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Design Framework for Plant-Wide Energy Analysis Using the Bridge Method

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Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*

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Cette thèse intitulée :

Design Framework for Plant-Wide Energy Analysis Using the Bridge Method

présentée par **Seyyed Alireza MOUSSAVI KARIMI**

en vue de l'obtention du diplôme de *Philosophiæ Doctor*

a été dûment acceptée par le jury d'examen constitué de :

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DEDICATION

To my parents, who installed in me the virtues of perseverance and commitment

and relentlessly encourage me to strive for excellence.

To my beloved wife, whose support, enthusiasm and tolerance enabled me to complete this work.

You are the light of my life.

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RÉSUMÉ

Les changements majeurs et les modernisations des procédés industriels sont des opportunités importantes pour améliorer l'efficacité énergétique à l'échelle de l'usine, tout en augmentant la rentabilité économique en accédant à de nouveaux marchés grâce à des stratégies de bioraffinage. Ces dernières années, le secteur forestier s'est concentré sur la mise en œuvre de la cogénération basée sur la biomasse, et cela continuera d'être important à mesure que le réchauffement climatique s'installera. D'autre part, surtout à la lumière de la baisse de la demande de produits dans plusieurs segments importants du secteur forestier et de l'importance des impacts des changements climatiques, l'industrie des pâtes et papiers envisage maintenant de faire la transition vers le bioraffinage forestier : de nombreuses entreprises font les premiers pas en développant des technologies pré-commerciales pour produire de nouveaux bioproduits.

Les principales raisons pour lesquelles le secteur forestier ne s’est pas tourné plus rapidement vers la bioéconomie sont les risques technologiques et de marché élevés liés à cette transformation, souvent associés à un faible retour sur investissement (ROI). En même temps, de nombreuses stratégies de bioéconomie ont d'importants besoins en énergie, tant dans les procédés centraux des usines que dans les opérations de séparation et de purification de la stratégie de bioraffinage proposée. Lors de la mise en œuvre de la bioraffinerie, le reprofilage du système énergétique peut avoir un retour sur investissement intéressant qui peut également se traduire en des avantages pour les processus opérationnels de base s'il est bien conçu de façon proactive.

Pour aborder les questions complexes de la gestion de l'énergie dans les procédés existants et nouveaux, une méthodologie pratique et systématique qui tient compte des situations de modernisation, de l'intégration à l'échelle du site et des systèmes d’utilités serait d'un grand avantage pour l'industrie. L'intégration énergétique classique a été adoptée dans une bien plus grande mesure dans les industries pétrochimique et chimique que dans l'industrie des pâtes et papiers, où son succès a été relativement limité, en grande partie parce que d'autres investissements dans les procédés produisent un rendement supérieur à celui des projets d'économie d'énergie incrémentaux.

Récemment, une nouvelle technique d'analyse énergétique appelée la méthode Bridge a été mise au point dans nos laboratoires de Polytechnique-Montréal afin d'identifier les modifications visant

à réduire la consommation d'énergie, en particulier son application au problème de la modernisation des usines en bioraffineries. Le principe fondamental derrière la méthode Bridge est que le flux de chaleur en cascade à travers les échangeurs de chaleur existants et le procédé dans la plage de températures entre les utilités chaudes et froides devrait être réduit pour minimiser la consommation d'énergie externe. Basée sur les lois fondamentales de la thermodynamique, la méthode Bridge permet à l'utilisateur de caractériser l'usine, y compris le procédé principal, et peut donc aborder des questions importantes telles que l'intégration énergétique à l'échelle du site, les opérations de mélange non isotherme et les modifications du procédé.

L'objectif de cette thèse est de développer un cadre de prise de décision séquentielle pour l'utilisation de la Méthode Bridge. Le cadre comprend une approche décisionnelle systématique et interactive avec l'utilisateur, dans laquelle les calculs de conception sont effectués et les décisions sont prises à différentes étapes du processus de conception, ce qui mène à un ensemble de recommandations pour l'optimisation énergétique de l'usine. Une revue critique de la littérature des approches classiques d'intégration énergétique a été effectuée, en plus d'expliciter le concept de la méthode Bridge et la nécessité d'un cadre décisionnel pour rendre cette méthode utile dans la pratique.

Cette méthode tient compte explicitement de la série séquentielle de décisions de conception, y compris (1) la sélection des différences de température minimum pour le transfert de chaleur entre courants du procédé, (2) des directives pour déterminer les modifications possibles du procédé et (3) la détermination des modifications au réseau d'échangeurs de chaleur (HEN). À chaque étape de la prise de décision, des données propres à chaque cas sont ajoutées au cadre au moyen d'une interface utilisateur graphique (GUI). Le système de gestion à l'intérieur du cadre est responsable de la gestion de la communication entre l'interface graphique, la base de modèles (mathématiques, comptabilité, etc.), la base de connaissances, la base de données et les moteurs de calcul. À chaque étape, les résultats sont représentés sur le tableau de bord pour aider les utilisateurs à prendre une décision et à renvoyer cette décision au système.

Une fois le cadre opérationnel identifié, des occasions se présentent d'utiliser la méthode Bridge mise en œuvre dans un algorithme informatique. Par exemple, pour trouver les modifications économiquement viables, un modèle de coût a été mis au point pour calculer le rendement économique de chaque modification du procédé ou du réseau d'échangeurs de chaleur afin de permettre une meilleure prise de décision fondée sur les coûts/rendements.

La méthode a été utilisée dans plusieurs études de cas, y compris la modernisation du réseau complexe d'échangeurs de chaleur d'une usine modèle de pâte scandinave ("*Future Resource-Adapted Pulp Mill*" ou FRAM). L'usine FRAM est à la fine pointe de la technologie du point de vue énergétique et n'a pas besoin de combustible fossile pour répondre à la demande en vapeur du procédé.

ABSTRACT

Major changes and modernizations of industrial processes are important opportunities for improving plant-wide energy efficiency, while at the same time increasing economic profitability by tapping into new markets with biorefinery strategies. In recent years, the focus of the forestry sector has been on implementing biomass-based cogeneration, and this will continue to be important as global warming increasingly takes hold. On the other hand, especially in light of the decrease in product demand in several important segments of the forestry sector and increasing importance of climate change, the pulp and paper industry is now considering transformation into forest biorefineries to produce biomass-based products, and many companies are taking the first steps by developing pre-commercial scale technologies to produce new bioproducts.

One of the key reasons why the forestry sector has not accelerated more quickly towards the bioeconomy is due to the high level of technology and market risk, often coupled with a modest return on investment (ROI) relative to the risks involved. At the same time, many bioeconomy strategies have significant energy requirements - in the core processes as well as in separation and purification operations of the proposed biorefinery strategy. During biorefinery implementation, there can be an attractive return on investment resulting from energy system reprofiling that can result in benefits also to the core business processes if proactively well-designed.

To address the complex issues of energy management in existing and new processes, a practical and systematic methodology that considers retrofit situations, site-wide integration, and utility systems would be of great benefit to the industry. Classical heat integration has been adopted to a far greater extent in the petrochemical and chemical industries than it has in the pulp and paper industry, where relatively speaking, it has had limited success in good part because other process investments yield a higher return than incremental energy-saving projects.

Recently, a novel energy analysis technique called the Bridge Method was developed in our labs at Polytechnique-Montréal to identify modifications for energy use reduction, targeting especially its applicability for biorefinery retrofit. The fundamental driver behind the Bridge Method is that the flowrate of cascaded heat through the existing heat exchangers and process operations across the temperature range between the hot and cold utilities should be decreased to reduce the external energy usage. Based on the fundamental laws of thermodynamics, the Bridge Method allows the

user to characterize the process system including the process operations and therefore, can address important issues such as site-wide energy integration, non-isothermal mixing and process operation modifications.

The objective of this thesis is to develop a sequential design decision-making framework for using the Bridge Method. The framework comprises a systematic and user-interactive decision-making approach, where design calculations are made, and decisions are taken at different points in the design process - leading to a set of recommendations for plant-wide energy optimization. A critical review of the classical heat integration approaches in the literature has been performed, along with elucidating the concept of the Bridge Method and the need for a decision-making framework to make it useful in practice.

The framework considers explicitly the sequential series of design decisions including (1) selection of stream-specific temperature differences needed for heat transfer, (2) guidance for identifying potential process operation modifications, and (3) identification of Heat Exchange Network (HEN) modifications. At each step of decision-making, case-specific data are added to the framework through a graphical user interface (GUI). The management system inside the framework is responsible for managing the communication between GUI, model base, knowledge base, database, and calculation engines. At each sequence, the results are represented on the dashboard to help users to make a decision, and send that decision back to the system.

Once the framework is operational, opportunities present themselves to employ the unique capability of the Bridge Method implemented into a computer algorithm. For example, to find the economically viable Bridge modifications, a cost model has been developed to calculate the economic return for each process operation or heat exchanger network modification considering the level of risk – exploiting the framework to enable better decision-making based on cost/return data.

The framework is demonstrated in several case studies, including retrofitting the complex heat exchanger network of the model of a Scandinavian pulp mill (the “Future Resource-Adapted Pulp Mill” or FRAM). The FRAM mill is state-of-the-art from an energy perspective and does not require auxiliary fuel to cover the total heat demand. The data used in the framework were extracted from the simulation, and the modifications identified based on the Bridge Method and framework – simulating a real implementation process in the framework to the extent practicable.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACC	Advanced Composite Curves
ACLC	Actual Cooling Load Curve
ACLC	Actual Cooling Load Curve
AHLC	Actual Heat Load Curve
CCC	Cold Composite Curve
CUC	Cold Utility Curve
$\dot{E}$	Flowrate of cascaded heat
EEP	Energy Efficiency Program
ES	Energy Specialist
ECLC	Extreme Cooling Load Curve
EHLC	Extreme Heat Load Curve
ETC	Energy Transfer Curve
ETD	Energy Transfer Diagram
GCC	Grand Composite Curve
$\dot{H}$	Enthalpy rate
$\dot{H_{in}}$	Enthalpy rate of inlet
$\dot{H_{out}}$	Enthalpy rate of outlet
HELD	Heat Exchanger Load Diagram

HEN	Heat Exchanger Network
HUC	Hot Utility Curve
HCC	Hot Composite Curve
PES	Plant Energy Superintendent
PO	Process operations
PPE	Plant Process Engineer
P. Si.	Process sink
P. So.	Process source
T	Temperature
T_a	Ambient temperature
$T_{h_{Source}}$	Hot end temperature of the process source stream
$T_{c_{Source}}$	Cold end temperature of the process source stream
$T_{h_{Sink}}$	Hot end temperature of the process sink stream
$T_{c_{Sink}}$	Cold end temperature of the process sink stream
TCLC	Theoretical Cooling Load Curve
THLC	Theoretical Heat Load Curve

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CHAPTER 1 INTRODUCTION

1.1 Problem statement

Today, the industry sector has been accounted for nearly 40% of total final energy use. According to the International Energy Agency (IEA), the industrial sector will soon overtake transportation to become the second-largest greenhouse gas (GHG) emitter after power generation [1]. Moreover, the IEA has identified radical GHG emissions reduction by the industry as an especially difficult and complex challenge due to a number of factors including the unique energy needs of different process sectors, energy use reduction constraints with cogeneration, and the essential requirement for production sites to remain competitive [2]. The energy use reduction projects have been difficult to justify in industrial plants due especially to incremental savings resulting from small capital projects, and competition resulting from productivity-oriented larger projects such as capacity increase. However, there is a substantial opportunity for radical GHG emissions reduction when considering major process changes and energy use reduction simultaneously. Here, the systematic site-wide energy analysis and re-optimization of the energy profile of a processing plant can result in a significant reduction in GHG emissions, an improvement in the project profitability, and an improvement in a long-term competitive position.

Recently, a novel energy analysis approach called the “Bridge Method” has been developed in our research group [3]. It employs the Energy Transfer Diagram (ETD), based on the first and second laws of thermodynamics, which is a representation of transferred heat through both process operations and the Heat Exchanger Network (HEN) as a function of temperature [4]. Reducing the hot utility consumption can be done by decreasing the flow rate of transferred heat in the temperature range between the hot utility and the ambient using Bridge modifications. A Bridge is a set of matches connecting the source of a cooler to the sink of a heater [5].

Bridge Method is a promising approach to identify energy-saving projects; however, it has never been applied in practice before. To implement this method, it needs to be integrated into a decision-making framework, that considers from the basic industrial process energy audit, through to the final recommendation of an economically-sound energy program. The framework can benefit from both design calculations and human decisions to assess energy use reduction opportunities considering design issues to identify a practical set of recommendations. Developing such an approach was the key motivation in this thesis.

1.2 Objectives

The main objective of this research is defined as follow:

- To develop and demonstrate a practical sequential decision-making framework based on the Bridge Method for the identification of plant-wide energy-saving opportunities for industrial processes.

The sub-objectives of this project are as follows:

- Specific Objective 1: To use the principals of the Bridge Method to quantify energy degradation across (1) process operations as well as (2) the heat exchange network, and identify how this information can be used to identify plant-wide energy use reduction opportunities.
- Specific Objective 2: To critically analyze the Bridge Methodology and identify (1) steps that can be addressed using a computer algorithm as well as (2) steps which are open-ended and best addressed using good engineering judgment.
- Specific Objective 3: To apply the core elements Bridge Method to the case of a complex industrial process, and demonstrate the core elements of the framework including both the Energy Transfer Diagram as well as design aspects.

1.3 Thesis organization

This thesis includes six chapters. In Chapter 2, the pertinent literature is critically reviewed to recognize the holes in the body of knowledge. Chapter 3 represents the research methodology and activities that have been taken during this project to achieve the objectives. At the end of this chapter, the case studies that are used to apply the methodology are briefly explained. Chapter 4 presents a summary of the articles, the linkage between them and hypotheses, and the demonstration of the developed framework to use the Bridge Method. In chapter 5, the general discussion is given, and in chapter 6, the conclusion and recommendations for future works are presented.

In Appendices A to D the articles that are the outcomes of this research project and were submitted to scientific journals are presented.

CHAPTER 2 LITERATURE REVIEW

Process integration (PI) refers to holistic methodologies for designing and optimizing integrated systems, such as individual processes and total sites for integrating new processes to the industrial clusters which refer to integrating different industrial plants, with emphasis on efficient use of energy to reduce the consumption of energy sources or environmental effects [6]. An industrial plant consists of process operation units, heat exchanger network (HEN), and utility systems. PI approaches seek to reduce the hot utility demand and therefore, reduce the annual energy cost by increasing the internal heat recovery. It implies better heat integration in HEN or modifying the process operations and reduce their total energy demand.

The HEN design and retrofit is an important field in Process Systems Engineering and has been a remarkable research subject over the past decades. Its importance can be imputed to its impact on the total energy cost of an industrial plant.

The HEN design problem considering the economic selection of exchangers size was introduced into the literature by Ten Broeck in 1944. He has developed formulations based on his previous studied [7] to estimate the investment and energy cost of exchangers considering the maintenance, the installation, and the increment of exchanger cost [8]. Until the early 1960s, the proper design of heat exchangers for different applications was considered by researchers [7, 9-13]. In the late 1960s, few methods have been developed aiming to find a way for integrated process design and its application for HEN design such as Branch and Bound synthesis [14-16]. These methods could guide an engineer to design heat exchanger networks, but there were usually far from an optimum network due to lack of energy optimization stage.

Hohmann [17] claimed that a minimum number of heat exchangers could be found for any system if parallel stream splitting is used. He found that different topologies for networks with the same utility requirements had similar values for $\sum UA$. Thus, for a given total area, networks will be cheaper if this area is concentrated into as few units as possible and the concept of heat recovery was presented by him.

Due to the oil crises in the 1970s, the oil price had risen from 3 dollars per barrel to almost 40 dollars, and studies in the process integration field were increased to find a way to reduce fuel consumption and increase the heat recovery ratio in HENs. In 1978, a similar approach was independently published by a group of Japanese scientists [18] and Linnhoff and Flower at Leeds University [19]. Umeda et al. [18] presented a graphical tool called Composite Heat Availability Line (CHAL), using the concept of heat recovery, minimum approach temperature, and pinch point (figure 2.1). The second team developed a systematic approach using the “problem table” to identify the minimum utility usage and maximum heat recovery [20, 21].

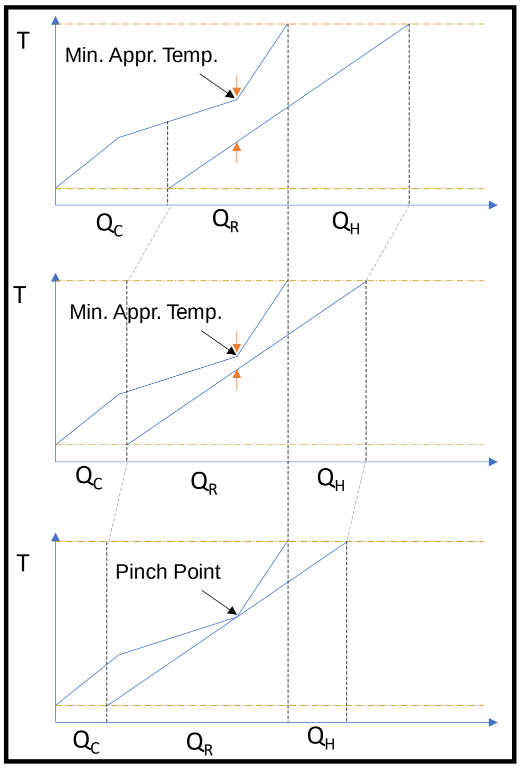

Figure 2-1 Heat availability diagram to consider heat recovery [18].

In the next sections, first, a critical review on the major methods for HEN retrofit including the Bridge Method is presented. Then the practical approaches for process operations integration and the potential of the Bridge Method to overcome limitations in this regard are explained. A separate section is prepared to discuss developed cost models to estimate the profitability of retrofit projects. The next section includes a review of the engineering design decision making process and computer-based systems to facilitate this procedure. The last section represents the success of existing approaches to solve complex industrial problems.

2.1 Heat integration

2.1.1 Heat exchanger network retrofit

The HEN retrofit, in general, can be categorized into three subgroups: mathematical programming-based methods, approaches based on thermodynamics and insight or engineering judgment, and hybrid methods. Mathematical programming-based methods comprise a formulation of a mathematical model followed by its solution using optimization approaches, which also referred to as optimization-based methods. The thermodynamics and insight-based methods or pinch based methods use the Pinch Method tools to solve the problem. The hybrid methods aim to use both the concept of pinch method and programming-based methods, to combine the strengths of both.

2.1.1.1 Mathematical-based approaches

Kobayashi et al. [22] developed a sequential approach for HEN design by using a two-step approach. They divided the HEN into an Interior system representing the process-process heat exchangers and exterior system representing heaters and coolers, and the objective function was fixed costs of the interior and exterior systems and the operating cost of the exterior system. A year later, the same group at the Tokyo Institute of Technology, developed an algorithm to provide an efficient structure for HEN with minimum heat transfer area. They studied the necessary conditions to have an optimal HEN structure [23].

Ciric and Floudas developed a two-stage approach for HEN retrofit [24]. The objective function in this study is to minimize total investment cost, including the cost of new heat exchangers, additional area cost, and piping cost. The first stage comprises five steps which start with selecting a heat recovery approach temperature (HRAT) either randomly from a reasonable range of values or using a targeting procedure for good estimation. In the second step, the minimum utility cost regarding the selected HRAT and the pinch point is selected. In the third step, all possible modifications including purchasing a new heat exchanger, re-piping or rearranging of the existing exchangers will be considered to create a retrofit model by categorizing the possible modifications into six groups and assigned a cost for each group. They defined an objective function, which is the sum of costs in all categories, and they used nonlinear programming to minimize the objective function. The first group is the matches that will not change during the modification and therefore, the piping cost of this category is zero. The second group is the exchangers that need to be relocated, but there is no need for piping, and only the cost of labor for removing the existing heat exchanger and installing the new heat exchanger will be considered. The third group represents a situation in which one of the streams of the existing heat exchanger needs to be replaced by another stream, and the cost of piping for one stream will be considered. In the fourth group, the existing exchanger needs two new streams, and therefore, the cost of piping for two streams must be considered. In the fifth group, a new heat exchanger must be purchased to replace the existing exchanger, and there is no need for re-piping. In the last group, a new heat exchanger needs to be purchased and for both streams, the cost of piping should be considered to form a MILP formulation for the first stage. In the second stage which is an optimization stage, the information from the first stage is used to create a superstructure containing all possible configurations and then a nonlinear programming problem (NLP) is used to optimize the heat exchanger orders with corresponding matches to find a network with minimum investment cost. One year later, Ciric and Floudas used an MINLP approach, which was the combination of two stages in the previous work to optimize the network structure [25].

Yee and Grossmann presented a systematic approach for pre-screening and optimizing of a heat exchanger network in a three-part article, for retrofit [26-28]. The pre-screening stage is employed to identify the economic feasibility of the retrofit for different HRATs to evaluate potential savings for a specific payback period. The selected modifications will send to the optimization stage and will be optimized using an MINLP model to minimize the total cost. In this stage, heat loads, minimum approach temperature, and stream matching are optimized and accounted for the trade-off between total investment and energy saving costs.

Abbas et al. [29] used a set of heuristics to develop a novel approach to solve the retrofit problem using constraint logic programming (CLP). While developing heuristics, they considered few steps such as the heat load shifting from utilities to the process-process heat exchangers, reducing criss-cross exchanges by repiping or stream splitting and adding a new heat exchanger. To calculate the payback period, a cost model was developed considering the cost of moving equipment, piping and new area. The method was tested by solving the case study [24] and the payback period was 25% better than the original study.

Ma et al [30] proposed a two-step approach for heat exchanger network retrofit. This approach optimizes the HEN configuration considering a Constant Approach Temperature (CAT) and the utility costs, structural modification and heat transfer area with constant approach temperature for all exchangers. Therefore, the area calculation was linearized, and the model could be solved as an MILP problem. This approach can determine a suitable HEN structure but not necessarily a feasible one. In the second step, an MINLP model is used to consider the actual approach temperatures.

