoidable and an avoidable contribution. The former is the flow rate of the cascaded heat through the assumed $\Delta T_{\text{min}}$. The aggregated unavoidable flow rate of cascaded heat through all the HXs is displayed by the grey region in the figure. The latter is the avoidable flow rate of cascaded heat through the existing HEN. This could be avoided by designing a more efficient HEN, which is the main objective of this study. The curve delimiting these two regions (displayed in blue) is the GCC when individual $\Delta T_{\text{min,PO}}$ are assumed for all the process streams. It allows identifying the pinch point and the energy targets as traditionally performed by means of the PTA. As displayed, for the case study the pinch point temperature is $T_{\text{pp}} = 58.1 \degree C$ while the energy saving potential is $\zeta = 440$ kW. Moreover, the ETCs intersecting the pinch point above the GCC graphically display the heat transferred across the pinch (traditionally known as pinch violations). These same considerations could be drawn by evaluating the balanced composite curves and heat cascaded through the HEN as can be seen in Appendix C.

After drawing the sitewide ETD, the potential for energy savings was evaluated in the open-ended decision making step and it was considered sufficiently promising for continuing the project.

5.3. Phase 5: Risk level definition

The connection table was generated and the risk of each combination of hot and cold streams was qualitatively evaluated following the scale presented in Section 3. This requires deep process knowledge and high expertise.

5.4. Phase 6: Analysis of the solution space

All the technically feasible bridges composed of up to 5 matches were identified and the maximum energy saving achievable, as well as the risk they involved, was calculated. The 6699 resulting bridges
were sorted based on the achievable energy saving. The first 20 are reported in Table 2. In the open-ended decision making step, seven of these were selected for further investigation (highlighted in grey). This decision was based on engineering judgement considering both achievable savings and risk level. More specifically, as first criterion, only bridges with potential energy saving exceeding the selected hurdle rate of $\xi = 200$ kW were considered. Among these, in case of equal energy-saving potential the bridges with the highest risk level were disregarded. An exception to this rule was made for the second bridge in the list, which was investigated even though its risk level was 4, as it displayed high energy-saving potential (288 kW, equal to 65% of the total potential).

5.5. Phase 7: Topology selection

Each of the seven bridges identified in Phase 6 were considered for topology modification. The list of matches composing the bridge provided guidance on the new connections to be made in order to save energy. Nonetheless, engineering judgement was paramount to formulate the final topology and in particular to decide the existing HXs to maintain in their actual positions, the ones to be relocated and the new HXs to place. For sake of exemplification, the considerations leading to a new topology for the bridge C1-E3a-E3b-E5a-E5b-H2 are reported in the following. The final topologies for the remaining bridges are reported in Appendix D.

With focus on bridge C1-E3a-E3b-E5a-E5b-H2, the bridge framework provided the following insightful information for helping the analyst in formulating a beneficial topology:

1. The portion of the existing network that should be involved by topology modification. This is formed by the HX suppliers and receptors involved in the Bridge and is displayed in Fig. 10.

2. The order in which new matches between HX suppliers and receptors should be formed. This is the order of the matches in the bridge. In this case, firstly a new match between the supplier of C1 and receptor of E3a should be established, secondly a new match between the supplier of E3a and the receptor of E3b, and so on.

3. The energy savings that could be reached by the proposed modifications. In this case, the bridge could save up to 217 kW.

No precise indication on where to place existing HXs and new HXs was provided. As a design principle, it was judged that in order to propose a cost-effective design it was important to achieve energy savings close to the calculated targets with a low number of modifications to the existing HEN. This meant to use the existing heat exchange area to the maximum possible extent and invest in a low number of new HXs of large duty. It was assumed that a heat exchanger can be re-used as long as its UA-value is constant and the temperatures and flow rates of the fluids involved do not vary to an extent that the overall heat transfer coefficient would significantly change compared to the existing situation. The resulting topology is shown in Fig. 11. The match C1-E3a was realised by relocating HX E3a downstream on the same stream after the mixing point in the IHR loop, while E3a-E3b was realised by using HX E3b. This was decided based on process requirements: in fact, glycol was required for exchanging heat with the receptor of E3b due to the risk of frost formation in winter periods. Hence, it was decided to employ the existing intermediary heat recovery loop (formed by HXs E3a and E3b) to reduce the number of required modifications. To complete the retrofit, a new unit (N1) was employed for realising match E3b-E5a, while HX E5a and E5b were kept in their existing location. All in all, this topology allowed to complete the bridge by relocating one existing HX and investing in one new HX. Finally, it should be noted that this is only one of the possible topologies that...
Table 2
Twenty bridges with highest energy-saving potential sorted in descending order. Grey cells highlight the bridges selected for further investigation.

| Bridge | $\zeta$ [kW] | Risk level | Bridge | $\zeta$ [kW] | Risk level |
|--------|---------------|------------|--------|---------------|------------|
| C1-E1-E5a-E5b-H2 | 288 | 2 | C1-E1-E5b-H2 | 175 | 2 |
| C1-E2-E1-E5a-E5b-H2 | 288 | 4 | C1-E2-E1-E5b-H2 | 175 | 4 |
| C1-E2-E5a-E5b-H2 | 251 | 4 | C1-E3a-E1-E5b-H2 | 175 | 2 |
| C1-E2-E3b-E5a-E5b-H2 | 217 | 4 | C1-E2-E3a-E1-E5b-H2 | 175 | 4 |
| C1-E3a-E2-E1-E5b-H2 | 251 | 2 | C1-E3a-E3b-E1-E5b-H2 | 175 | 2 |
| C1-E2-E5a-E5b-H2 | 217 | 2 | C1-E3a-E5a-E5b-H2 | 160 | 2 |
| C1-E3a-E2-E3b-E5a-E5b-H2 | 217 | 1 | C1-E2-E3a-E5a-E5b-H2 | 160 | 4 |
| C1-E2-E1-E3b-E5a-E5b-H2 | 175 | 4 | C1-E3a-E5a-E1-E5b-H2 | 160 | 2 |

Fig. 10. Grid diagram displaying Bridge C1-E3a-E3b-E5a-E5b-H2.

could be formulated for creating the bridge. There is no guarantee that the chosen topology is the best in terms of both profitability and risk. For this reason, experience is fundamental to achieve a satisfactory design.

5.6. Phase 8: Design proposals

At this stage, the final topology for all the seven design solutions was fixed, but the design parameters were not defined (indicated with green question marks in Fig. 11 for the analysed example). The design was then finalised by performing a techno-economic analysis and fine-tuning the design parameters to maximise the Internal Rate of Return (IRR). This Non-Linear Programming (NLP) problem (Zhu and Asante, 1999) was solved manually. The final design for the solution corresponding to Bridge C1-E3a-E3b-E5a-E5b-H2 is presented in Fig. 12 and in Appendix D for the remaining ones. Although the solution of this NLP problem might seem trivial, especially if computer-based optimisation tools are available, in practice it strongly relied on engineering judgement. Comparing Figs. 11 and 12, it can be noted that more parameters were modified in the latter (the final design) and many more HXs faced modifications in their operating conditions than what was prospected by the evaluated bridge. For example, HX E3b provided less heat to Stream PS8, PS9, PS10, and PS11 compared to the existing plant. As a consequence, heaters H3, H4, H5 and H6 faced an increased duty. Relying on process expertise, it was judged that the existing heaters could withstand the increased load and no new units were necessary for performing the task. However, it would have been difficult to consider this circumstance a priori without employing good engineering judgement. Finally, it should be noted that by solving this NLP problem and modifying the operating conditions of the HEN, the final design does not solely include bridge modifications, even though it was inspired by a bridge. In fact, bridges are “directions” of modifications necessary for reducing the energy consumption of the system and do not include variations of the operating conditions of existing units. However, a cost-effective design involves also other types of modifications, aiming at a reduction of investment cost or improved operability of the plant rather than energy saving. These ultimately require engineering judgement to be identified. In the studied solution, cost considerations led to variations in the operating conditions of heat exchangers and to an increased load of some heaters.