Ponce-Ortega et al. [31] proposed an MINLP model for solving HEN retrofit problems which consider the interaction between HEN retrofit and process modifications simultaneously. They considered the cost of utility and capital cost of the exchangers and piping. They mentioned that the cost of relocating the existing heat exchanger is usually higher than connecting new streams to the heat exchanger.

Athier et al. [32] developed an approach for automatic identification of optimum retrofit projects considering the purchasing new exchangers, reallocating the existing exchangers, adding exchanging area, and stream splitting. This approach is a two-level procedure and in the first level, they used a simulated annealing (SA) procedure to generate network topology modifications considering the feasibility constraints. An estimation of the repiping cost and investment cost for reassignment and placing new heat exchangers was done at this level. In the second level, the required additional area and new heat exchanger for each modification are optimized by an NLP algorithm. The investment cost was determined by using simplified cost formulations for new and exiting exchangers.

To have a cost-optimal HEN retrofit design, the existing constraints such as forbidden matches, restricted matches, types of streams, pressure drop, and distances should be considered. Some of the constraints can be reflected in the cost model by a quantitative parameter such as piping cost, pumping cost and cost of hot utility. Besides, the qualitative parameters such as safety, operability, and flexibility must be taken into account to identify more realistic solutions [33].

2.1.1.2 Thermodynamics-based approaches and hybrid methods

2.1.1.2.1 Pinch Method

Pinch method for heat exchanger network (HEN) greenfield design was developed in the late 1970s at the University of Leeds and introduced in a two-part paper [20, 21]. The idea behind it was to reduce external energy usage by increasing internal heat recovery. To identify the total heating and cooling demands of a process, a visualization tool was developed using a temperature-enthalpy graph called "composite curves" which includes a hot composite curve to represent cumulative heat source and cold composite curve to represent cumulative heat demand across the process plant [34].

To design a network, the ΔT_{min} between hot and cold composite curves should be known. Choosing low values for ΔT_{min} leads to larger and more costly heat exchangers and therefore, higher investment cost, and choosing high values gives us a higher hot and cold utility requirement, which means higher energy cost. So, a ΔT_{min} which minimizes the total cost should be selected [35].

Tjoe and Linnhoff used the Pinch analysis method to retrofit the heat exchanger networks [36]. They developed a useful numerical approximation to evaluate the minimum hat exchange area for a specific global ΔT_{min} which is shown in equation 1.

$$A_{target} = \sum_i^{intervals} \frac{1}{\Delta T_{LMTD_i}} \left[\sum_j^{streams} \left(\frac{q_j}{h_j} \right) \right]_i \qquad (1)$$

The curve was decomposed into temperature intervals and in the interval I, there were j hot and cold streams with their individual heat load (q_j) and heat transfer coefficient (h_j). The ΔT_{LMTD} for each interval i, decrease with the approach temperature difference, so the exchange surface area is inversely proportional to ΔT_{LMTD} between the curves in each interval.

A variable called area efficiency, α, was defined, which was equal to the ratio of the minimum area required (target) to the existing used area. For a range of ΔT_{min}, the target area and hot utility demand were calculated and presented in a graph with a constant-α curve. The constant-α curve is used as an upper boundary for good retrofit projects and help to discrete the doubtful economic projects area and appropriate projects area. It is shown in figure 2.2, for the existing network the capital cost and the HEN surface area can be identified.

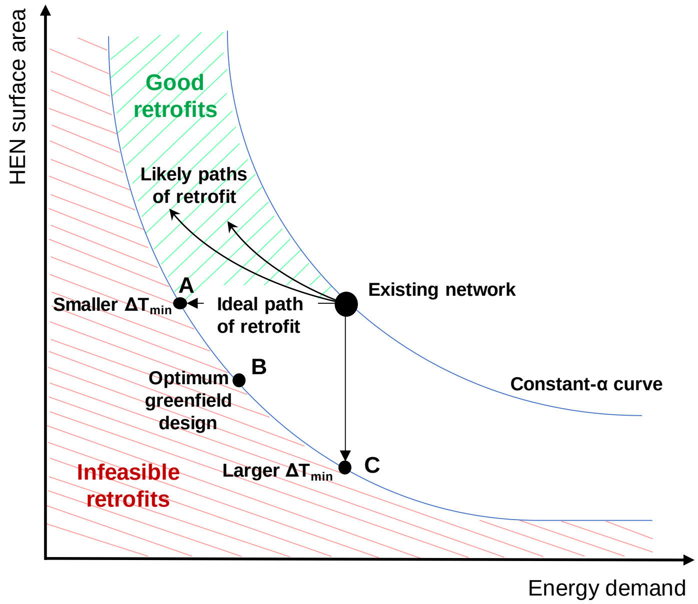

Figure 2-2 Appropriate paths of retrofit [36].

For HEN retrofit, different paths can be taken to reduce the energy demand of the system. First, for a range of ΔT_{min}, the minimum energy demand and required area can be determined using the pinch method. These data form a curve, which is the placement of optimum HEN greenfield design for different minimum temperature differences. The point B is the greenfield design of the existing network using the optimal $\Delta T_{min,}$ but to move toward that design, the existing area should be discarded, and it is not acceptable. The ideal point for retrofit is A by saving as much energy as possible using the existing area. However, in practice, we usually must invest some capital to make changes to an existing network by increasing the area.

They proposed three rules to eliminate the cross-Pinch transfer: eliminate coolers above the Pinch, eliminate heaters below the Pinch, and eliminate the process heat exchange across the Pinch (Figure 2.3).

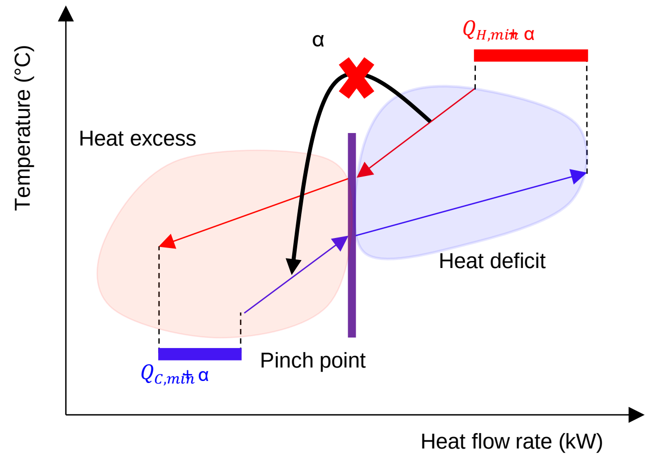

Figure 2-3 Using the heat from process sources above the Pinch point to heat cold stream below the Pinch point, increases the external energy usage.

It means that we are not allowed to transfer heat from a hot stream or a process source with the temperature above the Pinch point to a cold stream or a process sink with the temperature below the Pinch point, because it leads to an increase in external energy usage. After removing the Pinch violations, the heat exchanger network will be modified. This approach allows user interaction and has served as the basis for many studies on HEN retrofitting [37].

2.1.1.2.2 Advanced pinch-based methods

2.1.1.2.2.1 Path analysis and structural targeting

A significant drawback in the pinch analysis is the lack of information on how to rearrange the network after removing violated exchanges. Besides, since the HEN retrofit problems are complicated, many researchers attempted to find new approaches to reduce the complexity of retrofit. Van Reisen et al. developed a decomposition and pre-screening method to divide a large problem into subnetworks and evaluate the economic potential of them [38]. The evaluation of each subnetwork for energy savings and investments is done separately. By comparing the results, the most promising set of subnetworks is selected, and a retrofit design is made, using one of the existing procedures. Subnetworks are parts of the existing HEN that should follow two rules. They must be heat balanced and have at least one cooler and one heater. All possible subnetworks can be generated either by an expert user based on heuristics or by a computer algorithm. For each subnetwork, targeting procedure [36] should be used to create the investment-energy saving curve based on the constant-α concept. By comparing the curves for all subnetworks, projects with greater potential for energy savings can be identified and regardless of the remaining HEN, retrofit projects for each subnetwork can be implemented. The steps of the approach are summarized in figure 2.4.

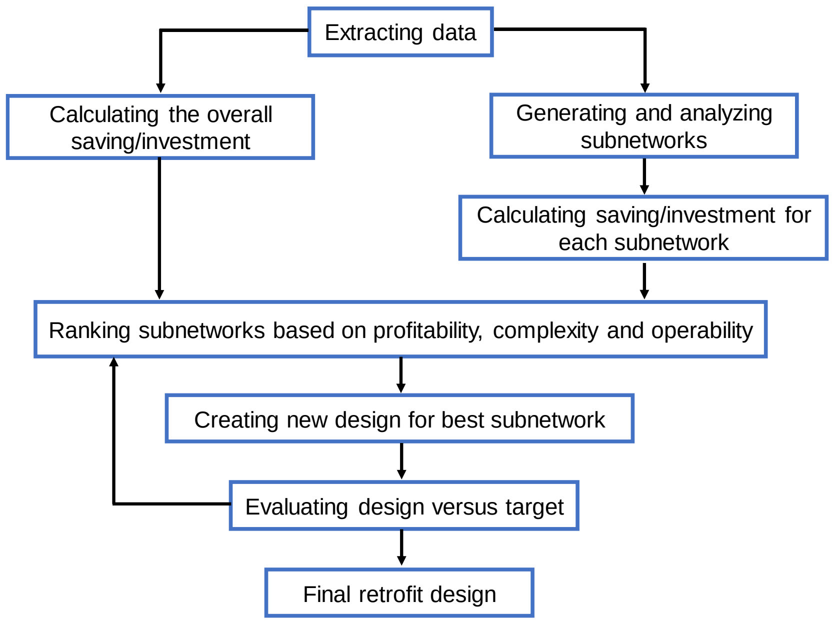

Figure 2-4 Summary of Path analysis steps

A path connects a cooler to a heater through at least one heat exchanger [39]. There is an excellent opportunity to use heat load loops and paths to relax retrofitted network and to increase compatibility with the existing network. After generating subnetworks, through a few steps, the subnets will be ranked based on energy-saving cost and investment cost, and the payback period will be identified for each subnetwork, and the most profitable network will be chosen for the retrofit design.

In another study, Van Reisen et al. developed a method called Structural targeting to identify what changes can be achieved in practice by breaking down the network into zones and then combining them into sub-networks. A zone contains one or more exchangers in the initial network and each heat exchanger must be included in only one zone, which is similar to the definition of Ahmad and Hui [40] who introduced this concept for greenfield HEN design. A heater-cooler path in the existing network can be included in a zone.

The existing network is broken down into zones that are easily integrable, according to heuristic rules. Then these areas are combined in sub-networks, starting with combinations of two zones, then three zones, etc., to the entire network. Heuristic rules for forming subnetworks from zone combinations are proposed. Each subnetwork must include at least one cooler and one heater. An area that includes both a cooler and a heater forms a subnetwork on its own. Each subnetwork is then evaluated by comparing its current energy demand with the target obtained by the pinch analysis of the subnetwork. Subnetworks are classified according to their potential savings of energy or profitability. The most promising are being modified by removing the exchangers that are crossing the pinch of a subnetwork and subsequent rearrangements, limited to the subnetwork, are identified. In some cases, unquantifiable factors such as controllability, safety, operability, and complexity as well as feasibility, may take into account. In subnetworks with a path, a designer has a chance to increase internal recovery by adding area to existing exchangers. Considering the results of quantitative and qualitative studies, the critical fraction of HEN that deserves for retrofitting can be identified [41]. Since path analysis deals with subnetworks instead of the whole network, it simplifies the problem significantly and allows engineers to do a retrofit with minimum structural changes of the HEN.

The logic behind this approach is the same as the pinch analysis. However, instead of analyzing the whole network, the Structural Targeting approach identifies zones with a high potential for energy-use reduction. Modifying a subnetwork including integrated ones is more realistic, and retrofit projects only concern a part of the network. Two main approaches are presented in this section. The first approach, the Path Analysis, focused on modifications along the cooler-heater paths and their creation. The second approach, Structural Targeting, considers all the possibilities of retrofitting with the targeting principle of pinch analysis, but this time for a subnetwork.

2.1.1.2.2.2 Network pinch approach

Before developing the network pinch approach, methods used for HEN retrofit design were either pinch based methods or mathematical programming-based methods. Pinch based methods enable user intervention during the design process, but manual techniques are potentially time-consuming, and pinch expert users are needed. On the other hand, mathematical programming-based methods have the advantage of being automated, but they are complicated and do not guarantee to find the global optimum. For covering deficiencies of Pinch based methods and mathematical programming techniques, Asante et al. proposed a method that can solve the retrofit problems in an automated procedure and at the same time provide proper user interaction [42]. The network pinch, which results from existing heat exchangers in the network, is different from the global pinch, which results from the existing steams and ΔT_{min} between hot and cold streams [43].

The general principle is to use heuristic rules to identify appropriate topological modifications in the network and then solve an optimization problem. When a heater-cooler path exists in a network, it is often possible to reduce energy demand without adding new pipes, and sometimes even without adding a new heat exchanger and it means less investment cost for the retrofit project.

When the surface is added to an existing heat exchanger along a path, the ΔT between the hot and cold streams decreases until reaching the minimum allowed ΔT which is called “network pinch”. Reaching the network pinch limits the energy use reduction on the heater-cooler path, and reducing further energy implies a topology change. Topology changes in a HEN can take the form of re-piping exchangers in the HEN, inserting new exchangers into the HEN, or creating stream splits within the HEN.

This situation means that by reducing heat recovery approaching temperature, HEN topology faces some limitations which are independent of the area of individual exchangers in the existing network. This method includes two key stages. The first step is the diagnosis stage to identify the best topology modification, and the second stage is an optimization stage to identify appropriate heat exchanger surface area, temperature, flowrate, and heat transfer load for selected topology modification to minimize the total cost using the non-linear programming (NLP) formulation [44].

2.1.1.2.2.3 Advanced composite curves

The Grand Composite Curve (GCC) has a few drawbacks for retrofitting; one of them is that there is no information about the existing heat exchanger network and therefore, it does not show any solution due to HEN modification. Nordman and Berntsson developed a new method to overcome these limitations. They proposed a graphical approach that includes eight composite curves which help to identify an estimation of the energy savings potential at lower investment costs that result from reducing the global temperature difference [45]. As it is shown in figure 2-5, four curves are placed above the pinch point and four curves are placed below the pinch point. The four curves above the pinch point are Hot Utility Curve (HUC), Actual Heat Load Curve (AHLC), Theoretical Heat Load Curve (THLC), and Extreme Heat Load Curve (EHLC) [46]. The HUC is the composite curve of hot utilities. The AHLC, which is the composite curve of existing heaters in the HEN, is between the EHLC and THLC. The EHLC is the maximum temperature available to place heaters, and the THLC is the minimum temperature for placing heaters [47]. EHLC is proportional to the extreme right part of the cold composite curve in pinch analysis. In other words, if we design a network with pinch analysis method, the heaters will be placed at the maximum available temperature, which corresponds to the spaghetti arrangement of the HEN. If the AHLC and THLC are close, it means that the heaters are at low temperature and there is an opportunity to save energy by removing this heater and placing them in higher temperature which leads to lower investment cost [48, 49].

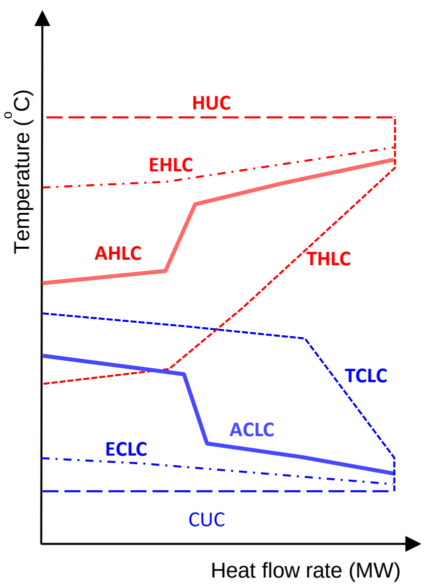

Figure 2-5 Advanced composite curves.

2.1.1.3 Bridge Method

Bridge Method developed by Bonhivers and Stuart based on the first two laws of thermodynamics [3]. The first law states that the total energy of a system is conserved and the second law states that the total entropy of an irreversible system always increases. In an industrial plant, high-quality energy (e.g., steam) is cascaded through all heat exchangers and process operation units to the cooling water [50]. Instead of sending heat to cooling water using coolers, there is a chance to use the heat somewhere in the plant. The idea behind the Bridge Method is to find a way to use this lost energy to satisfy heat demands in the plant. Bridge Method includes three powerful tools needed to characterize the existing system and to identify the energy-saving projects and convenient configuration of the final HEN. These three tools are Energy Transfer Diagram (ETD), Bridge identification and enumeration, and Heat Exchanger Load Diagram (HELD). Each tool will be explained subsequently [4, 51].

2.1.1.3.1 Energy Transfer Diagram

ETD shows the flow rate of transferred energy as a function of temperature through the whole temperature interval between the hot and cold utilities. The kinetic energy of molecules at the hot utility level is gradually transmitted to more molecules with less kinetic energy until the maximum energy degradation at ambient temperature. ETD shows the actual flow rate of transferred energy through a system (if heat is not converted to other forms of energy, e.g., chemical energy).

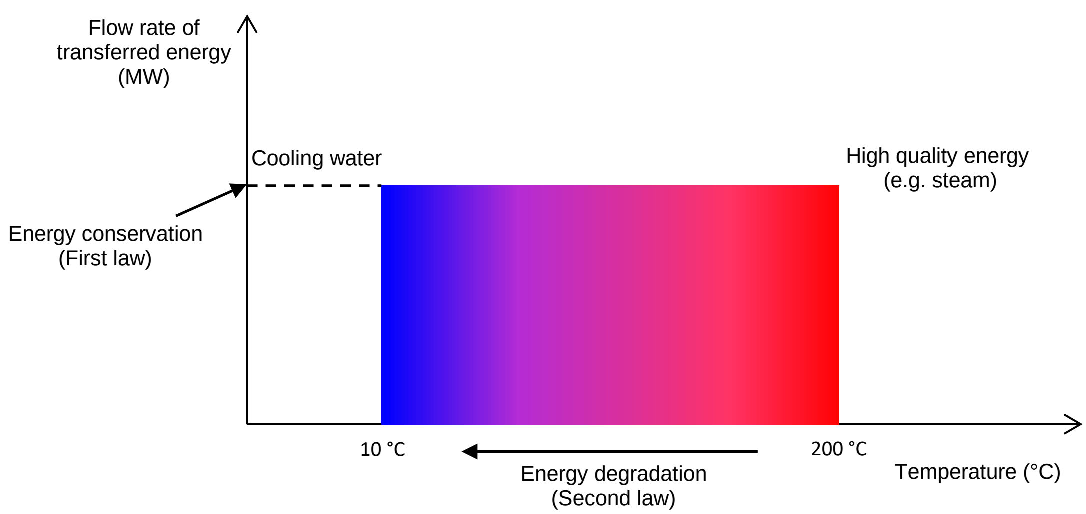

Figure 2-6 Energy conservation and degradation through heat exchangers and process operations

Figure 2-6 represents a schematic of energy degradation and conservation through all units in a plant. The flow rate of transferred energy through each unit in the system (heat exchanger or process operation) is the difference between the total outlet enthalpy rate and the total inlet enthalpy rate. As shown in Figure 2-7, cumulative enthalpy curves are shifted to the ambient temperature due to energy degradation through each unit in the system (the total energy is constant, but the energy quality decreases).

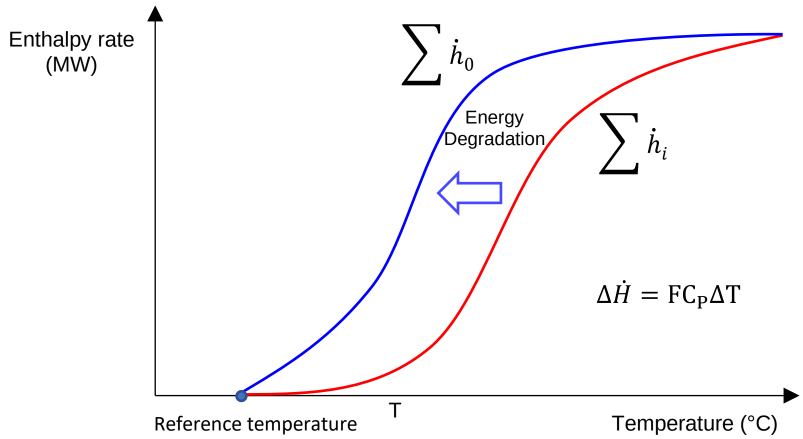

Figure 2-7 Energy degradation through each unit

At each temperature, T, the difference between the outlet and inlet cumulative enthalpy rate curves can be calculated as a function of temperatures, and it is called the energy transfer curve for this unit. So, for each heat exchanger and process operation, the energy transfer curve, which shows the energy degradation through the heat exchanger or process operation as a function of T can be calculated using the equation I:

$$ETC_{system}(T) = \sum_{out=1}^{Outlets} \dot{h}_{out}(T) - \sum_{in=1}^{Inlets} \dot{h}_{in}(T) \quad (I)$$

The energy transfer diagram is composed of energy transfer curves. It means if we calculate the ETC for all internal heat exchangers, heaters, coolers, and each process operation unit and then put them together as a function of T, we will build the energy transfer diagram. The energy transfer diagram comprises two parts: the process operation and the HEN. The process operation part can be shown above or below the heat exchanger part, because it is a cumulative curve. A schematic of the ETD is as shown in Figure 2-8, which is an area that corresponds to the transferred energy through the process operations above the HEN area. The energy is degraded from hot utility to the ambient through all units. The maximum heat saving capacity of HEN retrofit is the minimum of the HEN curve and to save more energy, the process operations need to be modified. The HEN curve is the border between the process operation area and the HEN area. To save energy, a set of modifications to reduce the cascaded energy between the hot utility and ambient is necessary. As mentioned earlier, the HEN area in the diagram can be decomposed into the individual heat exchangers, and the process operation area can be decomposed into the individual process operation units [52].