A summary of the main characteristics of the seven final designs is presented in Fig. 13. They are sorted in order of decreasing preference from a to g based on considerations guided by good engineering judgement. In particular, solution a (derived from Bridge C1-E3a-E3b-E5a-E5b-E2) was considered to be the best one despite the fact that it did not result in the best IRR (as solution f) or the best revenues (as solution b). This evaluation was based on risk and return considerations: solution a had the lowest risk level (level 1) meaning that all the proposed matches were already present in the existing plant. Moreover, it displayed a high IRR (34%) and revenues (54000 €/y) deriving from saving 219 kW of heating utility (50% of the energy-saving potential). In particular, the revenues deriving from the utility
savings were only 9000 €/y lower than the solution with maximum IRR (solution f), which in return was characterised by the highest risk level (level 4). 9000 €/y of extra savings was not considered a reasonable return for accepting the higher risk. Solution b was placed in second place even though it displayed a low IRR, because it granted the highest revenues with a moderate risk level (level 2). Solution c was ranked third despite having higher IRR than solution a and b because of its high risk (level 4), which was deemed too high for the obtained benefits. The others were of lower interest and were ranked firstly based on risk level and secondly on IRR. At last, it should be noted that solution c was preferred to solution f even though it resulted in a slightly lower IRR and had the same risk level. This was due to the lower number of HX involved in modifications (3 instead of 4), considering that a higher number of modifications would in practice result in higher costs of installation not accounted for in the techno-economic costing model employed.

6. Discussion

6.1. Critical analysis of the bridge framework application

The bridge framework was applied for the first time to an existing process plant. It was shown to be able to provide a rigorous structure for performing the analytical and design phases of the process retrofit project. The insight supplied by the tools composing the method were of high value for performing the numerous open-ended decision-making activities relying on engineering judgement. The following presents a critical step-by-step analysis of the major merits and criticality of the bridge framework experienced during the real-case application.

6.1.1. Phase 1: Problem definition

This phase is crucial for the project and completely relies on good engineering judgement for defining POs and HEN. A too detailed characterisation would result in long time for extracting the relevant data and large amount of data that could generate confusion. Conversely, a too rough definition would not provide sufficient insight towards the solution (El-Halwagi, 2017). No method is available to date that can provide rigorous guidance in this phase and the bridge framework is not different in this. As a result, ad-hoc decisions based on experience are required based on the specific case study.

6.1.2. Phase 3: Process operation modification

The ETD and the superimposed ETCs provide insight on the standalone and reciprocal role of POs in determining the site-wide energy consumption. As such, they proved to be effectively able to provide guidance in the perilous task of modifying POs. This constitutes a great improvement to the available tools in the field of process integration. These include the “plus/minus” principle, which makes use of the composite curves, or the “appropriate placement” concept, making use of the GCC (Kemp, 2007). However, these tools represent a composite effect of all the POs and intuition is required to identify which specific PO should be modified for producing a positive effect. The ETD represents an improvement, as it describes the contribution of the individual POs by means of their ETC, effectively describing the region below the GCC. However, despite being a very clear graphical representation, it can only suggest directions to investigate rather than specific parameters to modify. This activity still requires high process expertise.

6.1.3. Phase 5: Risk level definition

The connection table and risk definition provided a solid aid for the selection of the most beneficial retrofit design. In particular, it allowed for automatically calculating risk-related metrics for bridges, which proved to be essential in the open-ended decision-making activities on the following phases. Moreover, this step obliged to rationally ponder the risk related to each possible connection with a common scale. This activity would otherwise be omitted, and risk-related considerations would be performed later on in the project purely based on perception of risk. This phase strongly relies on good engineering judgement, as the risk definition is qualitative, even though framed in a risk scale.
As such, the experience of the analyst is paramount and can highly influence the results. Moreover, depending on the size of the process this task can require significant time for evaluating all the possible 2-ways connections of process streams. As an example, it would not be uncommon to study a plant composed of, say, 30 hot streams and 30 cold streams. This would result in the necessity to estimate 900 risk levels.