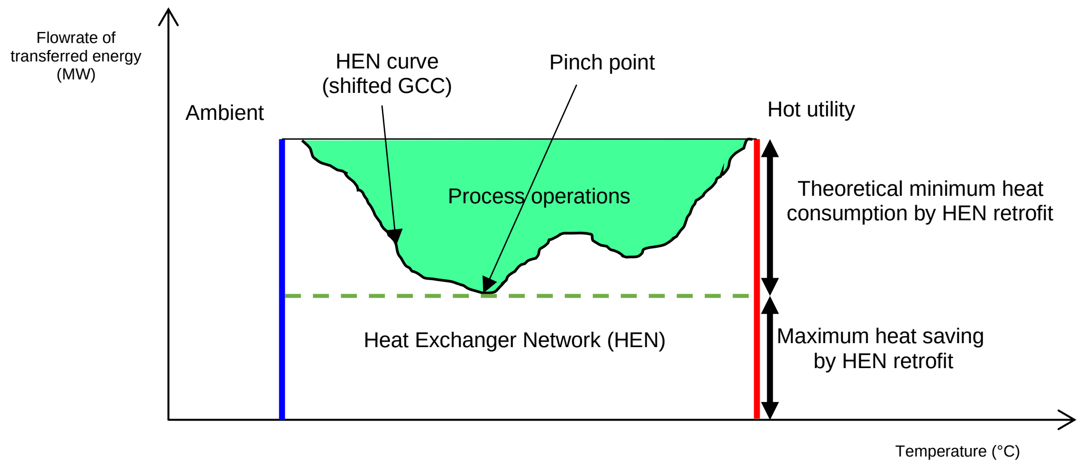

Figure 2-8 Energy Transfer Diagram (ETD) and linkage with GCC.

The HEN curve corresponds to the Grand Composite Curve (GCC) of Pinch Analysis if the global minimum temperature difference is equal to zero, and the minimum of HEN curve corresponds to pinch point at it is shown in figure 2-8 [53]. Another way to represent the ETD is to show it between hot and cold composite curves. The key advantage of the ETD is to characterize the energy profile across existing units. It can be used for visualization of energy-saving opportunities and analysis of HEN and process operations.

2.1.1.3.2 Bridge identification and enumeration

As earlier mentioned, the lost energy can be used somewhere in the process to satisfy heat demands in the plant. The set of necessary HEN modifications to use this lost energy (ready to transfer to the cooling water) somewhere else is called Bridge. Each Bridge includes at least one connection between hot and cold streams, and each connection is called a match. To transfer heat through a match, the process source should be hot enough to heat the process sink, and in that case, the match would correspond to a heat exchanger.

In some cases, the match corresponds to an existing heat exchanger, and in some cases, it corresponds to a new one. Regardless of the match's feasibility, a list of all possible ways (Bridges) to transfer the lost energy to the process sink s should be prepared. Then for each Bridge, the heat transfer capacity of each match would be calculated, and the minimum capacity would be the potential heat saving capacity of that Bridge.

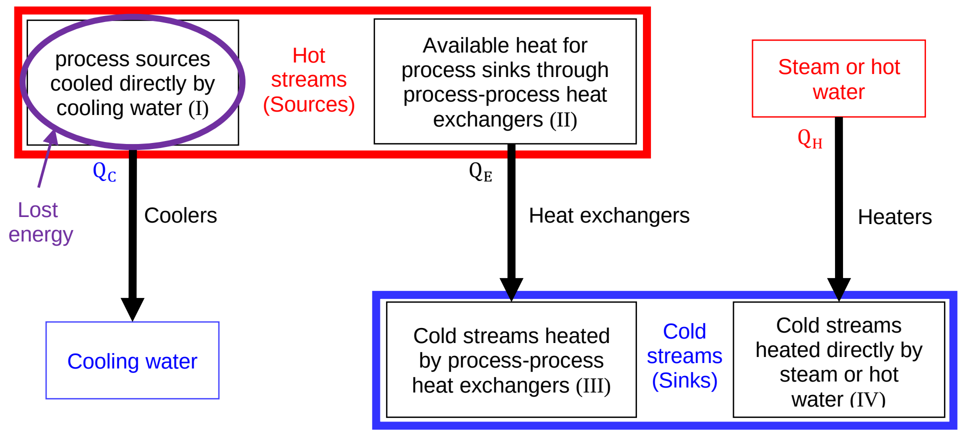

Figure 2-9 Bridge definition

As shown in Figure 2-9, the process sources or process sources have been divided into two categories. A part of process sources is used to satisfy a part of the process sink (II) via process-process heat exchangers and the second part which is the lost energy (I) has been sent to cooling water using coolers. Process sinks or process sinks are also include two parts. One part (III) is heated up by process-process heat exchangers, and the other part (IV) is heated directly by steam or hot water via heaters. The Bridge is a set of modifications to be used (I) for either (III) or (IV), and it reduces the steam or hot water consumption.

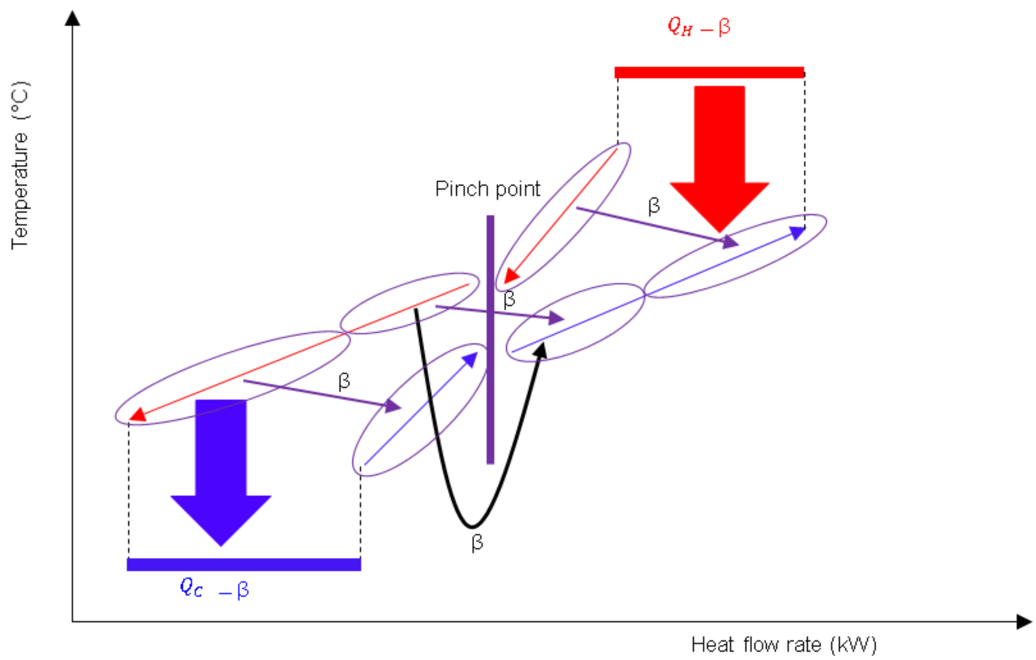

Figure 2-10 Bridge modification to decrease the lost energy and steam or hot water consumption

Despite the pinch violations (cross-pinch transfer which the heat source above the pinch point uses to satisfy the heat sink below the pinch point), heat below the pinch point can be used for the heat demand area above the pinch point. As shown in Figure 2-10, instead of sending heat to the cooling water, heat can be used for a heat demand below the pinch point, and it releases the heat source that was supposed to send heat to this part of the process sinks. So this available heat can be used for another part of the heat sinks, and finally, the steam usage will be reduced.

2.1.1.3.3 Network table

The network table is a Bridge Method tool to identify and evaluate the Bridge modifications. In this table, all streams are presented by their process-process exchangers, heaters, and coolers. Each row corresponds to a heat exchanger supplier and each column corresponds to an exchanger receptor. Each intersection between a row and a column represents a potential or existing heat exchanger and the thermodynamically available heat to transfer through this exchanger.

2.1.1.3.4 Heat exchanger load diagram

The heat exchanger load diagram (HELD) can identify a convenient exchanger configuration corresponding to Bridge modifications and for the design of new networks. The HELD includes the heat load (kW) of the process sources and the process sinks that are involved in modifications as a function of temperature. The concept of the HELD is simple, and it represents the enthalpy curve corresponding to each part of a stream as a function of temperature. It shows the existing HEN and all the heat exchangers, heaters, and coolers, but both hot and process sinks, so for each unit, there is information about the temperature and heat load. HEN modifications are represented on this diagram by vertical shifts of process sources. The plot of the difference between the hot and cold streams curves an exchanger in the HELD as a function of T is equal to the corresponding energy transfer curve in the ETD.

Bridge Method is an energy analytics methodology, which considers extracting all streams. It also considers energy degradation across process operations as well as HEN. Therefore, there is an opportunity to identify energy-saving solutions.

Energy analysis is at its foundation a process design and needs to be done in a practical way that considers all the constraints such as scaling, the complexity of implementations and etc. Traditionally process design is conducted by a series of design steps that go from many process options to the selected one and executed in a staged manner. It is the procedure of making choices by identifying a problem, gathering case-specific data, using existing knowledge and models, and assessing solutions.

Sequential open-ended decision-making (SDM) can be an integral part of a framework and it is a practical approach that can help people to make more thoughtful decisions. This approach increases the chances of selecting the most preferred solution, among others [54]. More specifically, it enables energy analysis with respect to comparing different process configurations and site-wide options and assessing the consequences of each energy scenario.

Open-ended decision making cannot be computerized, and it allows good engineering judgment (GEJ) to be implicated in the design process. While the Bridge Method lends itself well to being formulated in computer algorithms, numerous open-ended decisions need to be made from a practical perspective. For example, modifying the process operations, identifying infeasible connections or assessing the corresponding risk for each modification are all the activities that need to be done by expert users. Different qualitative and quantitative parameters need to be considered to deal with these open-ended decisions.

2.1.1.4 Critical analysis

The concept behind the Pinch analysis method for greenfield design is not hard to understand, and it is a stepwise approach with user intervention to achieve more practical results. However, only streams data are considered in representing the composite curves, and there is no information about the existing HEN, and it leads to some difficulties in a retrofit. Besides when we apply the Pinch method in retrofit, we actually compare the existing network with its greenfield design network. The connections that do not follow the pinch rules will be removed and new connections will be added to similarize the modified network to its greenfield design. This approach may work on cases with few pinch violations, but especially for the old mills, the existing network is far from its optimum design.

In path analysis, to improve the internal heat recovery, the heat exchanger area needs to be increased, and it is not always a practical solution. Besides, for a big problem, with lots of process streams and exchanger units, the number of probable subnetworks will be increased significantly, and calculations would be considerably time-consuming. The network pinch approach uses path analysis to reduce energy demands, but in some cases, there is no heater-cooler path, and some heuristics must be applied to create a new path. There is one allowed modification at that time, so it helps to achieve a robust sequential design, but it is time-consuming due to executing one modification at a time.

The advanced composite curves give a qualitative answer more than a quantitative one, and it helps to screen the solutions. Unlike pinch analysis, information about the temperature level of the actual heaters and coolers in the existing network is represented in advanced composite curves. However, there is no information about the existing process-process heat exchangers and process operations, and it limits the identification of heat-saving opportunities.

2.1.2 Process operation

Energy systems analysis can involve the following areas in a plant: (1) the utility system which includes the electricity and hot and cold utility production, (2) the process operations, and (3) the HEN. In principle, process operation modification results in reducing fuel consumption or increasing power generation in co-generation systems. In the early 1990s, the concept of total site energy analysis based on the pinch method was developed [51].

2.1.2.1 Total site analysis

Total site analytics is an energy-saving method for heat integration at the total site level. It was established as an extension to classical pinch analysis by Dhole and Linnhoff [55]. “Total sites” are industrial plants including different processes, using a central utility system. Total site targeting was developed to integrate the Total required energy of individual process operations in a total site.

The GCC represents the heat deficit, and heat excess of the process after heat recovery has taken place within the process. So the first step is to extract data from process operations and evaluate the GCC for each process discretely. The next step is to represent total heat sources into a composite total site source curve, and do the same for the total heat demands to calculate the composite total site sink curve. The final step is the creation of total site profiles that represent the total amount of available heat that can be employed by the total site heat deficit area through the steam system infrastructure. The philosophy behind the total site methodology is that the heat sources from the site processes can be used to provide heat to the heat sinks of the site processes by the generation and use of steam. The steam is used as an intermediate between the site heat sources and sinks. Thus, the total amount of external heating and cooling, which needs to be supplied to the Total Sit, will be reduced. A diagram of total site profiles is presented in Figure 2-11 [5].

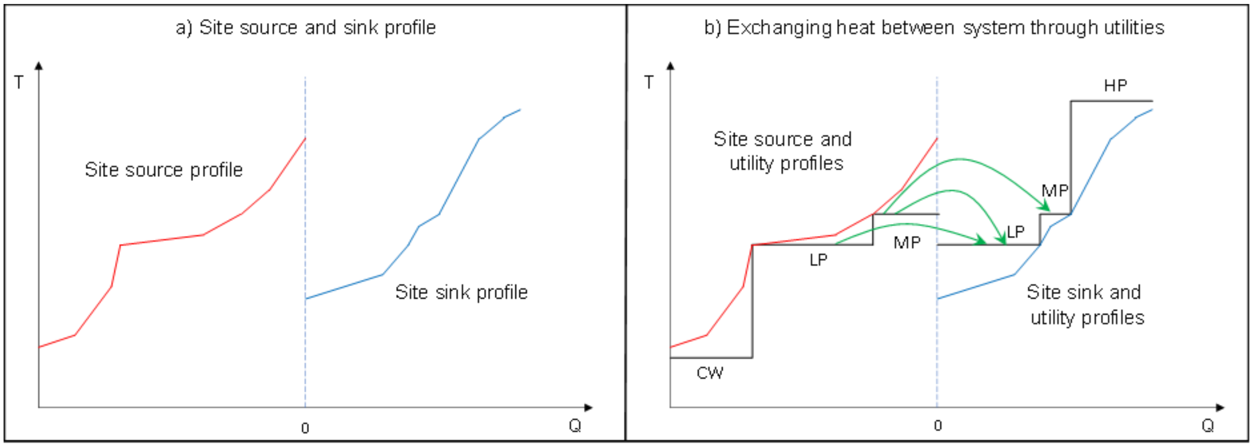

Figure 2-11 Total site profile

Hui and Ahmad [56] proposed a graphical procedure based on pinch and exergy analyses to design the total site utility systems. This approach works in 4 steps. The first step is to calculate the steam costs by using a developed correlation. After obtaining the steam cost, the next step is to find the ideal utility profile. To achieve this, the steam temperature levels at every 10 or 20°C is selected according to the shape of GCC, and it often gives good results, but for a more precise solution, there is an optimization stage to minimize the total HEN cost and determine the optimum steam duties. After optimization, some of the original steam levels may not exist in the solution. The third step is to choose the most practical steam levels based on heuristics. Finally, the energy capital trade-off has to be carried out to confirm that the optimum cost target for the selected steam levels is close enough to the optimum solution.

A mathematical-programming approach was developed by Maréchal et al. to target and synthesizing total-site utility [57]. In the proposed approach, each process requirement is defined by its respective HCC and CCC, and is used to calculate the minimum energy requirement of the industrial site. They used the site grand composite curve to identify appropriate integration opportunities. The method was applied in solving a problem which led to reduce the operating cost by 36%. In addition, another method was developed by the same group for optimizing utility systems considering sequential changes in utility demands across an industrial site [58].

2.1.2.2 Foreground/Background analysis

The foreground/background approach was developed in Chalmers University for energy analysis of two systems or two parts of a system. In this method, after calculating the GCC of two systems, one of them is mirrored, and the other GCC should be shifted to the write until two GCCs be in contact. The overlap between the two GCCs is the maximum energy saving capacity for those systems [59]. The limitation of this method is that it was developed for energy integration of a maximum of two systems at a time.

2.1.2.3 The Plus/Minus principle

The Plus/Minus Principle in pinch analysis has been developed to identify process modifications leading to energy savings. In the area above the pinch point, the goal is to increase the heat available by process sources (+) or decrease the heat demands of process sinks (−). Conversely, below a pinch, the goal is to increase the heat required of process sinks (+) or decrease the heat available by process sources (−).

2.1.2.4 Critical analysis

Total site energy analytics is a method for targeting heat integration in industrial processes by considering potential heat integration between different process streams and their interaction with a common utility system. In this method, an intermediate stream is employed to transfer heat between processes. In case of any unpredicted operational issue such as unit shutdown, the required steam for the downstream process can be provided by the utility system. The foreground/background approach can be used to analyze two systems at a time, but in many cases, there are more than two systems and using this approach does not consider all opportunities to save energy.

2.2 Engineering design decision-making process

The plant-wide energy analytics is, at its foundation, an engineering design where the design statement is to reduce energy use consumption in heat exchangers and process operations, and it needs to be done in a practical way that considers all the constraints such as scaling, pressure drop, the complexity of implementations, etc.

Traditionally, engineering design is conducted by a series of design steps that go from many options to the selected one and executed in a staged manner (order of magnitude analysis, pre-feasibility analysis, feasibility analysis, definition engineering, detailed engineering) and finally construction [10]. Sequential decision-making in engineering design refers to a procedure whereby from a set of possible design options, the user sequentially triages the options to include more insight, better data, and with these, reduces risk. As the decision-making process moves forward, the user learns more about the system and can make a better decision [11].

2.2.1 Sequential decision making

Sequential decision making in engineering design or sequential design decision making refers to a procedure whereby from a set of possible design options, the user sequentially triages the options to include more insight, better data, and with these, reduces risk. As the decision-making process moves forward, the user learns more about the system and can make a better decision [60].

To design a sequential decision-making process, the objective at each design step needs to be identified. Each sequence is designed to fulfill a specific objective and to do that, it comprises a set of activities, and at the end of each sequence, a decision is made, and it is used as new information in the next sequence to make a new decision. The Bridge Method can be executed in practice by designing a state-of-the-art framework that systematically considers the design process with input from process engineers, energy analysts, etc.

Figure 2.12 shows a generic single-step decision-making process in engineering design. It illustrates one sequence of engineering design decision-making, which is influenced by sets of controlled and uncontrolled conditions [61]. The controlled conditions are generally in control of the business owners such as fundamental and stochastic models necessary to calculate the decision metrics, product, and process design to create a new product, and design practices and good engineering judgment (GEJ). The uncontrolled conditions comprise the fuel price or product price, legal and business consideration, and government regulation (energy contract of the mill).

The inputs of the decision-making process are design objective, data and design constraints, and knowledge. The decision objective means the final goal that would be accomplished through the decision-making process. The design constraints include safety, cost, timing, and manufacturability. Decision metrics represent the quantitative measures such as graphs, tables, or numbers used to help decision-makers for assessing risks, comparing results, and finally make a better decision.

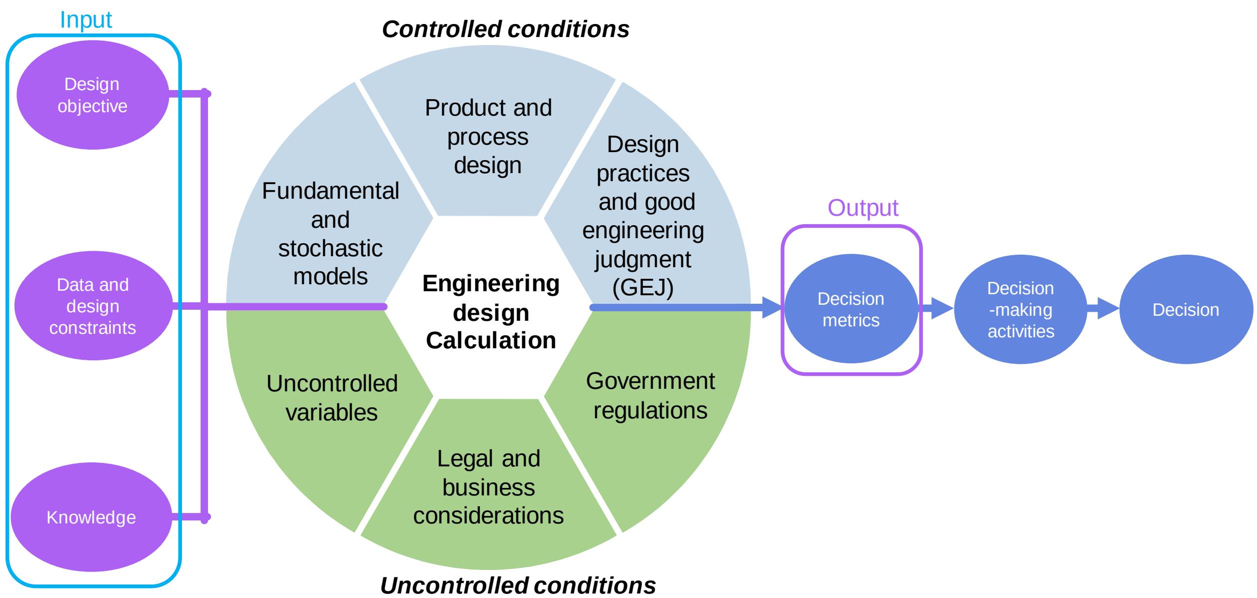

Figure 2-12 Generic single-step decision-making process in engineering design

As mentioned before, the design process in engineering, is a series of sequences, and in each sequence, a decision needs to be made, and decisions in earlier steps are interdependent to the later decisions. To define a sequential design decision-making framework, it is necessary to repeat this sequence for each decision objectives until making the final decision. A schematic of a generic sequential decision-making framework is shown in figure 2.13.

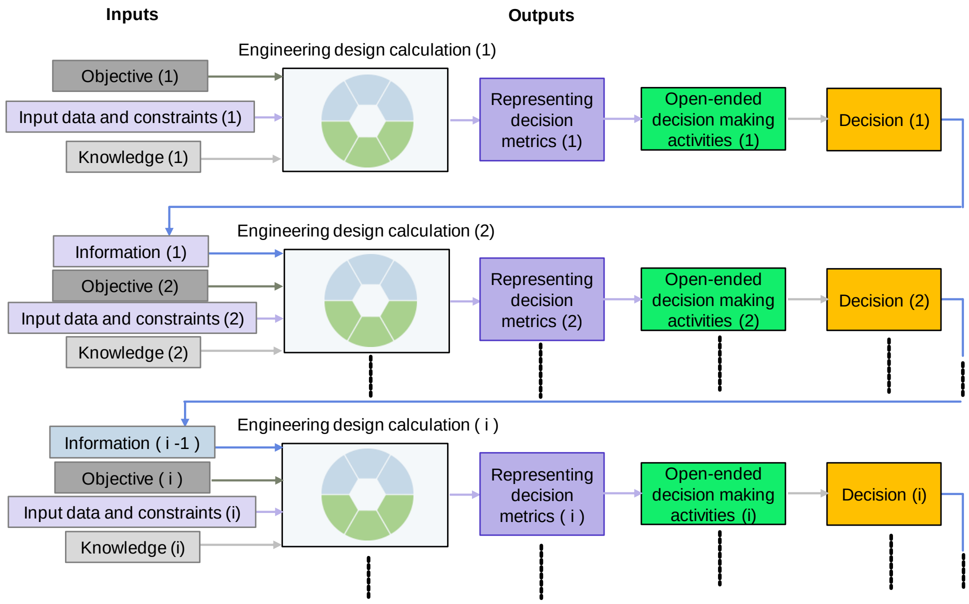

Figure 2-13 The generic sequential design decision-making process

The necessary activities to make a decision can be categorized into two groups. The first group is the activities that can be done automatically by a computer through algorithms without any user intervention. The second group is the activities that need to be done by expert users to find solutions for open-ended decisions. In each sequence, the objective, case-related data and constraints, and knowledge should be identified and added to the system as input information. These data will be employed for calculating and generating necessary decision metrics such as graphs and tables, using the computer algorithm. Then, decision-makers use these metrics along with their knowledge and experiences to select appropriate options and make a decision. The green boxes in figure 2-13 represent the activities that need to be done by expert users, and it may take days or months to reach a practical decision. The new decision at each sequence will be used in the next sequence as new information to narrow down the options and help to make the next decision.

To make an effective decision-making process, especially for a complex problem with massive volumes of data, we need a computer-based system to input necessary data, use them to calculate decision metrics, and represent the results to the user. In the next section, the need for a computer-based information system is explained [62].

2.2.2 Framework for a decision support system

The Bridge Method is a systematic approach that lends itself well into a computer algorithm, but implementing it into practice requires a computer-based information system (CBIS) to interact with the user and help to organize information and provide better decisions.

When a vast amount of information is involved, the Decision Support System (DSS) as an interactive, adjustable, and versatile type of CBIS is the best choice to make the complex decision-making process effective and efficient [63]. It can get the data from different sources, provide reports and presentations using textual and graphical tools that suit the user's needs. Besides, it can perform complicated analysis, using computer-based software to do optimization and solve problems to achieve appropriate scenarios [64].

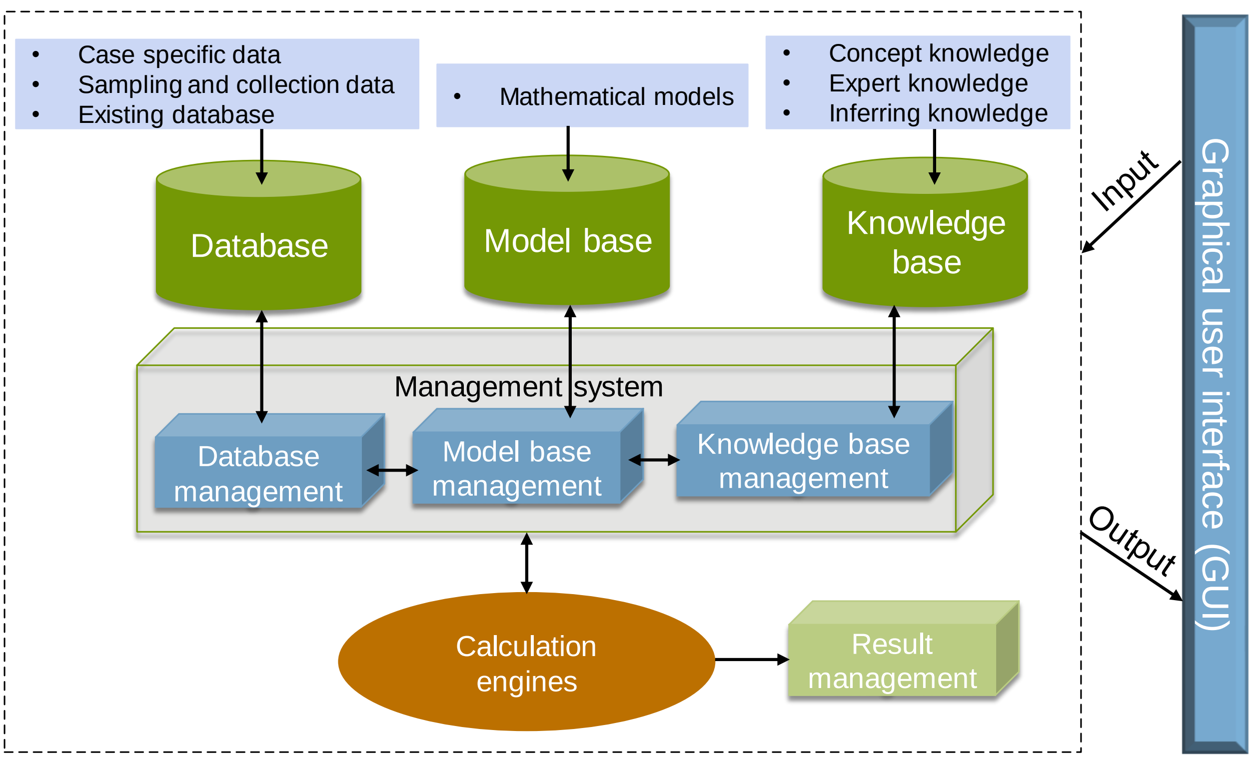

Figure 2-14 Architecture of a decision support system inspired by Xia et al. [65]

An architecture of a DSS is shown in Figure 2-14 [65]. A DSS commonly includes a Graphical User Interface (GUI), model base, knowledgebase, database, calculation engine, and management system. The GUI is a front-end tool for data input and output results [65]. It has a module to ask the user to input the information and to pass that information to the management system. It also includes an output module, known as the dashboard, to visualize results for further analysis [66]. The database is an organized collection and storage of information that generally is relevant to the case study. In addition, the results of the analysis and assessment of the case study are stored in the database. The model base is a place to store all necessary models to support the process of decision-making. The knowledgebase is a base which the human expertise, heuristic knowledge, concept knowledge, expert knowledge, and inferential knowledge, are efficiently stored and accessed. The calculation and data analysis engine, also known as “calculation engine,” is responsible for assessing and calculating parameters and indicators. The management system includes the database management module, the model base management module, and the knowledge base management module. These management modules allow the user to create a new database and append, modify, delete, and browse the data, models, or knowledge. The GUI can communicate with a database, model base, knowledgebase, and calculation engine through the management system.

2.3 Gaps in the body of knowledge

Based on the critical analysis of pertinent literature, the following gaps in the body of knowledge were identified:

- There is a need to develop a systematic approach to identify potential process operation modifications to reduce the overall energy demand of an industrial plant. This approach should be able to identify the impact of each process operation on overall energy consumption of the plant and propose appropriate modification opportunities
- Over the past years, the Bridge Method has been applied in simple and complex cases to show its true value. It has been compared with most used approaches for HEN retrofit and in all those cases it got the same or better results, but it has never been applied in a complex problem considering the constraints and economic analysis of the results.
- Implementing Bridge Method in practice need a decision-making framework specifically designed for energy analysis, to benefit from the automated calculations and user interaction to make decisions in a sequential way.

2.3.1 Hypotheses

The main hypothesis of this research project can be summarized as follows:

- The Bridge Method can be the foundation of a sequential design decision-making framework for addressing plant-wide energy analysis.

The sub-hypotheses supporting the main hypothesis are as follows:

- Sub-hypothesis 1: The Bridge Method can be expressed as a series of steps that can be assembled into a framework, considering engineering design constraints including capital and operating costs, in a sequential design decision-making context.
- Sub-hypothesis 2: The Bridge Method can be used to quantify the energy degradation across both the HEN and process operations, making it possible to identify potential modification opportunities for plant-wide energy use reduction.
- Sub-hypothesis 3: The core elements of the Bridge Method framework can be demonstrated in a complex process context.

CHAPTER 3 OVERALL METHODOLOGICAL APPROACH

A design decision-making framework for using the Bridge Method in practice has been developed. This chapter represents the methodology overview following the introduction of the developed framework. The following sections provide details of the steps in the project methodology, as well as a brief description of the case studies.

3.1 Methodology overview

The critical analysis of the well-known process integration approaches revealed the potential of the Bridge Method to address shortcomings of advanced pinch-based methods. As mentioned earlier, the key objective of this research project is defining a design decision-making framework. The Bridge Method needs to be integrated into a framework to address different design issues in practice. Such a framework should benefit from both automated calculations using algorithms and user interaction at various stages of decision making. Figure 3-1 below shows an overview of the methodology of this research project, as well as publications that resulted from the demonstrating of each section.

As it is illustrated in figure 3-1, the project was done by following two main sections:

1) Elucidating the Bridge Method and the concept of energy degradation including the interactions between process operations and HEN, and its novel application in identifications of potential process operation modifications.

2) Developing a sequential design decision-making framework incorporating the bridge method and design aspects, demonstrating how to identify the economically viable retrofit projects in complex industrial problems

In Figure 3-1, each main section is broken down into intermediate steps that are explained in the following sections.

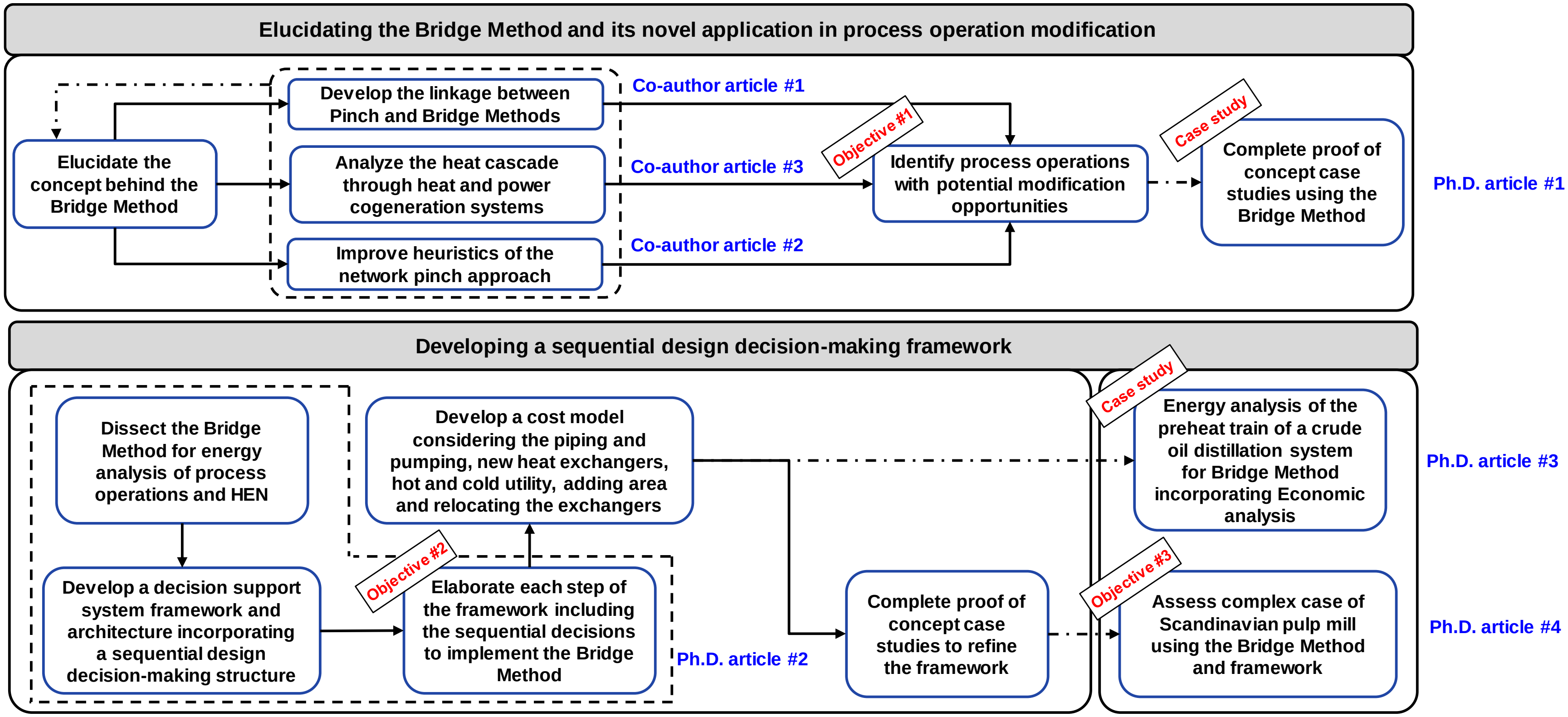

Figure 3-1 Overview of the methodology

3.2 Elucidating the Bridge Method and its novel application in process operation modification

To address the first sub-objective, the principals of the Bridge Method is employed to calculate energy degradation across process operations as well as the heat exchange network to identify potential modification opportunities for energy use reduction for process operations. It starts by understanding the philosophy behind the energy transfer diagram and elucidating the Bridge Method. To have a better understanding of the Bridge Method and show the real potential of employing ETD, three activities were defined; developing the linkage between Pinch and Bridge Methods, improvement of heuristics of network pinch approach, and analyzing the heat cascade through heat and power cogeneration systems.

3.2.1 Developing the linkage between Pinch and Bridge Methods

One of the main challenges at the beginning of this project was to improve the representation of the Bridge Method and find common ground with expert pinch method users. So the next activity was to make a linkage between the visual tools of the pinch method and the ETD and comparing these methods in solving several case studies [53].

The heat degradation through an exchanger as a function of T is equal to the difference between the total inlet enthalpy (or cumulative load curve of its sources) and total outlet enthalpy (or cumulative load curve of its sinks). The cascade heat through all exchangers is equal to the difference between the cumulative load curve of all its sinks and the cumulative load curve of all its sources. HEN sinks are composed of the cold utility curve and the process sinks or cold composite curves. HEN sources are composed of the process sources or hot composite curve and the hot utility curve. As a consequence, the cascade heat through each existing exchanger can be represented between the cold and hot balanced composite curves. Representing the ETD between these curves can finally attract the pinch experts who are used to put the temperature on the vertical axes and work with hot and cold composite curves. It brings more insights into the visual tools of the pinch method including the information about the existing exchangers.

3.2.2 Improvement of heuristics of network pinch approach

This part of the methodology was designed to improve the network pinch approach using the concept of pinch analysis. The network pinch approach is the most used approach for energy analytics of industrial sites. An important stage of this method is to identify a heater-cooler path and reduce the energy consumption of it by increasing the surface area of exchangers in the path until reaching a limit called network pinch. If no cooler-heater path can be found in the HEN, the network pinch approach uses heuristics to create a new path by adding one new connection between hot and process sinks. In the network pinch approach, one modification at a time can be done to limit the investment costs and the number of possibilities. We used the concept of Bridge Method to improve heuristics for creating new cooler-heater paths in the network pinch approach. In problems with no existing heater-cooler path, the Bridge Method can systematically identify new paths.

3.2.3 Analyzing the heat cascade through heat and power cogeneration systems

To investigate the potential of Bridge Method in site-wide energy analysis, for the first time, the heat cascades through a plant, including a boiler, a turbine, process operations, and exchangers, was represented on a single diagram. It makes it possible to analyze utility components and find opportunities to reduce hot utility demand. The relation between the cascaded heat and energy degradation or exergy loss has been described in this section. The energy flowrate from the fuel combustion to the boiler heat exchanger system, producing high-pressure steam, its expansion through a turbine to produce electricity and low-pressure steam, and the heat cascade from low-pressure steam through operations and exchangers to the ambient temperature is represented in this part of the methodology.

3.2.4 Identification of process operations with potential modification opportunities

This section of the methodology, which is related to the first sub-objective, is designed to develop an approach to use the ETD for identification of process operations potential modification opportunities. The ETD of a plant comprises two zones. The first zone belongs to the HEN and the second zone shows the energy degradation through process operations. In this section, the focus was on representing the process operations in the ETD alone and investigate the opportunities for energy use reduction. We developed a systematic approach to prioritize the process operations by considering their impact on the overall energy usage of the plant.

The procedure of process modification in an open-ended decision-making procedure which comprises user intervention and good engineering judgment to find a solution. For example, increasing the number of effects in the black liquor evaporation system in the pulp and paper industry results in both reducing the height and increasing the width of the corresponding area in the ETD, or modifying the system's pressure to shift the corresponding area to the left or to the right. Using new technologies such as infrared radiation (IR) in the pulp dryer can lead to steam use reduction.

3.3 Developing a sequential design decision-making framework

This part of the methodology comprises steps to developing a decision-making framework for implementing the Bridge Method. It starts with the identification of necessary steps to execute the Bridge Method, developing a sequential decision making incorporated into a framework, integrating the framework and the Bridge Method, economic analysis of the retrofit projects and using the framework to solve a complex case study.

3.3.1 Design steps necessary to implement the Bridge Method

Until now, the Bridge Method has been used to demonstrate the possible HEN modification by solving theoretical case studies without considering connection constraints, economic analysis, and case-specific design issues. To have a realistic retrofit solution, a list of design steps is prepared to find an appropriate solution using the Bridge Method. It considers the use of minimum ΔT contribution for each stream considering the material composition and therefore, can help to eliminate the thermodynamically infeasible Bridge modifications. The next important step is to determine connection constraints such as restricted and forbidden connections or non-accessible heat exchangers in the existing network. It should be done by the plant process engineer (PPE). For the rest of the connections, it is possible to rank them based on the associated risk such as complexity and safety. These are the unquantitative parameters that can help to find viable Bridge modification. Calculating the investment cost and payback period for each modification is the last step to evaluate the viable solutions.

3.3.2 Developing a decision support system framework architecture incorporating the sequential design decision-making and the Bridge Method

The plant-wide energy analytics is, at its foundation, an engineering design and needs to be done in a practical way that considers all the constraints such as scaling, pressure drop, the complexity of implementations, etc. The engineering design is conducted by a series of design steps to narrow down options and find the appropriate solution. In this part of the methodology, a sequential design decision-making structure has been defined. The objective of each sequence is to find a solution for each design step of the Bridge Methodology.

The necessary activities to make a decision can be categorized into two groups. The first group is the activities that can be done automatically by a computer through algorithms without any user intervention. The second group is the activities that need to be done by expert users to find solutions for an open-ended decision-making process. The elements of a decision support system such as Graphical User Interface (GUI), The management system, calculation engines, and dashboard are integrated into the framework to deal with a large volume of data.

3.3.3 Economic analysis of retrofit projects

To evaluate the profitability, for each practical Bridge modification, the payback period (PBP) and Internal Rate of Return (IRR) has been evaluated in this research. The PBP determines how long it would take to recover the total investment cost. A short PBP shows that the project can pay for itself within a short time frame. When there is a limited amount of funds for retrofit projects, the projects with higher PBP become more attractive for its faster investment cost recovery. One of the significant drawbacks of PBP is that it assumes that the value of money does not change over time. The assumption in calculating the PBP is that the value of the money in the first year is equal to its value in the next year which is not true.

Another critical parameter for the economic analysis of retrofit projects is IRR. The IRR shows the estimated percentage return from the project, it uses the total investment cost and the estimated future cash flow to find the interest rate. Calculating the IRR needs a try and error algorithm, using different interest rates to have a net price value (NPV) equal to zero. In this research method, we assumed that the future cash flows for the next 10 years are equal to the energy saving cost in the first years and IRR is the interest rate that makes the NPV equal to zero in 10 years. For high-risk projects, IRR should be higher than 30-40% to make the project attractive for investment.

3.4 Case study introduction

The developed sequential design decision making framework has been applied in two complex case studies: a preheat train of a crude oil distillation system without process operation and an average Scandinavian pulp mill model including process operation. In this section, the process description and data of each case study is presented.

3.4.1 Preheat train of a crude oil distillation system

In the crude oil distillation systems, the HEN known as the “preheat train” recovers heat from the distillation process to preheat the incoming crude oil feed. This heat is recovered in the condenser and the pump-around, and by cooling the various product streams.

In this case study, for some streams, the heat-saving capacity is highly dependent on temperature, and the temperature range of those streams is broken into several intervals. The network contains 24 exchangers with a total area of 4000 m^2, and the hot utility consumption of the existing network is 89MW [67]. The hot and cold utilities temperatures are 400°C and 10°C respectively. The heat-transfer coefficients for all streams, the hot utility, and the cold utility were assumed to be constant and equal to 1 $kW/°C.m^2$, 2 $kW/°C.m^2$, and 2.5 $kW/°C.m^2$ respectively.