6.1.4. Phase 6: Analysis of the solution space

The concept of bridge and the automatic procedure for listing them allowed a detailed and rigorous analysis of the solution space, which was not possible with other user-driven process integration tools (such as the traditional pinch analysis Tjoe and Linnhoff, 1986). This provided an important aid to engineering judgement, indicating the most promising directions of modifications of the heat exchanger network. Nonetheless, the application of this procedure showed some critical points that could be strengthened in the future for increasing the utility of the analytical method:

1. **High number of bridges.** The adopted method lists all the thermodynamically feasible prime bridges made of up to 5 matches, resulting in 6699 possibilities in this plant. An even higher number is expected for more complex networks. Engineering judgement is necessary to reduce the number of “promising” bridges to consider for formulating a final design, which might prove difficult. Other options for reducing the considered prime bridges on beforehand based on heuristics might be considered. For instance, for each couple cooler/heater, only a few bridges with high energy saving potential and low risk could be displayed. In this way, the most promising “directions” of modification could be displayed in a short list, providing additional insight to the engineering judgement. As no systematic procedure was proposed to date for accomplishing this task, this could be part of future work in the field.

2. **Evaluation of intermediate heat recovery loops.** The adopted procedure considered all the existing heat exchangers when listing bridges, both between process streams and encompassing streams of the intermediate recovery loop. Although this allows listing in detail all the existing heat exchangers involved in a bridge, other options might be considered. One possibility is to avoid considering suppliers and receptors of heat exchangers.
6.1.5. Phase 7: Topology selection

The results clarified that generally the final retrofit solution is not solely confined to bridge modifications. Nonetheless, bridges provide clear directions for formulating modified topologies. In particular, they focus the attention on reduced regions of the HEN, greatly aiding in the open-ended decision-making design activity. Design decisions are completely demanded to the analyst, who is allowed making full use of their process expertise. All in all, the results showed that good engineering judgement is fundamental for designing cost-effective retrofit topologies.

6.1.6. Phase 8: Design proposals

The activity of refining the topology and sorting the identified solutions is completely based on good engineering judgement and the bridge framework does not provide additional guidance in this phase. However, based on the previous steps, it allows evaluating a selection of promising designs among which the most beneficial solutions can be identified based on risk and return considerations. Depending on the previous decisions, the level of detail in the analysis of the solution space varies and the time required for completing this activity and the rigorousness of the results vary accordingly. An analysis of the trade-off between rigorousness and expedition when studying non-energy-intensive industrial processes is proposed by Bergamini et al. (2020c) as a follow-up of this work. Finally, the topology selection step (Phase 7) results in reducing the design problem from a MINLP to an NLP problem, potentially allowing for the usage of relatively fast automated software. However, the obtained results suggested that it would be challenging to convey on beforehand to a software all the design constraints employed when good engineering judgement is used and that manual refinement could achieve acceptable results.

6.2. Significance of the modifications to the ETD

The proposed modification to the ETD, distinguishing between avoidable and unavoidable heat degradation in the HEN, completely links the theory of ETD and PTA (as illustrated in Section 4) and sheds light upon the real meaning of the potentially ambiguous terminology commonly used in pinch analysis. In particular, the introduction of fictitious temperature scales (e.g. the concept of “shifted temperature” Kemp, 2007, or “modified temperature” Klemeš, 2013) employed in the PTA might result in confusion regarding the actual physical phenomenon represented in the GCC. The PTA dictates that \( \Delta T_{min-cont,i} \) is added to supply and target temperature of cold stream \( i \) and that \( \Delta T_{min-cont,k} \) is subtracted from supply and target temperature of hot stream \( k \) for all the identified streams. This operation is commonly termed “shifting” probably due to the related geometric transformation happening when streams are represented in a \( T-Q \) diagram: as a result of this operation, the streams are shifted upwards or downwards in the diagram. However, this historically lead to introducing a fictitious temperature scale, naming the temperature of this graph “shifted temperature” or “modified temperature”. In this way, a clear