3.4.2 Scandinavian pulp mill model

For demonstrating the developed methodology in solving a complex case including the process operation, a Scandinavian kraft pulp mill model is used in this thesis [68]. The mill produces 1000 ADt/day of bleached market kraft pulp from 2065 t/day of softwood. Figure 3.2 shows the simplified representation of the FRAM kraft pulp mill fiber line and chemical recovery system.

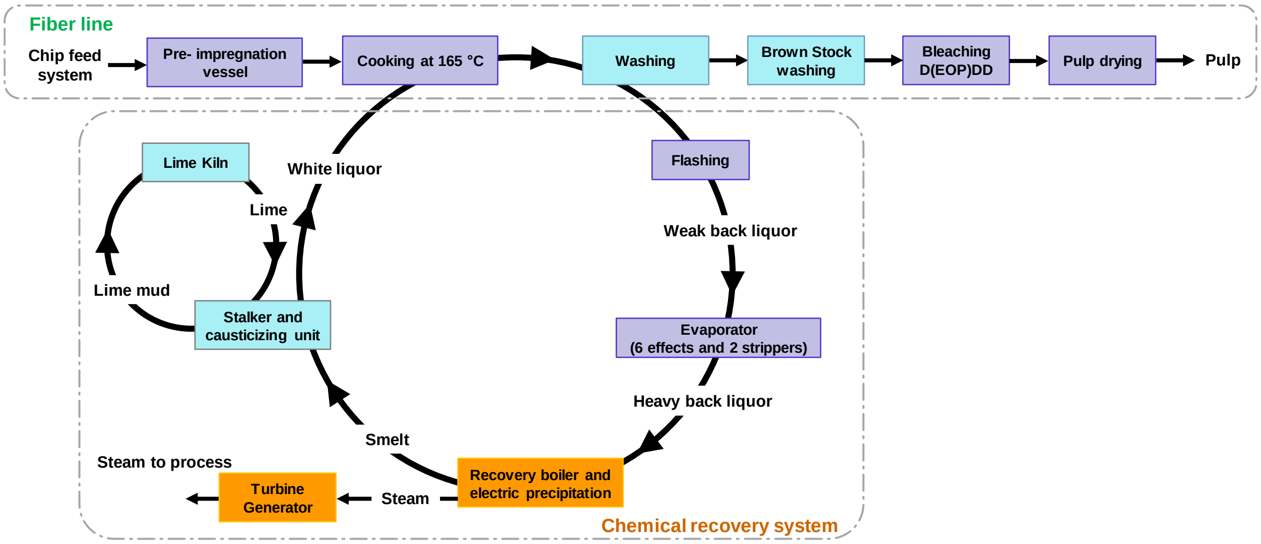

Figure 3-2 Simplified representation of the FRAM kraft pulp mill fiber line and chemical recovery system

The continues cooking is performed at relatively high alkalinity at 165 °C. The continues digester system includes two flash systems. The first flash supplies steam to the chip bin for impregnation and preheating, while the steam from the second flash is utilized for hot water production. The digester is followed by a brown stock washing system. The bleach plant is designed with four stages in the sequence D(EOP)DD that gives 90% ISO final brightness. The press section in the pulp machine provides a dryness of 47% before the dryer.

The evaporation plant is a conventional 6-effect system utilizing LP and MP steams to give 73% solids content in the heavy liquor. LP steam is used at the first effect and steam evaporated from this effect is used to the next effect, and so on until the sixth effect from which heat is evacuated through a surface condenser to freshwater for the production of warm water. The evaporation system is the largest energy user in the mill.

The HEN includes 40 units, i.e. 13 coolers, 19 heaters, and 8 internal heat exchangers. The $\Delta T_{min,cont.}$ for each stream is also included. The hot utility consumption before retrofit is equal to 147 MW.

CHAPTER 4 PUBLICATION SUMMARY AND SYNTHESIS

4.1 List of publications

The following articles, as the outcomes of this research, are presented in Appendices A to D of this thesis:

- Article 1: A. Moussavi, J.-C. Bonhivers, and P. R. Stuart, "Plant-wide energy analysis of industrial sites using Bridge Method: Part I – Fundamentals," submitted to Energy & Environmental science, 2020.
- Article 2: A. Moussavi and P. R. Stuart, "Plant-wide energy analysis of industrial facilities using the Bridge Method: Part II – Framework for decision support," submitted to Energy & Environmental science, 2020.
- Article 3: A. Moussavi and P. R. Stuart, "Cost analytics for energy analysis of industrial facilities using the Bridge Method," submitted to Energy & Environmental science, 2020.
- Article 4: A. Moussavi, J.-C. Bonhivers, and P. R. Stuart, "Plant-wide energy analysis of industrial facilities using the Bridge Method: Part III – Framework application," submitted to Energy & Environmental science, 2020.

In addition, a list of pertinent conference presentations can be found as follows:

- Moussavi, A. & Stuart, P.R., Reducing Energy Consumption During Biorefinery Implementation [Oral presentation]. Presented at the PaperWeek- BioFor Conference, 2016, Montreal, QC, Canada.
- Moussavi, A., Bonhivers, J.C. & Stuart, P.R., Bridge Method for Site-Wide Energy Analysis and its Application in the Pulp and Paper Industry [Oral presentation]. Presented at the 67th Canadian Society for Chemical Engineering (CSChE) Conference, 2017, Edmonton, AB, Canada.
- Moussavi, A. & Stuart, P.R. (2018). Introducing Bridge Method: making believers from those who are familiar with pinch analysis [Oral presentation]. Presented at the PaperWeek-BioFor Conference, 2018, Montreal, QC, Canada.

- Moussavi, A. & Stuart, P.R. (2019). Site-wide retrofit energy analysis using the Bridge Method, Presented at the PaperWeek- BioFor Conference, 2019, Montreal, QC, Canada.

4.2 Links between publications

Figure 4-1 presents the linkage between articles and hypotheses. The main results of this study are presented in three articles (parts I, II and III), which are submitted to *I&EC Research*. The part I article (appendix A) represents the theoretical background of the Bridge Method and energy degradation through process operations and heat exchangers [69]. This work reviewed the advanced pinch based approaches for energy analytics of industrial plants and elucidated the fundamentals of Bridge Method for energy analysis and the way it can be used to employs the ETD to describe energy degradation in the existing process is described. The need for developing a decision-making framework to address design issues in reality to incorporate the Bridge Method has clarified in the last section of this paper. The summary of the theoretical background of the Bridge Method and energy degradation through process operations and heat exchangers was Briefly presented in the PaperWeek- BioFor Conference in Montreal, Canada (2016).

The part II article (appendix B) was written on developing a sequential design decision-making framework to implement the Bridge Method in practices [70]. The Bridge Method Framework employs a user-interactive sequential decision-making approach, where automated design calculations are made, and certain open-ended decisions are taken in the design process leading to a practical set of recommendations. The structure of a sequential decision-making framework incorporating the Bridge Method is presented and the overall decision support system framework incorporating the Bridge Method and the idea of sequential design decision making is represented.

The third article (appendix C) considers developing a cost model to have a realistic estimation of Bridge modifications [71]. The result of this article is submitted to TAPPI Journal. The mathematical programming-based approaches have considered investment and operating costs in their models for the past five decades to optimize the total cost of HEN retrofit projects but in thermodynamic-based approaches, either the cost has not been considered or a simplified formulation has been used to calculate the total cost of each retrofit project. A critical review of existing approaches and the way they have dealt with cost formulation is presented in this paper. The Bridge framework can identify the final HEN topology of each retrofit modification Which means the total cost estimation can be done more precisely.

The results from the second and third articles are used in part III article (appendix D) for energy analysis of a complex case study. In this article, the key elements of the framework are demonstrated by retrofitting the heat exchanger network of a Scandinavian pulp mill model.

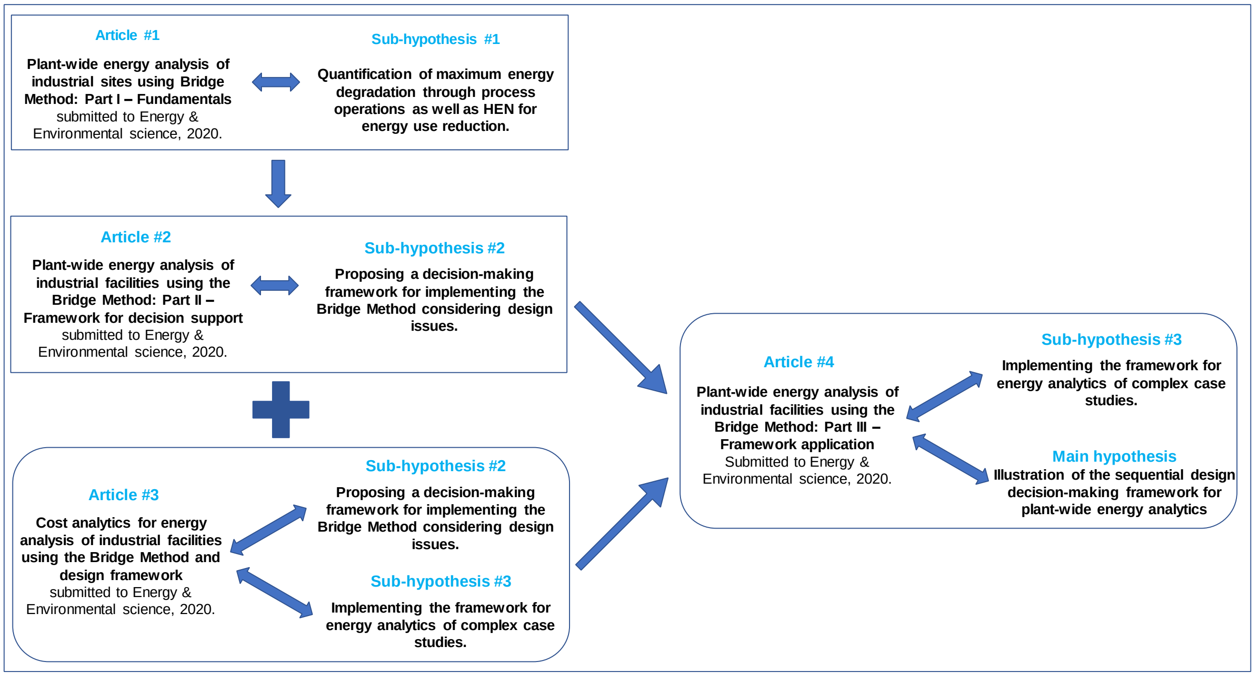

Figure 4-1 Linkage between publications and hypotheses

4.3 Synthesis

In this section, the results of this research are presented. The focus is on a) Elucidating the concept of Bridge and using the ETD to identify process operations that need to be modified and prioritize them based on their impact on the overall energy use reduction of the plant, b) dissecting the Bridge method, c) developing a sequential decision-making structure incorporating the Bridge Method, d) defining the architecture of a decision support system framework incorporating the Bridge Method and the sequential decision-making.

4.3.1 Energy analytics of process operations using ETD

As it is mentioned before, the difference between total inlet and total outlet enthalpy of each process operation as a function of temperature creates a polygon that represents the cascaded energy for each individual unit. According to the Bridge Method conventions, the ETD is divided into two parts which are process operation and HEN. In this section, our focus is on the process operation part in the ETD which comprises the cascaded energy through all process operations as a function of temperature. The ETD shows the flowrate of transferred energy at each temperature. For example, consider a chemical process with four process operations. For each process unit, the inputs and outputs data are extracted from a simulation file and the ETD is shown in figure 4-2a.

The maximum of the process operation curve shows the theoretical minimum heat consumption by HEN retrofit and to reduce it further, the process operations need to be modified. To lower the peak of this curve, we need to identify the process operations that have an impact in this temperature. As it is presented in figure 4-2a, at the temperature at the maximum of process operation curve (T), two process operations exist. Both P3 and P4 have an impact at T temperature on the total heat degradation of process operations. To reduce the total heat demand for process operations, we need to modify P3 or P4. At it is clear in the figure, P4 has a higher impact at T temperature. In fact, from analyzing the ETD, we can prioritize the process operations that need to be analyzed based on their impact.

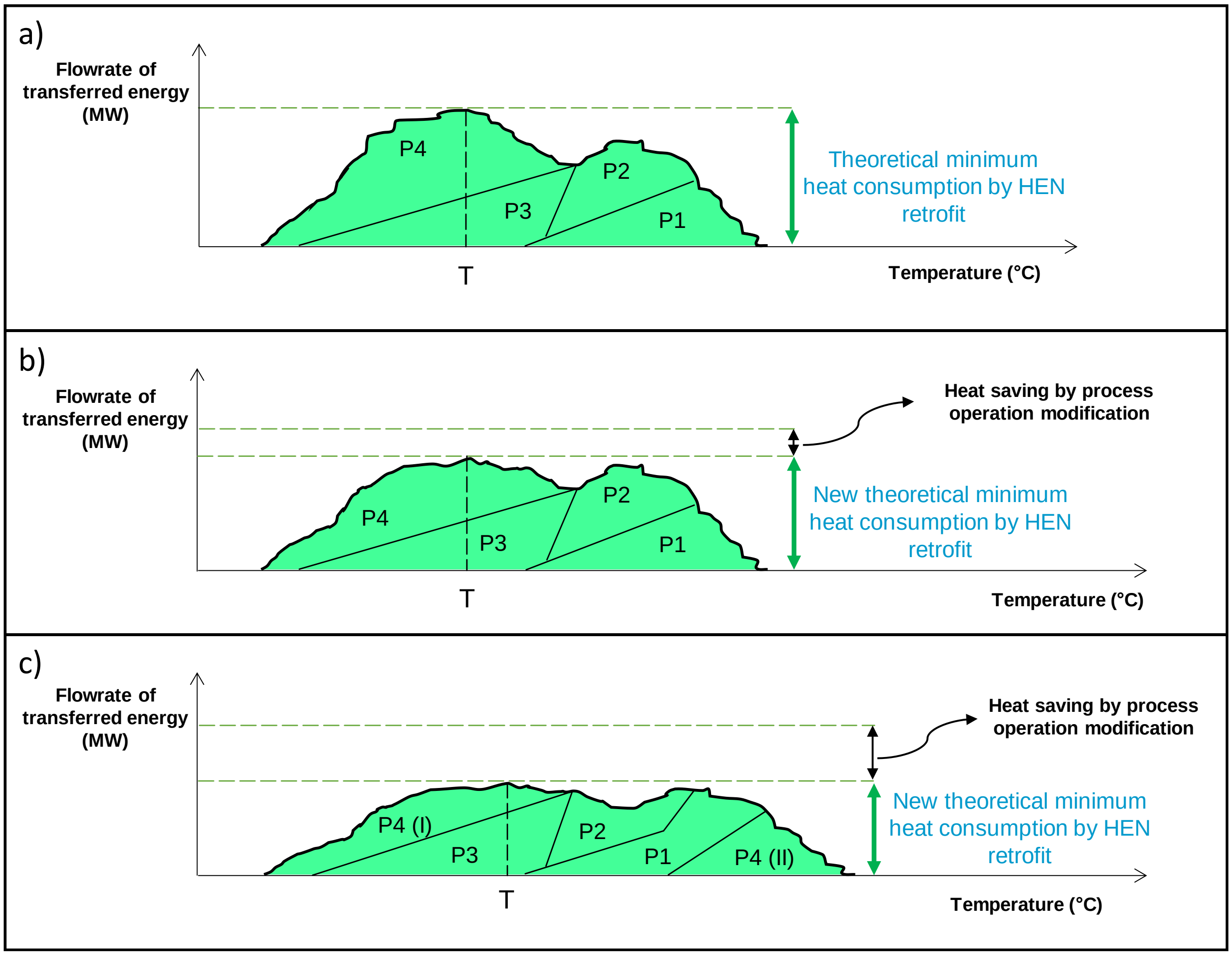

Figure 4-2 The heat degradation through individual process operations a) before modification, b) after modification of Process operation number four (P4)

The procedure of process modification in an open-ended decision-making procedure which comprises user intervention and good engineering judgment to come to a solution. Depending on the operation unit type, different solutions could be proposed. The modifications can either be incremental like optimizing the process operation or modifying the operating conditions of each process operation or using new technology which has lower hot utility demand. For example, by modifying the operating conditions around a distillation column such as temperature and pressure, we can shift the corresponding part in the ETD to the left or to the right and reduce the overall energy demand. Another example could be increasing the number of effects in the black liquor evaporation system in the pulp & paper industry to reducing the height and increasing the width of the corresponding area in the ETD. Replacing the existing technology with a new one with lower energy usage is another option. For example, using an electric evaporator or adding an infrared radiation (IR) system in the dryer can work. Figure 4.2b and 4.2C present the ETD of process operations after modifying P4 which leads to a new lower theoretical minimum heat consumption by HEN retrofit.

4.3.2 Dissection of the Bridge Method

The Bridge Method like any other energy analytics approaches needs energy-related data. The first step of all these approaches is to extract data from a validated and verified simulation file, but in most cases, there is no such simulation available for the plant. The first step in our methodology is to do energy auditing. In Bridge Method, there is an opportunity to extract all data from a simulation file and use them to characterize the energy degradation through heat exchangers and process operations.

The first step in the Bride method is to identify the global minimum temperature difference or $\Delta T_{min,\ cont.}$ for each stream which is necessary to identify the maximum heat saving capacity in the ETD. In pinch based approaches, this parameter is identified by rough estimation of investment and energy cost and for different minimum temperature differences and plotting the total cost versus minimum temperature differences to find the optimum ΔT_{min} with minimum total cost. In the Bridge Method, there is an opportunity to use minimum temperature contribution specific to each stream.

Generally in an industrial plant, both liquid and vapor streams are present, which have a significantly different heat transfer coefficient, and for these cases, using the same minimum temperature difference does not seem to be a good approach [72]. The concept of minimum ΔT contribution was initially proposed to incorporate non-vertical (criss-cross) heat transfer for minimum area predictions [73, 74]. The actual temperature of process source and sink streams can be shifted by the individual ΔTmin contribution of each stream using Eq. 1 and Eq. 2.

$$For\ process\ source\ stream\ (i):\ T_i^* = T_i - \Delta T_{min,cont,i} \qquad (1)$$

$$For\ process\ sink\ stream\ (j):\ T_j^* = T_j + \Delta T_{min,cont,j} \qquad (2)$$

T_i* and T_i are the shifted and existing temperatures of process source stream i, and T_j* and T_j are the shifted and existing temperatures for process sink stream j, and $\Delta T_{min,cont,i}$ and $\Delta T_{min,cont,j}$ are the individual ΔTmin contribution of process source stream i and process sink j. It means that to connect stream i and stream j, the ΔTmin will be $\Delta T_{min,cont,i} + \Delta T_{min,cont,j}$.

The Bridge method has the ability to consider individual ΔT_{min} contribution for each stream, so the first step will be the identification of individual ΔT_{min} contribution for each stream which is a function of heat transfer coefficient, and few correlations have been developed to calculate it [37, 75]. There are also some tables that can help to identify the individual ΔT_{min} contribution based on heuristics [76]. These data can be used by an expert user to make a decision and determine an appropriate value for each stream.

The Bridge Method has the ability to represent the cascaded energy through process operations, which is pertinent to the energy degradation in each unit. The heat cascade through process operations has an impact on the minimum hot utility consumption because process sources in a HEN come from operations and process sinks in a HEN are inlets to operations. According to the onion diagram, which emphasizes the sequential nature of process design, the design starts from process operation and moves outward to the heat exchanger network and utilities [77]. So, process operation modification should be done before the HEN retrofit design.

Calculating and generating the ETD for the process operations alone can be done using a computer algorithm. As it is mentioned in part I of this paper, the energy demand of the process operations can be decreased by reducing the maximum process operation curve. First, the temperature of the maximum of the process operation curve should be identified. At this temperature, the process operations that have an impact should be listed for further analysis. Modification of the process operations is an open-ended decision-making problem and it needs expert users to do the feasibility study for possible modification. The modifications such as changing the operating pressures and temperature can be considered, and for each one, the feasibility and viability of that modification should be evaluated. After that, for potential modification opportunities, a re-simulation process should be done, and all data should be extracted for the next steps.

In an industrial plant, there are many process-process heat exchangers, heaters and coolers, and therefore, many Bridge modifications can be formulated. To reduce the search space and save time, the infeasible connections must be identified and removed from the network table before the Bridge enumeration step. A table can be generated by computer to take into account all connections between process source and process sink streams. Some connections are thermodynamically infeasible and automatically can be identified by the computer, but the forbidden or restricted connections should be identified by someone like the plant process engineer (PPE). For the rest of the connections, it is possible to rank them based on the associated risk such as complexity and safety. These are the unquantitative parameters that can help to find viable Bridge modification.

The fourth step is to enumerate the practical Bridge modification and calculate the energy-saving capacity of each one using the computer algorithms. In practice, the solutions with less than five modifications are more likely to be selected for implementation, so the Bridge modifications with four matches or less can be selected by the user for further analysis.

The fifth step is to calculate the investment cost and payback period for each modification, and it can be done by a computer algorithm. A cost model should be developed to consider the investment cost for each Bridge modification. This model helps to find the list of modifications that meet the payback period, and for each modification, the level of risk, which is identified in the previous step, will be represented. This list can be sorted by the amount of saving energy or the risk (unquantitative parameter). Then expert users can do a detailed analysis for each bridge and calculate the more precise investment cost by considering the type and number of new heat exchangers needed for each modification, the cost of adding area or relocating the heat exchangers.

In conclusion, five steps need to be considered to identify the most viable Bridge modifications in the conceptual design step:

- Identification of individual ΔT_{min} contribution for each stream
- Identification of possible process operation modification opportunities
- Identification infeasible stream connections
- Identification of practical Bridge modification
- Identification of economically viable Bridge modification

4.3.3 Developing a sequential decision-making structure incorporating the Bridge Method

As mentioned in chapter 3, engineering design by its nature is a sequential decision-making process whereby from a set of possible design options, the decision-makers sequentially triage the options as they include more insight, better data and with these reduce risk. In this section, the result of developing a sequential decision-making overall structure is presented. Plant-wide energy analysis is at its foundation a process design and needs to be done in a practical way that considers all the constraints such as scaling, the complexity of implementations and etc.

Figure 4-3 represents a step of a decision-making process. The necessary input information in each step will be added through Graphical User Interchange (GUI) which is a front-end tool for data input and output results which also is called "dashboard". Each step comprises two parts. The first part is the computerized calculation engines using algorithms. The result then will be represented in the dashboard and will be used for the second part in each step which is an open-ended decision-making problem and it needs expert users to do the feasibility study for possible modifications and make a decision. The decision then will be used as new information for the next sequence.

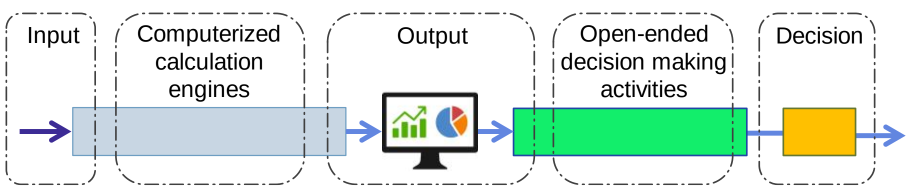

Figure 4-3 Generic single-step decision-making process in engineering design

Open-ended decision making cannot be computerized, and it allows good engineering judgment (GEJ) to be implicated in the design process. While the Bridge Method lends itself well to being formulated in computer algorithms, there are numerous open-ended decisions that need to be made from a practical perspective.

To make the final decision, the problem should be broken down into series of small dependent decision-making problems and using a sequential decision-making structure with one decision-making activity at each sequence in which the decisions made in early steps will affect the results in following steps. Figure 4-4 represents a schematic of a sequential decision-making structure.

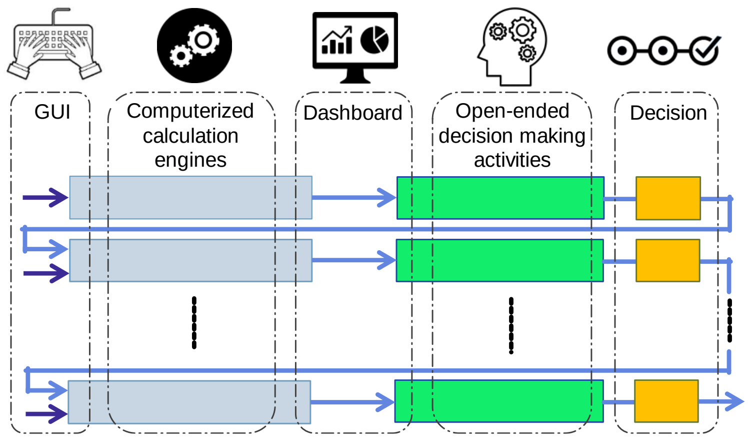

Figure 4-4 the overall structure of the proposed sequential design decision making process

Each sequence has an objective which is to make a specific decision and to do that, first specific data and constraints, and knowledge should be added to the system as input. These data will be employed for calculating and generating necessary decision metrics such as graphs and tables, using computer algorithms. Then, decision-makers use these metrics along with their knowledge and experiences (good engineering judgment) to make a decision through an open-ended decision-making process. The new decision at each sequence will be used in the next sequence as new information to narrow down the options and help to make the next decision.

4.3.4 defining the architecture of a decision support system framework incorporating the Bridge Method and the sequential decision-making

To make an effective decision-making process, especially for a complex problem with huge volumes of data, we need a computer-based information system (CBIS) to input necessary data, use them to calculate decision metrics and represent the results to the user. The Decision Support System (DSS) as an interactive, adjustable, and versatile type of CBIS is the best choice to make the complex decision-making process effective and efficient [63]. It can get the data from different sources, perform required analysis and optimizations, and provide reports and presentations using textual and graphical tools that suit the user’s needs [64].

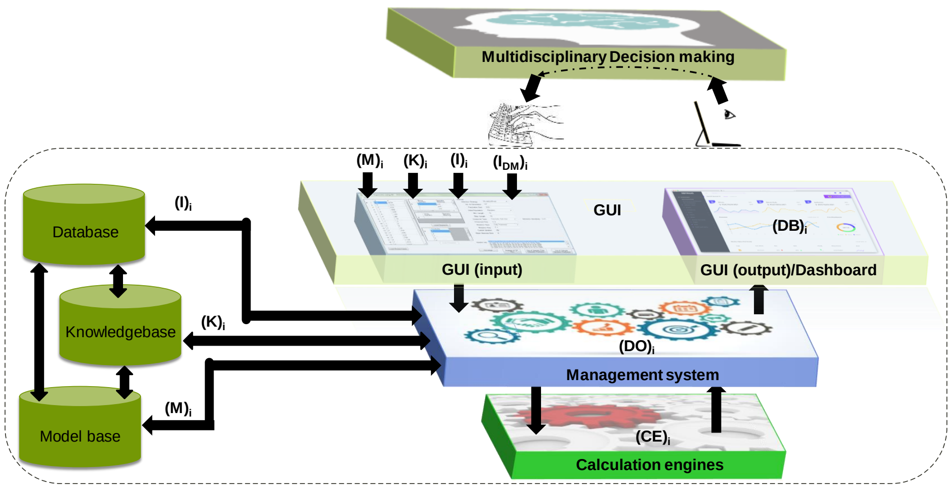

Figure 4-5 Overall Architecture of a decision support system framework incorporating the sequential decision-making process

Figure 4-5 shows the proposed Architecture of DSS to use for a sequential design decision-making process. The GUI includes input modules and the output modules or dashboard. The decision objective $(DO)_i$ determine what framework needs and what it should represent to users in the dashboard in each sequence. The case-relevant data $(I)_i$ or in some cases, new knowledge $(K)_i$ or models $(M)_i$ are added through the GUI and will be stored in the knowledge base, model base, and database by the management system. The Management system also includes the list of the decision objectives in execution priority order. Based on this list, at each sequence, the GUI asks for the necessary information relevant to the specific decision objective. The information is sent to the calculation engine to calculate and generate tables, graphs, or texts which are then represented in the dashboard $(DB)_i$. A multidisciplinary decision making committee is needed to take a decision based on information represented on the dashboard and their experiences and judgment. Regarding the new decision in each sequence, new information is added to the framework $(I_{DM})_i$.

Before the framework execution for Bridge Method, an energy auditing step is necessary to extract required energy-relevant data for the framework. Figure 4-6 shows a schematic of an appropriate energy auditing process. Before starting an energy analysis project, having the senior management commitment to decrease energy usage and GHG emissions is crucial. The mill manager must be the primary motivator of the project, as evidenced by attending the meeting, giving priority to energy matters, choosing an energy champion and identifying the hurdle rate (the minimum rate for return on investment) for the energy project. The energy champion is the leader of the energy projects with enough authority and skill to set up the initial program and to implement the first few phases.

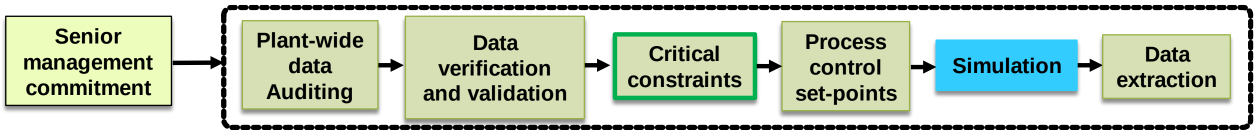

Figure 4-6 Energy auditing to identify some energy projects that have obvious savings before the design decision-making framework

In order to do the energy auditing, a multi-disciplinary team should be built because a wide variety of experience and skills is required to understand all aspects of energy utilization in the plant. Team members should include key representation from management, technical, engineering, operations, and maintenance departments.

The next step is to do a plant-wide data auditing for the industrial processes which normally have a large and complex steam generation and distribution system. In this step, the operating data have to be validated and verified to use them for the overall mass and energy balance of the plant. The critical constraints, particularly for the cogeneration system, such as boilers and turbines limitations including the energy contract, the minimum and maximum fuel usage of boilers and the minimum steam flowrate of turbine inlet should be considered. The next step is to take a look at the process control set-points and tuning them, which can lead to an energy saving with zero or near-zero capital cost. After that, a steady state simulation must be done by using the verified data from the previous step to calculate the energy and mass balance and produce a process flow diagram that is well balanced [78]. The extracted data from the simulation then will be used in the developed sequential decision-making framework.

The first step of the framework is to identify the $\Delta T_{min,\ cont.}$ for each stream. It can be the same for all streams, or it can be specific to each stream. Therefore, the objective of the first sequence of the framework, which is represented in figure 4.7, is to identify the individual ΔT_{min} contribution for all streams.

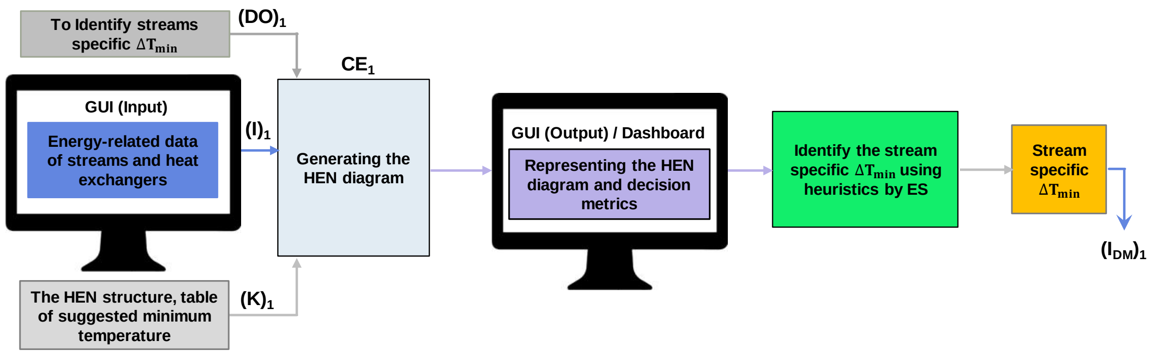

Figure 4-7 Identification of the individual ΔT_{min} contribution for streams

In this step, the user needs to input Energy-related data of streams and heat exchangers through the GUI. They are necessary to generate the existing HEN, including the hot and process sinks and existing exchangers. These case-specific data include initial and final temperature, mass flowrate and heat load for each stream, hot and cold utility temperature and heat load for each heater and cooler, placement of every exchanger with initial and final temperatures of the hot-end and the cold-end streams. Also, some information such as the knowledge to generate the HEN diagram and the list of suggested values for individual ΔT_{min} contribution for different types of streams will be used as inputs and will be sent to the calculation engine through the management system.

The calculation engine will generate the HEN diagram and represents a table which includes suggestions for stream specific ΔT_{min} according to the composition and physical phase of each stream. Then the HEN diagram will be represented on the dashboard with the table of suggested ΔT_{min}. In the next step, the decision-maker can accept the suggested values or refine them using his or her knowledge and expertise. The final ΔT_{min} for each stream will be added through the GUI and will store in the database.

The objective of the next sequence in the framework is to identify the process operation modifications. The Bridge Method will be useful here by showing the energy degradation through each process operation in the ETD. Figure 4.8 shows the sequence of the identification of process operations.

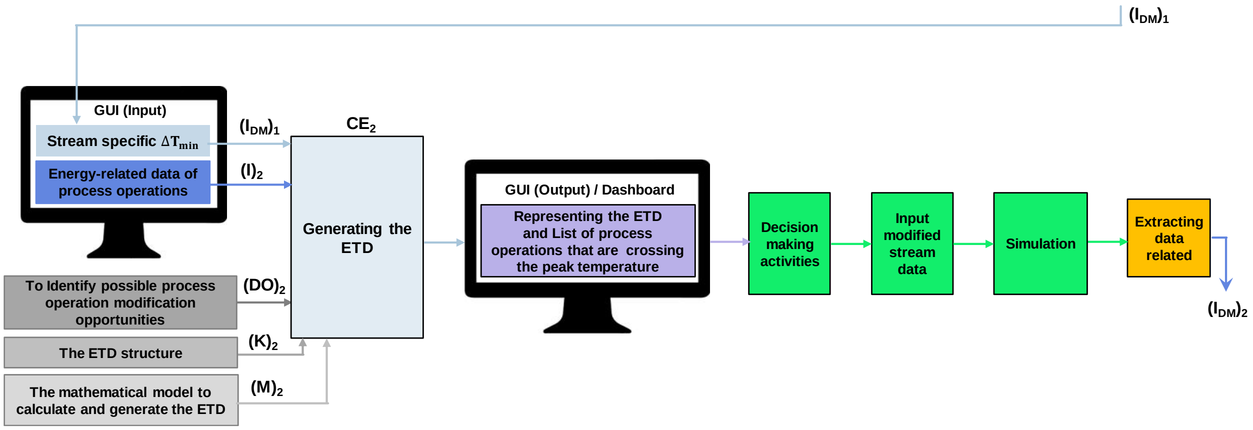

Figure 4-8 Identification of possible process operations modification opportunities

To calculate the ETD, the energy-related data for all process operations such as the list of process operations with input and output temperature, mass flowrate, heat load, and exothermic or endothermic reactions will be added to the framework by the user. Besides, the ETD structure and the mathematical formulation to calculate the ETD which are stored in the knowledge base and model base respectively, will the sent to the calculation engine through the management system. The energy transfer curve of a system is the difference between the sum of the outlet enthalpy rate curves and the sum of the inlet enthalpy rate curves (Eq. 3).

$$ETC_{Process\ operation}(T) = \sum_{out=1}^{Total\ outlets} \dot{H}_{out}(T) - \sum_{in=1}^{Total\ inlets} \dot{H}_{in}(T) \qquad (3)$$

The ETD is the combination of the ETCs of all process operations, and the maximum of the ETD will show the maximum hot utility consumption by process operations and to reduce that, the cascaded heat through the process operations that have an impact in the maximum of the curve should be reduced [5]. By calculating the temperature of the maximum of the ETD, and detecting the process operations which have an impact on the ETD at that temperature, the potential process operation modification can be identified. The ETD and the list of identified process operations will be represented on the dashboard, and we need to answer the question of the most viable process operation modification opportunities. The next step is to assess the list of process operations by Plant Process Engineer (PPE) and Plant Energy Superintendent (PES) using Good Engineering Judgement (GEJ) and to find possible opportunities to improve the energy efficiency of process operations that merit for their examination. After that, they need to confirm the operational viability of each modification. For each modification, we need to re-simulate the system and extract the data for the bridge modification. All following sequences of the framework should be executed for each potential process operation modification.

Figure 4.9 shows the next sequence of the framework, which is the identification of infeasible stream connections. Before calculating the Bridge modification, the infeasible connections need to be identified. Infeasible connection means a connection that is thermodynamically impossible, or it is categorized as the forbidden connection. The extracted data for each modification will be added to the system through the GUI. The Connection table will help to identify the infeasible connections. The columns in this table are assigned to the process sinks, and the rows represent the heat source. So each cell in this table belongs to a connection between hot and cold streams. This table will be generated by the calculation engine and will represent on the dashboard. Identification of infeasible stream connections will be done by the plant process engineer using the energy data and Good Engineering Judgment (GEJ).

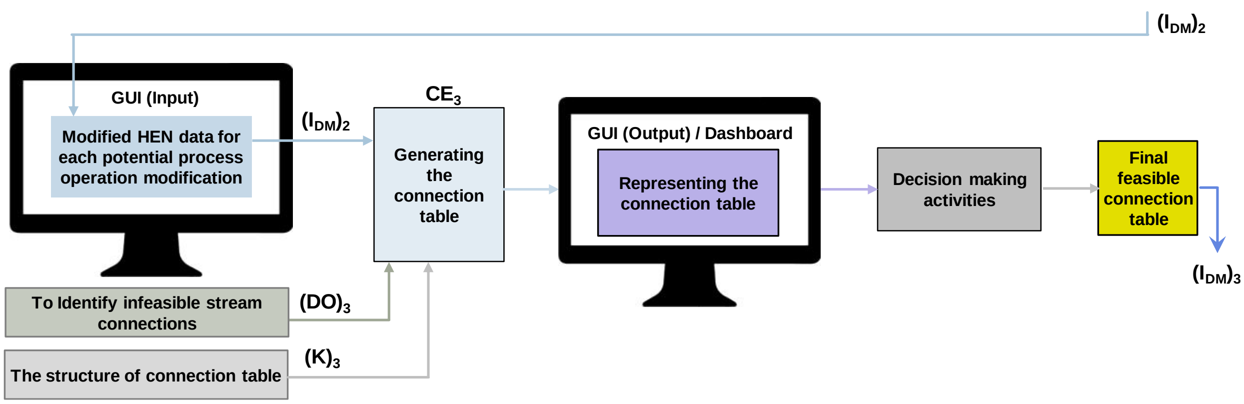

Figure 4-9 Identification of infeasible stream connections

To identify a viable solution, many parameters should be considered. These can be categorized into qualitative and quantitative parameters. In heat exchanger network retrofit, the qualitative parameters are safety, complexity, operability, and controllability and the quantitative parameters are the cost of the heat exchanger equipment and external utilities [33]. T consider the qualitative parameters, the plant process engineer and plant energy superintendent can identify high-risk connections, medium-risk connections, and low-risk connections using the GEJ.

The low-risk connections are the existing connections in which there is no need for piping and construction, and they can be assigned by number 1. The new connections that are close together, and there is no concern about any risk or complexity are categorized as medium-risk connections, and they are assigned by number 2. The connections that are far from each other, or there is a topology restriction or any complexity or controllability issues are categorized as the high-risk connections, and they are assigned by number 3.

For all feasible connections, the qualitative assessment needs to be done, and a number should be assigned to each connection. The list of weighted feasible connections will be added to the system by the user through the GUI.

Figure 4.10 shows the next sequence of the framework to identify the practical Bridge modifications. The Bridge Method has a tool named the network table to enumerate the Bridges. Each cell in this table belongs to a feasible connection between process sources and process sinks. Equation 2 shows the potential heat transfer capacity for each connection. The calculation engine will generate the list of all possible Bridges with a maximum of three matches, and it will calculate the average weighting factor for each Bridge. Then the sorted list of Bridges based on the energy-saving capacity with their average weighting factor will be represented on the dashboard. This list will give the decision-makers a good starting point for further assessment of the Bridge modifications. Besides, the modifications with more than five matches are more likely to be impractical.

$$Potential\ heat\ transfer\ capacity = Max\left(Min\left(FCp_{source} \times \left(T_{h_{Source}} - Max\left(T_{c_{Source}}, T_{c_{Sink}} + \Delta T_{Source} + \Delta T_{Sink}\right)\right), FCp_{Sink} \times \left(Min\left(T_{h_{Source}} - \Delta T_{Source} - \Delta T_{Sink}, T_{h_{Sink}}\right)\right)\right), 0\right) \quad (2)$$

The list of sorted Bridges will and for each modification, the added area and disposed area should be identified. Some modifications need few new heat exchangers and disposing areas or using smaller heat exchangers, and the investment cost for those modifications are made them impractical choices. The decision-makers then have to make a tradeoff between energy saving capacity and the weighting factor based on their experience and GEJ. The list of practical Bridge modifications will then be added to the system through the GUI.

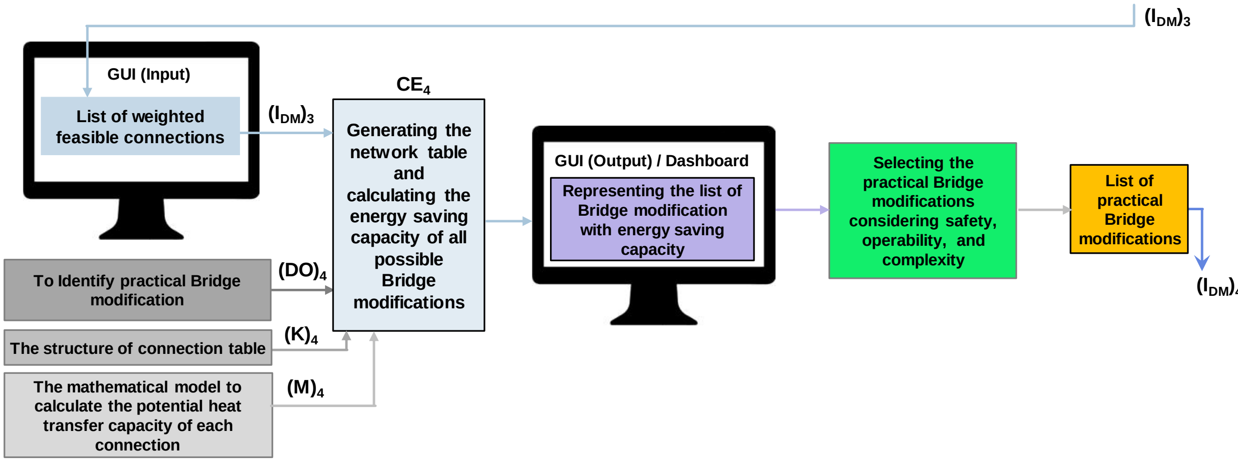

Figure 4-10 Identification of practical Bridge modifications

Figure 4.11 is the last sequence in the framework to identify the economically viable Bridge modifications. The input of this sequence is the list of practical Bridge modifications with the energy saving capacity and the weighted factor, which represent the complexity, controllability, operability, and risk for each connection.