![Fig. 13. Summary of the main characteristics of the proposed retrofit designs. Black bars indicate the range of uncertainty.](image-url)
explanation of the physical meaning of this operation (and related graphical representations) was never provided, and instead a potentially confusing terminology was introduced. Temperature is a physical property of matter and as such it cannot be shifted, as it does not relate to the concept of “position”. Moreover, it cannot be “modified” by mathematical operations, but changes occur only if thermodynamic transformations take place. Hence, in relation to the PTA, which purely constitutes a mathematical procedure, the represented temperatures have an absolute meaning and it might be confusing to define the GCC, which is the graphical representation of the PTA, as “a plot of the net heat flow against the shifted (interval) temperature” (Kemp, 2007), as traditionally done. The distinction between avoidable and unavoidable heat degradation in the HEN introduced in Section 4, also familiar in the field of advanced exergy analysis (Tsatsaronis, 1999), provided an explanation of this operation: the addition or subtraction of \( \Delta T_{\text{min}} \) to process streams identifies the temperature of their limit heat transfer interface. As such, the PTA (and the GCC) describes the cumulative enthalpy flow rate deficit (if above the global pinch point) or surplus (if below the global pinch point) of the process operations as function of temperature of the limit heat transfer interface. This is the extreme temperature at which the process could receive and release heat to the HEN without incurring in avoidable thermal exergy losses. Accordingly, the balanced GCC describes the avoidable flow rate of cascaded heat through the heat exchanger network (composed of heaters, coolers and process/process HXs) as function of temperature of the limit heat transfer interface.

6.3. Other proposed tools

Besides applying the bridge framework on an actually operating plant, discussing its merits and caveats and clarifying a modified ETD, two additional tools were proposed: (i) a modified version of the well-known grid diagram and (ii) a systematic procedure for calculating the potential energy savings of bridges. The grid diagram in Fig. 2 (and all the grid diagrams displayed in the paper) present some important modifications: (i) streams are displayed vertically instead of horizontally and the hot streams are positioned to the right of the cold streams, (ii) five regions clearly distinguish between utilities, process streams and intermediary heat recovery loops, (iii) inlet and outlet temperatures are displayed for all the suppliers and receptors of heat exchangers and (iv) heat exchangers are listed dividing between coolers (at the bottom), process/process HXs (in the middle) and heaters (at the top). The aim of this proposed version of the grid diagram is to clearly represent the heat exchanger network with its most important characteristics and to follow the same convention of the ETD regarding the direction of heat transfer. In the grid diagram heat is cascaded from right to left as in the ETD. This feature, combined to the aforementioned distinction of regions in the graph, aims at easing the identification of the bridge modifications in the graph, supporting engineering judgement in the design procedure. Finally, the proposed method for calculating the energy-saving potential of the bridges is systematic, easy to apply and can be automated. Moreover, based on the problem table algorithm it can be understood by pinch practitioners with no need to learn additional tools. This might lower the knowledge barrier for using the bridge framework in the common process integration practice.

7. Conclusion

The Bridge framework was applied for retrofitting an actually operating milk powder production plant and a critical discussion of its merits and limitations was performed. Moreover, a clarification of the Energy Transfer Diagram (ETD) was provided, describing the avoidable and unavoidable heat degradation through the heat exchanger network. Finally, a modified version of the grid diagram following the conventions of the energy transfer diagram and a novel method for calculating the energy-saving potential of bridge modifications were introduced. The results allowed drawing the following conclusion:

• The bridge framework allows rigorously performing the retrofit of industrial plants with a process integration perspective. Its tools guide the analyst in retrofitting both the process operations and the heat exchanger network, allowing proposing multiple designs to be evaluated based on economic and risk-related factors. Seven retrofit designs were proposed for the evaluated case study and the best one was identified, achieving a 54000 €/y of cost savings deriving from a reduction of heating utility equal to 50% of the total theoretical potential, with a nominal internal rate of return (IRR) of 34% and a minimum risk level. An IRR of 52% could be achieved in other designs, but they were not recommended as the economic benefits did not justify the higher process risk level they introduced.