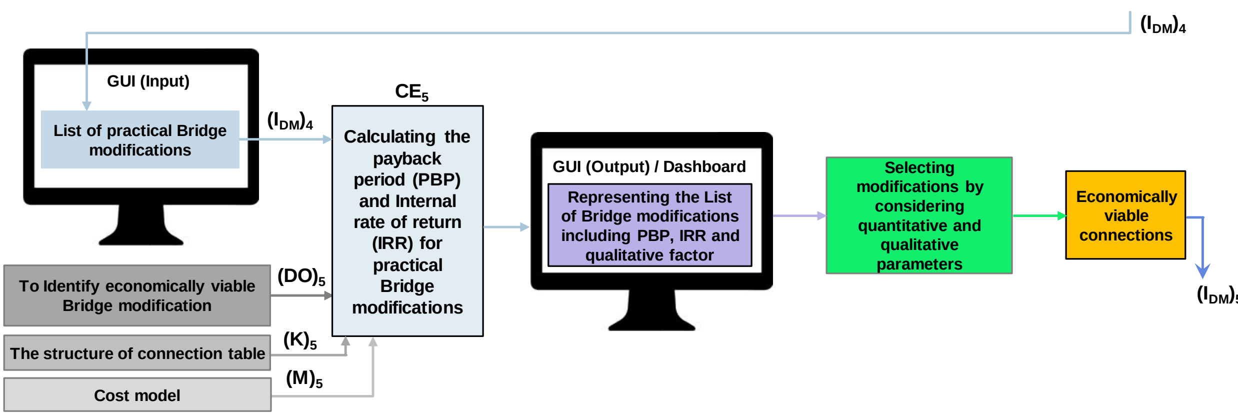

Figure 4-11 Identification of economically viable Bridge modifications

To meet the minimum payback period that was defined by the manager at the beginning of the energy analysis project, the payback period for each modification has to be identified. To calculate the investment cost, we need a model to consider the cost of purchasing a new exchanger, adding area to existing exchangers, relocating the heat exchangers and the cost of piping and pumping. Several studies have been done to develop a cost model for heat exchanger network retrofit. After calculating the investment cost, the payback period can be calculated for each Bridge modification, and it will be represented on the dashboard. So, for each modification, the payback period, which is a quantitative parameter and the risk level, which is a qualitative parameter are identified. Based on the GEJ and trading off between the two parameters for each solution, the decision-makers can come to a list of 10 to 20 economically viable modifications for each potential process operation modification.

4.3.5 Applying the framework considering the economic analytics

In this section, the results of applying the framework for energy analytics of a preheat train network is presented. An introduction to this case study has given in the previous chapter. The first step of the framework is to select or refine the minimum temperature contribution for each stream. The necessary information that needs to be added through the GUI is presented in Appendix C.

to generate the existing HEN diagram which is represented in figure 4.12.

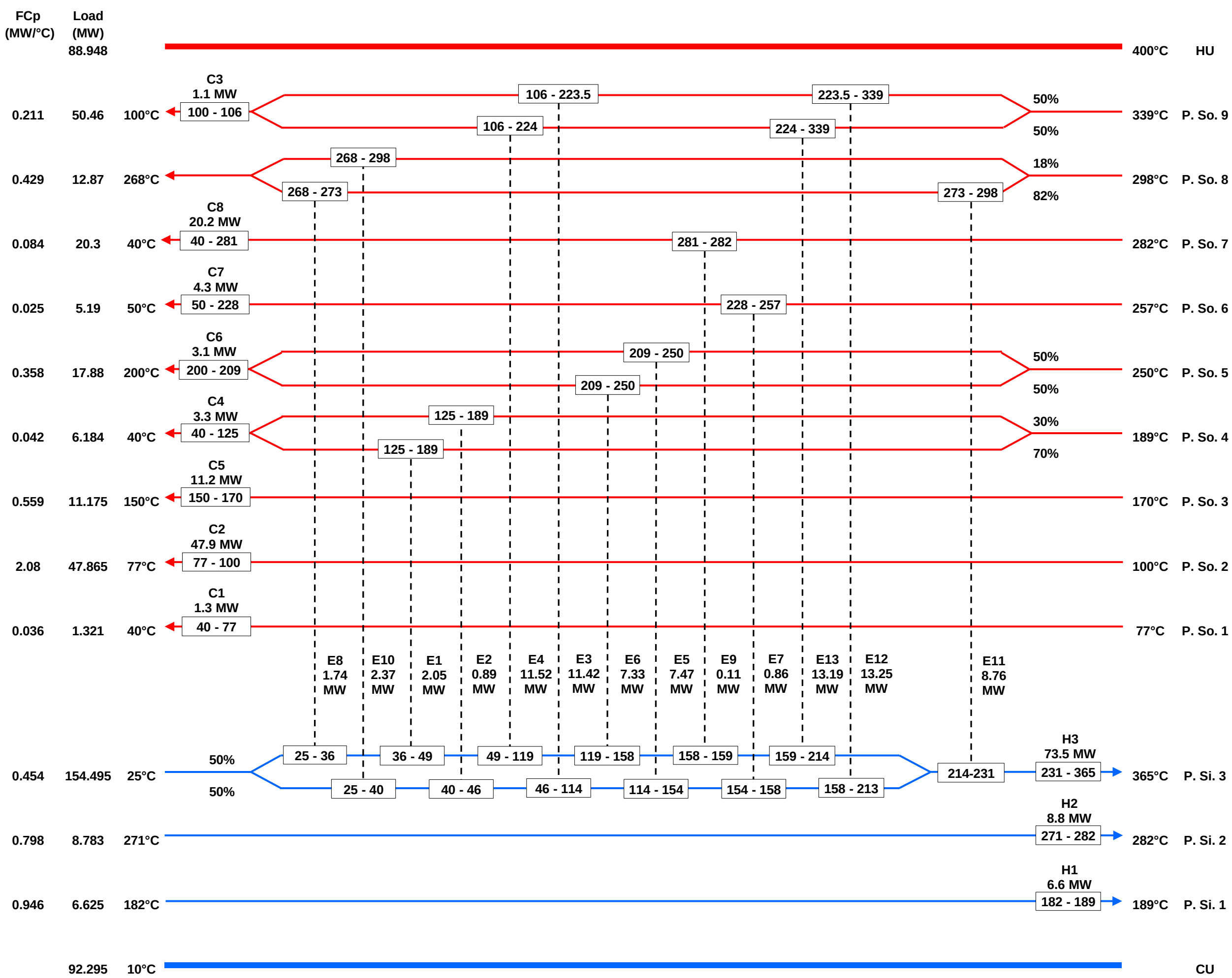

Figure 4-12 Initial Heat Exchanger Network (HEN)

In this case study, the focus is on economic analysis of Bridge modifications to identify viable solutions. We assumed that the minimum temperature contribution for all streams is equal to 5°C and there were no constraints on connecting streams. This means that all matches were feasible.

Figure 4.13 represents the ETD of the existing network before the retrofit. It shows that the maximum energy-saving capacity is 50 MW. In this example, the focus is on HEN modification, and information about the process operations part is not illustrated. ETD can help identify the Bridge modifications using a set of downward arrows.

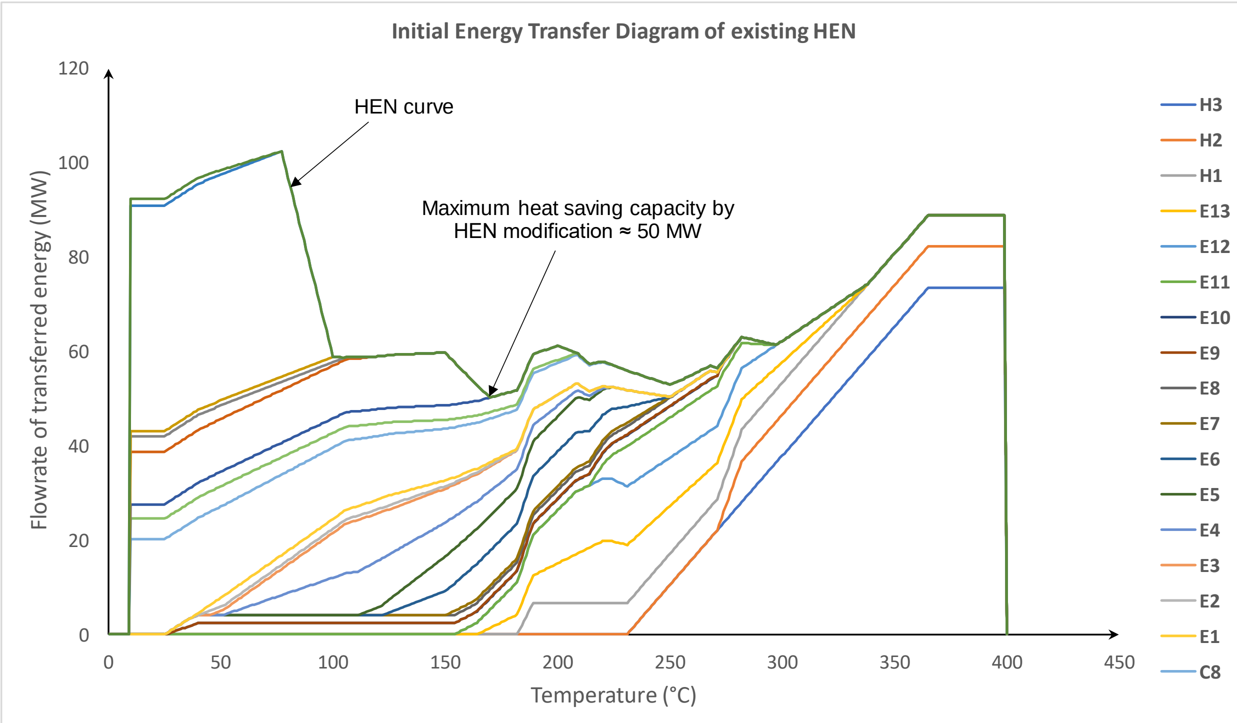

Figure 4-13 ETD of the existing HEN

In the fourth step of the framework, a list of Bridge modifications and their energy saving capacity are prepared. The network table is used to calculate the energy saving capacity of each Bridge modification which is shown in table 4.1. In this table, the process sources are placed in the first column, and the process sinks are placed in the first row. Each cell shows the maximum transferable energy between a process source and a process sink. For example, to enumerate C1H1, one should look at the cell at the intersection between C1 and H1, which is 0.

Table 4-1 Network table

	CU	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	H1	H2	H3
HU																	
E13														13.2	6.6	6.1	10.3
E12													13.3	12.2	6.6	6.1	10.3
E11												8.8	8.8	8.8	6.6	6.0	8.8
E10											2.4	2.3	2.3	2.3	2.3	1.3	2.3
E9										0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
E8									1.7	0.2	1.8	1.8	1.8	1.8	1.8	0.0	1.8
E7								0.9	0.7	0.2	0.7	0.7	0.7	0.7	0.7	0.0	0.4
E6							7.3	0.9	2.6	0.2	3.5	4.7	7.3	7.3	6.6	0.0	1.6
E5						7.5	7.3	0.9	2.6	0.2	3.5	4.7	7.3	7.3	6.6	0.0	1.6
E4					11.5	9.2	8.9	0.9	2.6	0.2	3.5	0.0	6.3	5.3	3.4	0.0	0.0
E3				11.4	12.4	9.2	8.9	0.9	2.6	0.2	3.5	0.0	6.3	5.2	3.3	0.0	0.0
E2			0.9	0.8	0.8	0.8	0.7	0.4	0.8	0.2	0.8	0.0	0.3	0.2	0.0	0.0	0.0
E1		2.1	1.2	1.9	1.9	1.9	1.7	0.9	1.9	0.2	1.9	0.0	0.7	0.4	0.0	0.0	0.0
C8		3.1	1.2	9.2	15.5	9.2	8.9	0.9	2.6	0.2	3.5	4.8	9.8	9.0	6.6	0.0	3.4
C7		3.1	1.2	2.7	4.2	2.7	2.4	0.9	2.6	0.2	3.5	0.1	1.6	1.4	0.9	0.0	0.0
C6		3.1	1.2	3.2	3.2	3.2	3.2	0.9	2.6	0.2	3.2	0.0	3.2	3.2	3.2	0.0	0.0
C5		3.1	1.2	9.2	11.2	9.2	8.3	0.9	2.6	0.0	3.5	0.0	1.4	0.0	0.0	0.0	0.0
C4		3.1	1.2	0.2	2.7	0.2	0.0	0.0	2.6	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0
C3		1.3	1.2	0.0	1.3	0.0	0.0	0.0	1.3	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0
C2		3.1	1.2	0.0	8.5	0.0	0.0	0.0	2.6	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0
C1		1.1	1.0	0.0	0.6	0.0	0.0	0.0	1.3	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0

The network table is used to calculate the energy saving capacity of each Bridge modification which is shown in table 4.6. In this table, the process sources are placed in the first column, and the process sinks are placed in the first row. Each cell shows the maximum transferable energy between a process source and a process sink. For example, to enumerate C1H1, one should look at the cell at the intersection between C1 and H1, which is 0. Tables 4-2 and 4-3 present the list of Modifications with one and two matches.

Table 4-2 List of Bridge modifications with one match

Bridges with one match	Heat saving capacity (MW)
C8H1	6.6
C8H3	3.4
C6H1	3.2

Table 4-3 List of Bridge modifications with two matches

Bridges with one match	Heat saving capacity (MW)
C8E12,E12H3	9.8
C8E13,E13H3	9.0
C5E5,E5H1	6.6
C5E6,E6H1	6.6
C8E5,E5H1	6.6
C8E6,E6H1	6.6
C8E12,E12H1	6.6
C8E13,E13H1	6.6
C8E12,E12H2	6.1
C8E13,E13H2	6.1

The fifth step of the Bridge Framework is to calculate the payback period and IRR for each modification. To calculate the energy cost, the following cost model is used [79]:

Energy cost (USD) = 312000 *(Q(kW))

The following equations are employed to estimate the investment cost regarding a new heat exchanger of adding the area to an existing exchanger:

*purchasing new heat exchanger (including the cost of piping and installation) = 188186 + 2254*A*

Cost of adding area to an existing heat exchanger = $2254*A^{0.68}$

To calculate the IRR, the interest rate was set to 10% for ten years. The payback period and IRR of the most interesting Bridge modifications are shown in Tables 4-4 and 4-5.

Table 4-4 List of Bridge modifications with one match

Bridges with one match	energy saving (MW)	Capital cost ($)	Energy saving cost ($/year)	Parback period (Year)	IRR
C8H1	6.6	1,253,866	2,032,954	0.6	165%
C8H3	3.4	1,247,392	1,031,520	1.2	84%
C6H1	3.2	1,391,668	989,154	1.4	72%

The economic analysis results for Bridges with one match are presented in figure 4-14. The first modification which is C8H1, the payback period is less than a year, and the IRR is higher than the other two projects. C8H3 and C6H1 modifications can be done together because they are independent projects. For this group (C8H3, C6H1), the payback period is 1.3 year and the IRR is 78% and it can lead to 6.6 MW of energy saving.

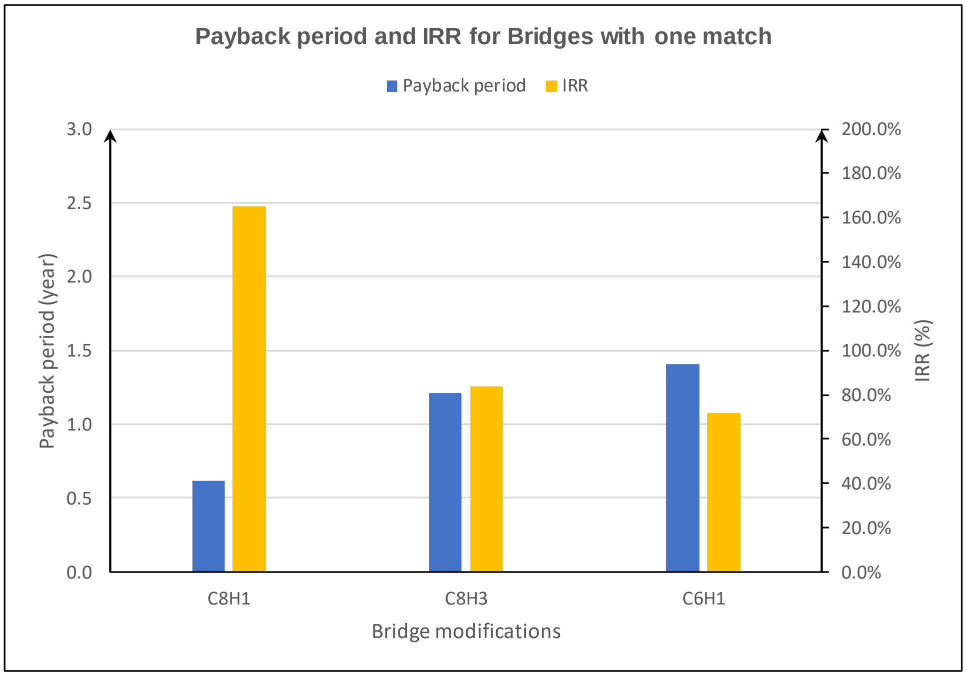

Figure 4-14 Payback period and Internal Rate of Return for Bridge modifications with one match

Table 4-5 List of Bridge modifications with two matches

Bridges with two matches	energy saving (MW)	Capital cost ($)	Energy saving cost ($/year)	Parback period (Year)	IRR
C8E12,E12H3	9.8	2,702,622	3,017,196	0.9	112%
C8E13,E13H3	9.0	2,747,938	2,759,316	1.0	100%
C5E5,E5H1	6.6	2,822,255	2,032,954	1.4	72%
C5E6,E6H1	6.6	2,937,297	2,032,954	1.4	69%
C8E5,E5H1	6.6	2,436,231	2,032,954	1.2	83%
C8E6,E6H1	6.6	2,442,316	2,032,954	1.2	83%
C8E12,E12H1	6.6	2,295,505	2,032,954	1.1	88%
C8E13,E13H1	6.6	2,298,489	2,032,954	1.1	88%
C8E12,E12H2	6.1	2,258,101	1,878,533	1.2	83%
C8E13,E13H2	6.1	2,260,570	1,878,533	1.2	83%

Figure 4-15 shows the results of Bridges with two modifications. It is safe to say that all modifications have an acceptable IRR with payback periods lower than 1.5 years. It shows that (C8E12, E12H3) is the most interesting modification and it can be done at the same time with (C5E5, E5H1) or (C5E6, E6H1) to save more energy.

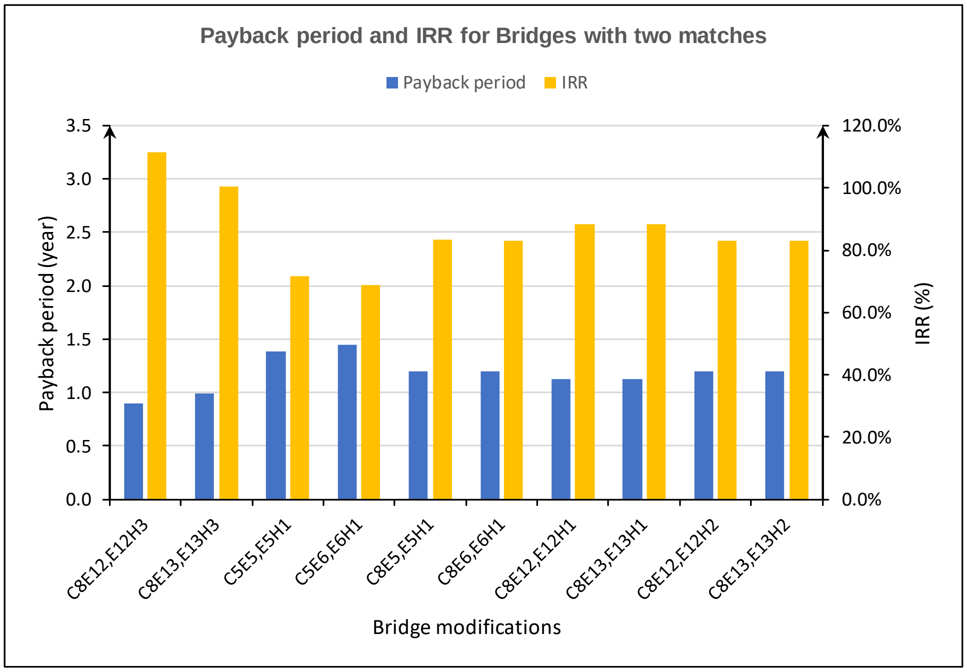

Figure 4-15 Payback period and Internal Rate of Return for Bridge modifications with two matches

4.3.6 Energy analytics of a Scandinavian kraft pulp mill model using the framework

It has been shown in section 4.3.4 that how different steps of the framework are designed to make a specific decision through the retrofit design. To demonstrate the framework, a Scandinavian pulp mill model has been analyzed in this section. The process description has presented in the previous chapter. The case-specific data that are needed in the first step of the framework are presented in Appendix D. All these data should be added to the framework through GUI and will be used to generate the existing HEN diagram.

The calculation engine uses the input data and the knowledge of creating the HEN diagram and generates the existing HEN diagram which is shown in figure 4.16. For streams with the liquid phase, the minimum temperature difference contribution is between 3 to 5 °C according to the literature and for gas streams, it goes up to 10 to 15 °C. Selecting a suitable value for each stream is not easy and needs an expert engineer to decide which one is more appropriate. In this case, the simulation of the mill was done using the $\Delta T_{min\text{-}cont.}$ for each stream which is shown in table 4-6.