• The bridge framework successfully assists the open-ended decision-making procedure by providing valuable insight. Nonetheless, engineering judgement is essential for formulating beneficial solutions, both economically feasible and resulting in a reasonable process risk.

• The proposed modification to the ETD provides a complete link between the ETD and pinch analysis tools. The concept of “limit heat transfer interface” was introduced, identifying the temperature limit at which heat could be provided to the process (in case of heat deficit) or removed from the process (in case of excess heat) by means of the heat exchanger network without causing unavoidable destruction of thermal exergy. This allows describing the meaning of the “grand composite curve” from a thermodynamic viewpoint, avoiding the introduction of fictitious temperature scales (e.g. “Shifted temperature”).

All in all, the bridge framework proved to be a powerful tool in analysing the energy use and degradation throughout existing industrial plants and proposing retrofit solutions able to reduce energy demand and operating costs in an economically feasible way. As such, this tool can provide great help in transitioning to cleaner industrial production processes, requiring lower amounts of energy and contextually reducing energy-related emissions.

CRediT authorship contribution statement

Riccardo Bergamini: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing, Visualization . Alireza Moussavi: Conceptualization, Methodology, Validation . Hamid Reza Shahhosseini: Conceptualization. Tuong-Van Nguyen: Supervision, Validation. Lorenzo Bellemo: Resources . Brian Elmegaard: Project administration, Funding acquisition, Validation. Paul Stuart: Project administration, Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Techno-economic analysis

The techno-economic analysis was performed by considering the investment costs and the reduction in costs related to energy purchase deriving from the HEN retrofit.
A.1. Investment cost

The cost model employed considered only the Fixed Capital Investment (FCI), while neglecting any Working Capital Investment (El-Halwagi, 2017). The FCI was estimated scaling the delivered cost of equipments by the Hand factor (Hand, 1958):

\[
\text{FCI} = \sum_{i=1}^{N} f_i C_i \tag{A.1}
\]

where \(N\) is the number of new components, \(f_i\) is the Hand factor for component \(i\) and \(C_i\) is the delivered cost of component \(i\). The proposed solutions were limited to investment in new heat exchangers, for which the Hand factor was assumed to be \(f_i = 3.5\). The proposed HXs were of two types: (i) liquid/gas fin and tube HX and (ii) liquid/liquid plate HX. Two different correlations were used for calculating the respective delivered costs:

- **Fin and tube HX.** The delivered cost was calculated based on 10 quotes provided by a HX supplier for this specific case study. The quotes included the cost of the heat exchanger, weld joints, flanges, legs and delivery. The costs of the 10 units were fitted as function of the UA-value of the HXs resulting in the following correlation displaying a coefficient of determination \(R^2 = 0.94\). The cost calculated is in €:
  \[
  C_i = 16810 - 14660 \log_{10} \frac{\text{UA}_i}{10} + 21550 \log_{10}^2 \frac{\text{UA}_i}{10} \tag{A.2}
  \]

- **Plate HX.** The delivered cost was calculated based on one quote provided by a HX supplier, which was scaled with a power law based on the ratio of UA-values (El-Halwagi, 2017). The cost calculated is in €:
  \[
  C_i = 227.97 \left( \frac{\text{UA}_i}{0.239} \right)^{0.68} \tag{A.3}
  \]

Finally, as the cost model used belongs to preliminary feasibility estimations, it was estimated that such estimations had an uncertainty of \(+50\%/-30\%\) (El-Halwagi, 2017).

A.2. Revenues

The revenues of the retrofit project derived from the avoided costs of energy purchase due to the reduction of energy consumption. The purchase price of hot utility was estimated to be \(c_{\text{HU}} = 0.0335\) € per kWh of heat delivered to the process. This accounted for the purchased price of natural gas and conversion and distribution losses in the plant and was assumed to remain constant in the lifetime of the plant. The purchased price of electricity was not considered as no savings of electricity were accounted for in the proposed solutions. The generated revenues \(R\) were calculated as:

\[
R = e_{\text{savings}} \cdot f_{\text{operation}} \cdot c_{\text{HU}} \tag{A.4}
\]

where \(e_{\text{savings}}\) is the heat flow saved and \(f_{\text{operation}}\) is the yearly hours of operation of the plant, which was assumed to be 7350 h/y.

Appendix B. Calculation of energy-saving potential of bridges: numerical example

This section presents an applicable example of the novel method for calculating the energy-saving potential of a bridge presented in Section 3. Let us consider the heat exchanger network in Fig. B.1, composed of one cooler (C1), one heater (H1) and one process/process heat exchanger (E1). The existing network requires 80 kW of hot utility and 30 kW of cold utility. Let us estimate the energy-saving potential of the bridge C1-E1-H1. The procedure starts by considering the supplier of C1 (stream PS2) and the receptor of C1 (streams PD1) and calculating the problem table as displayed in Fig. B.2a. After removing the pocket above the pinch point (green area in Fig. B.2b) the remaining heat flow rate deficit is calculated (red segment in Fig. B.2b). The heat flow rate “freed” from the supplier of E1 is calculated next. The problem table is calculated considering the remaining heat flow rate deficit resulting from the previous step and the supplier of E1 (stream PS1), as displayed in Fig. B.2c. After removing the pocket below the pinch, the remaining heat flow rate surplus is evaluated (red segment in Fig. B.2d). Finally, the maximum heat that can be released to the receptor of H1 is calculated. The problem table is computed by considering the remaining heat flow rate surplus and the receptor of H1 (stream PD2), as displayed in Fig. B.2e. The minimum hot utility requirement results to be $H_{\text{min}}=55$ kW. Knowing that the existing network requires 80 kW of hot utility, this means that the energy-saving potential of the bridge is $80 - 55 = 25$ kW.

Appendix C. Composite curves

Fig. C.1 shows a modified representation of the balanced composite curves, displaying the heat cascaded through the HEN in between the curves and distinguishing between avoidable (coloured region) and unavoidable (grey region) heat degradation in the HEN. As highlighted in the figure, it is possible to graphically identify the actual hot and cold utility consumption, as well as the pinch point and potential energy savings when individual minimum temperature difference contributions higher than zero are assumed for the process streams. This completes the link between Bridge analysis and pinch analysis.

Appendix D. Retrofit design proposals

This section collect the design proposals for the six remaining retrofit solutions. The corresponding grid diagrams considering the portion of the HEN subject to modifications are presented in the Figs. D.1–D.6.
Fig. B.2. Numerical example of calculation of the energy-saving potential of a bridge: Problem table, grand composite curve and remaining surplus and deficit heat.
Fig. C.1. Balanced Composite Curves displaying heat cascaded through the HEN.
Fig. D.1. Grid diagram displaying the final design b inspired by Bridge C1-E1-E5a-E5b-H2. Only the portion of the plant involved in modifications is displayed.
Fig. D.2. Grid diagram displaying the final design c inspired by Bridge C1-E2-E5a-E5b-H2. Only the portion of the plant involved in modifications is displayed.
Fig. D.3. Grid diagram displaying the final design inspired by Bridge C1-E3a-E3-E5a-E5b-H2. Only the portion of the plant involved in modifications is displayed.
Fig. D.4. Grid diagram displaying the final design inspired by Bridge C1-E1-E3a-E5a-E5b-H2. Only the portion of the plant involved in modifications is displayed.
Fig. D.5. Grid diagram displaying the final design $f$ inspired by Bridge C1-E1-E2-E5a-E5b-H2. Only the portion of the plant involved in modifications is displayed.
Fig. D.6. Grid diagram displaying the final design $g$ inspired by Bridge C1-E2-E1-E5a-E5b-H2. Only the portion of the plant involved in modifications is displayed.