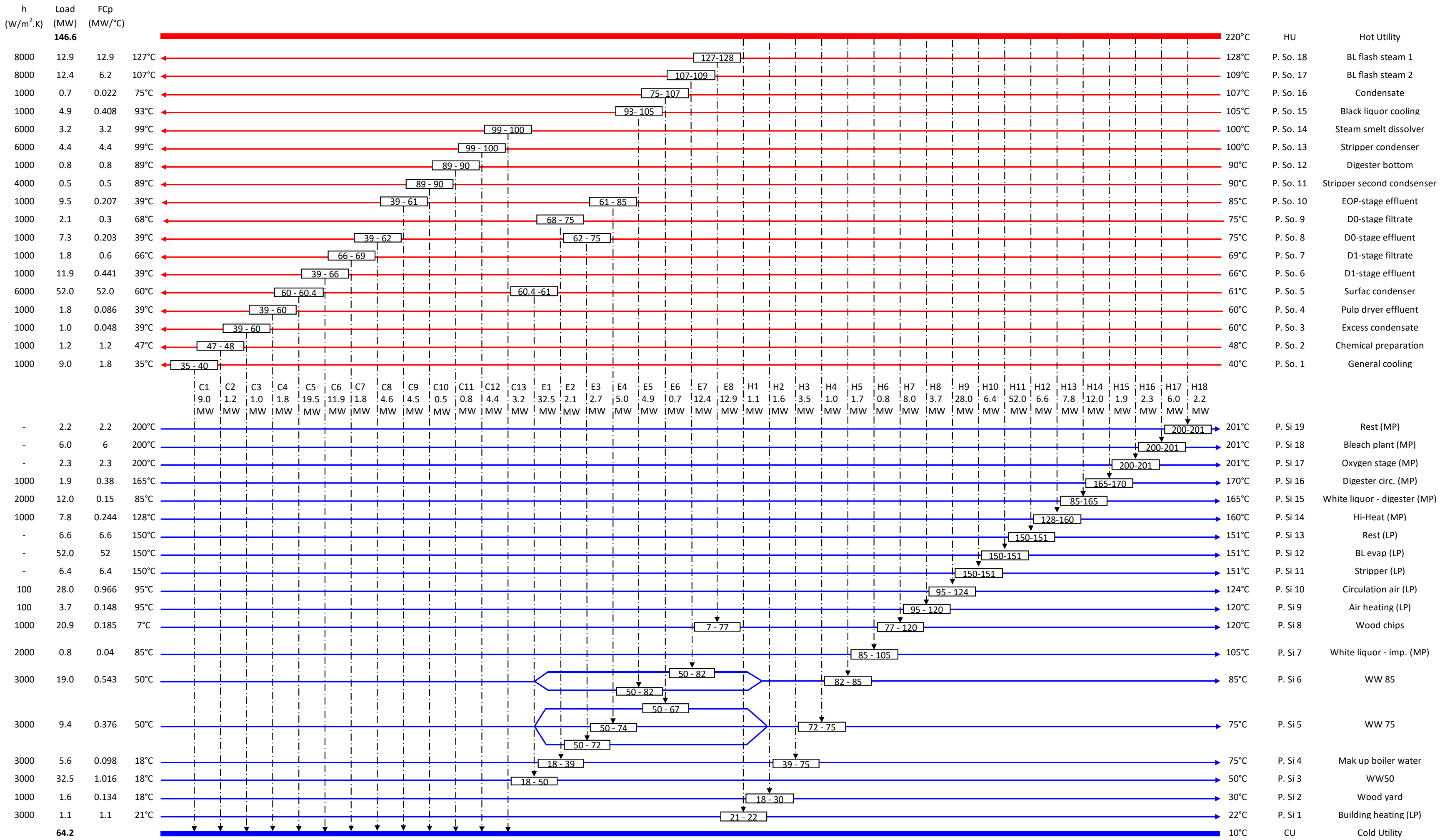

Figure 4-16 Existing HEN diagram

Table 4-6 The $\Delta T_{min\text{-}cont.}$ for each stream

Stream No.	Min ΔT contribution $\Delta T_{min\text{-}cont.}$ (°C)	Stream No.	Min ΔT contribution $\Delta T_{min\text{-}cont.}$ (°C)
P. So. 1	3.5	P. Si. 1	8.0
P. So. 2	3.5	P. Si. 2	4.0
P. So. 3	3.5	P. Si. 3	2.5
P. So. 4	3.5	P. Si. 4	2.5
P. So. 5	2.0	P. Si. 5	2.5
P. So. 6	3.5	P. Si. 6	2.5
P. So. 7	3.5	P. Si. 7	3.5
P. So. 8	3.5	P. Si. 8	3.5
P. So. 9	3.5	P. Si. 9	8.0
P. So. 10	3.5	P. Si. 10	8.0
P. So. 11	4.0	P. Si. 11	0.5
P. So. 12	3.5	P. Si. 12	0.5
P. So. 13	2.0	P. Si. 13	0.5
P. So. 14	2.0	P. Si. 14	3.5
P. So. 15	3.5	P. Si. 15	3.5
P. So. 16	3.5	P. Si. 16	3.5
P. So. 17	2.0	P. Si. 17	0.5
P. So. 18	2.0	P. Si. 18	0.5
-	-	P. Si. 19	0.5

Values of $\Delta T_{min\text{-}cont.}$ should be added to the system. The second step of the framework is to find opportunities for potential process operation modifications. A Simplified process diagram was presented in the previous chapter. The data related to input and output of pre-impregnation vessel (PO1), digester (PO2), the first and the second flash system, the bleaching plant, pulp dryer, evaporator and stripper are added to the framework. The calculation engine uses these case-specific data to calculate the ETD of the process operations. The calculation engine must first analyze each process operation individually and then put them together to have a whole picture of energy degradation through all units.

The procedure of calculating ETD is explained here by showing how it is done for the first unit which is the pre-impregnation vessel. Figure 4.17 shows a schematic of this unit with energy-related data of input and output streams.

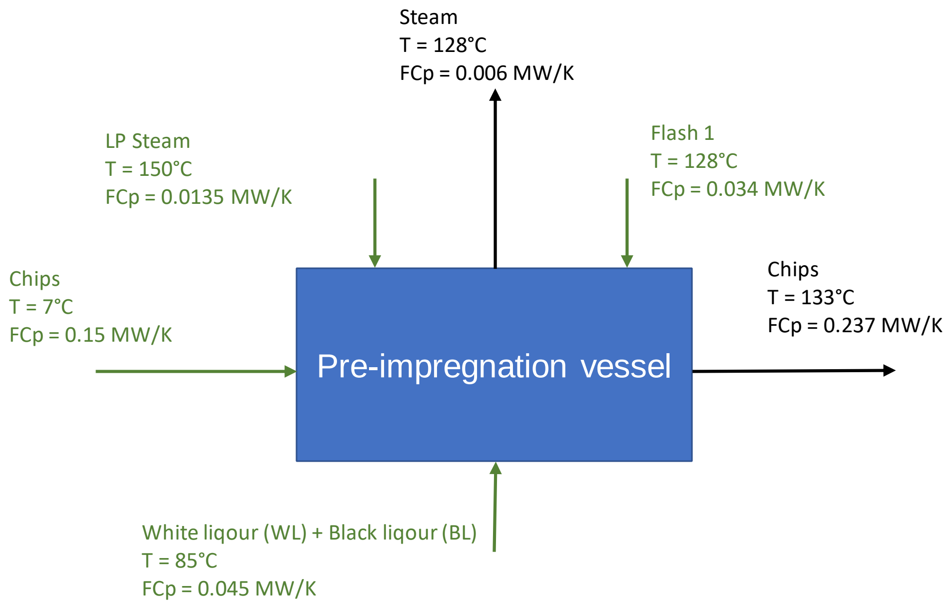

Figure 4-17 Pre-impregnation vessel input and output streams

Based on these data and the enthalpy formulation, the curves of the total inlet and outlet enthalpy of the pre-impregnation vessel are calculated and shown in figure 4.18.

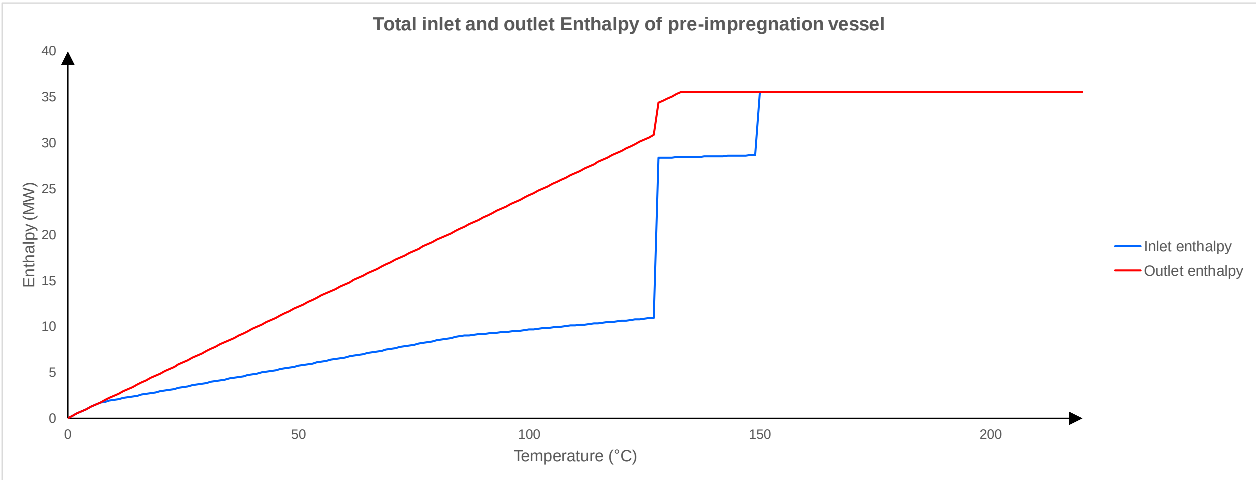

Figure 4-18 Total inlet and outlet enthalpy curves of the pre-impregnation vessel

The flow rate of transferred energy through this unit in the difference between the total outlet and inlet enthalpy rate. Figure 4.19 represents the flow rate of transferred energy as a function of temperature or ETD of the pre-impregnation vessel.

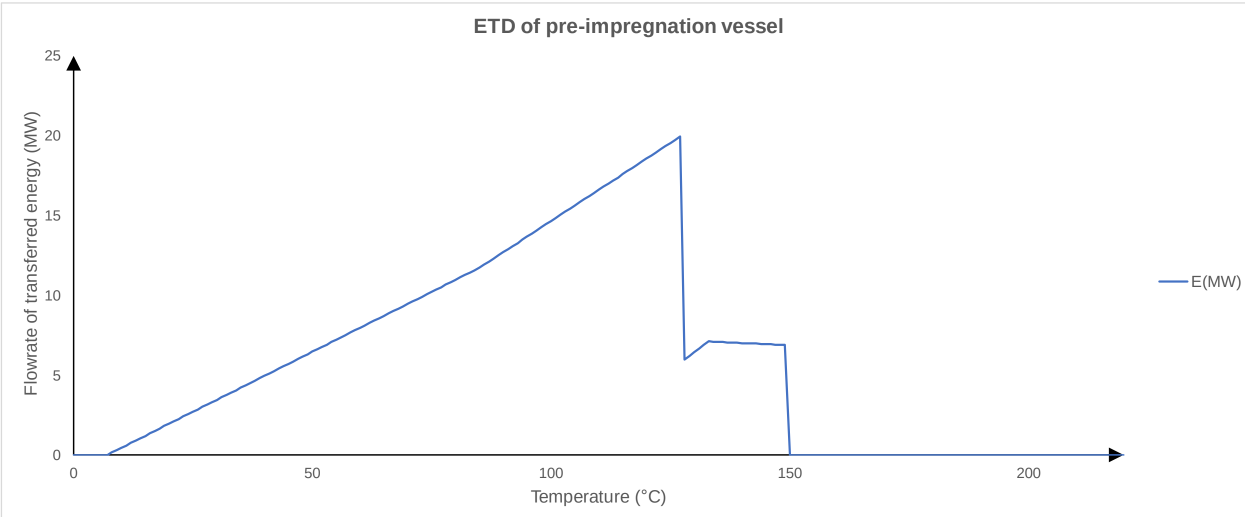

Figure 4-19 ETD of the pre-impregnation vessel

This procedure has been done for all units and the final ETD is presented in figure 4-20. This diagram represents how energy cascades through different units. As it is mentioned before, this diagram helps to identify process operation modifications.

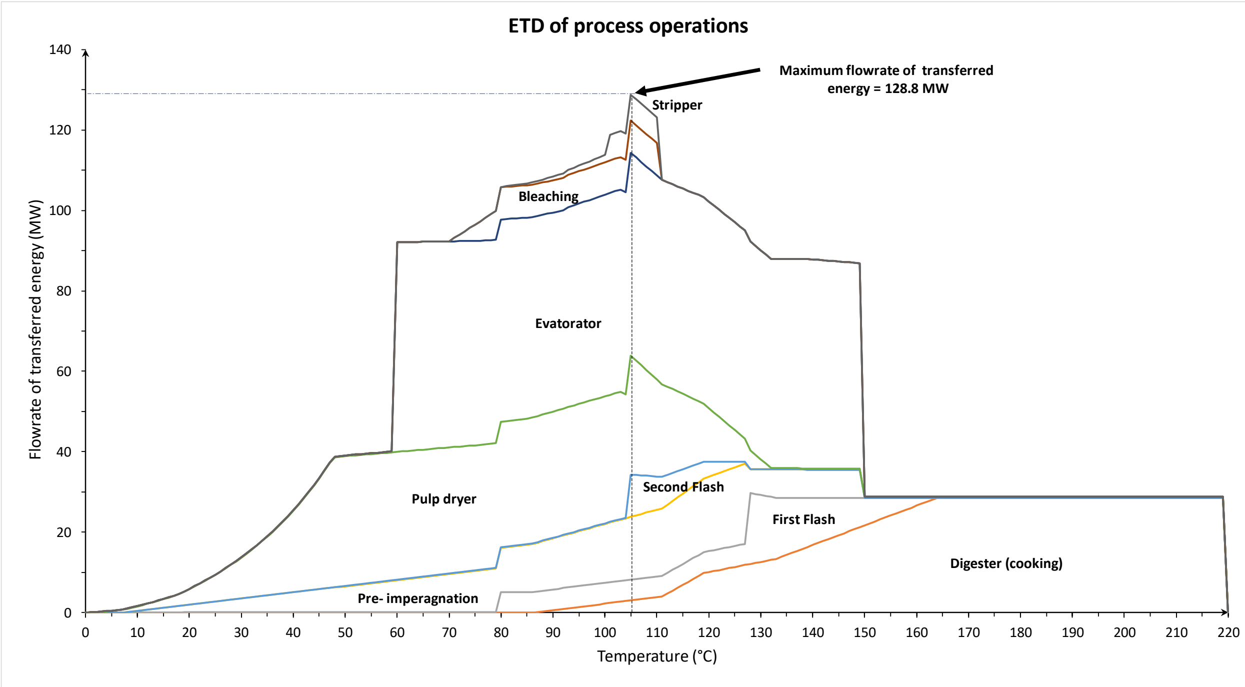

Figure 4-20 The ETD of all process operations

The maximum of the process operation curve happens at 105 °C. At this temperature, the total flowrate of energy or total energy transferred is equal to 128.8 MW. As it is represented in table 4-7, the evaporator and the pulp dryer have the highest impact on total transferred energy.

Table 4-7 The sorted list of process operations

Sorted list of procss operations based on their energy degradation at the peak temperature	
Evaporator	50.5 MW
Pulp dryer	29.5 MW
Pre-impregnation	15.6 MW
Second Flash	10.5 MW
Bleaching	8 MW
Stripping	6.5 MW
First Flash	5.2 MW
Cooking	3 MW

A calculation engine can automatically generate the ETD and information in table 4-7. Based on this information the focus of the open-ended decision making process in this step is on finding a solution to modify the evaporator and pulp dryer. The ETD of the evaporator is shown in figure 4.21. In this case, LP steam is used as an input in the first effect of the evaporator and the steam from the first effect is sent to the next effect. The steam from the sixth effect is employed by the surface condenser to generate warm water at 50 °C.

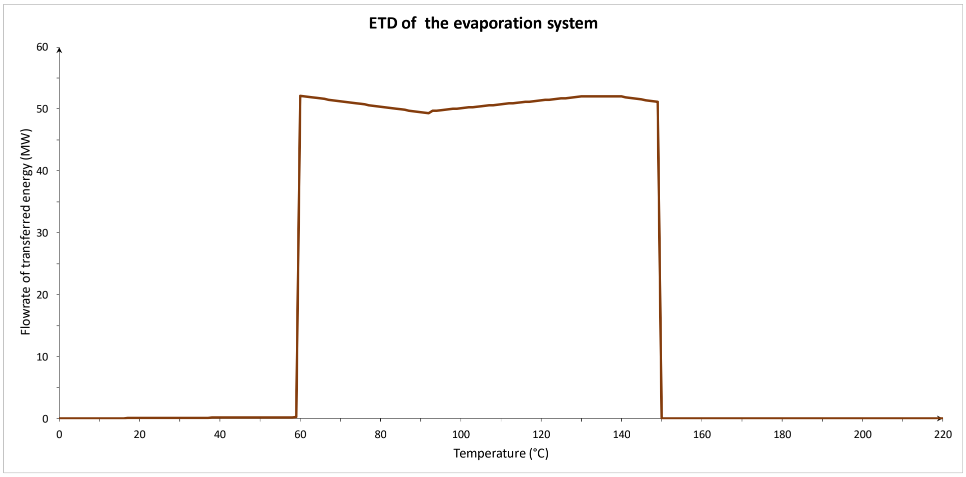

Figure 4-21 The ETD of the evaporator

To decrease the hot utility usage of the evaporator, the number of effects can be increased. It leads to an increase in investment cost and a techno-economic analysis is needed to assess the profitability of this project. Another solution is the method developed in Chalmers University to use excess heat from a process at high temperature at using it in the fourth or fifth effect of evaporation train and reducing the LP steam demand. Using new technology such as electric evaporator can significantly decrease the hot utility demand and could be an interesting option to consider. Figure 4.22 represents the individual ETD of the pulp dryer.

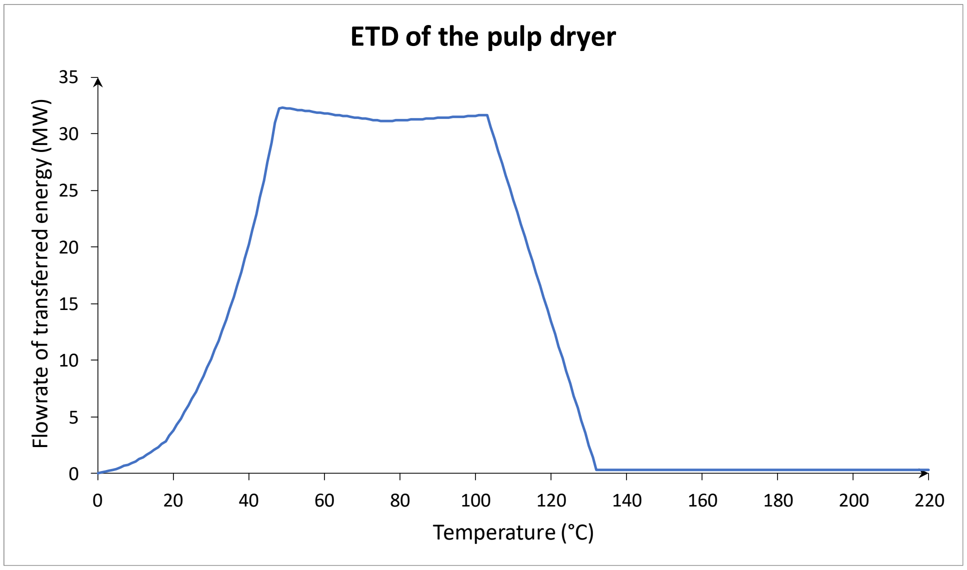

Figure 4-22 ETD of the pulp dryer

The inlet air to the pulp dryer is preheated with the warm outlet air and an LP steam. An option to reduce energy consumption is to increase the surfing area in the dryer and reduce the hot air flowrate. Another option is to use new technologies such as infrared radiation to reduce steam demand. In general, the plant process engineer, and the plant energy superintendent are working together to assess the process operations, confirm the operational viability, and do the simulation for viable modification.

In the third step of the framework, the feasibility of connecting process sources and sinks are evaluated. Figure 4-23 shows the connection table that is utilized to identify infeasible connections and the level of risk associated with the rest. Since this case is a hypothetical model of a mill, the risk level of connections does not reflect the reality of the process.

			BuilE:Pding heating (LP) P. Si 1 H1	Wood yard P. Si 2 H2	WW50 P. Si 3 E1	Make up boiler water P. Si 4 E2 - H3	WW 75 P. Si 5 E3-E4-E6-H4	WW 85 P. Si 6 E5-E7-H5	White liquor - imp. (MP) P. Si 7 H6	Wood chips P. Si 8 E8 - H7	Air heating (LP) P. Si 9 H8	Circulation air (LP) P. Si 10 H9	Stripper (LP) P. Si 11 H10	BL evap (LP) P. Si 12 H11	Rest (LP) P. Si 13 H12	Hi-Heat (MP) P. Si 14 H13	White liquor - digester (MP) P. Si 15 H14	Digester circ. (MP) P. Si 16 H15	Oxygen stage (MP) P. Si 17 H16	Bleach plant (MP) P. Si 18 H17	Rest (MP) P. Si 19 H18
General cooling	P. So. 1	C1																			
Chemical preparation	P. So. 2	C2			1		1	1	1								1				
Excess condensate	P. So. 3	C3		1	2	2	2	2	1								1				
Pulp dryer effluent	P. So. 4	C4			2	1	2	2													
Surfac condenser	P. So. 5	C5 - E1			2	2	2	2	2								2				
D1-stage effluent	P. So. 6	C6			2		2	2	1								1				
D1-stage filtrate	P. So. 7	C7			2		2	2	1								1				
D0-stage effluent	P. So. 8	C8 - E3			2		2	2	1								1				
D0-stage filtrate	P. So. 9	E2			2		2	2	1								1				
EOP-stage effluent	P. So. 10	C9 - E4			2	1	2	2	1								1				
Stripper second condenser	P. So. 11	C10		1	2	2	2	2	1								1				
Digester bottom	P. So. 12	C11			3	1	3	3	3								3				
Stripper condenser	P. So. 13	C12		1	2	2	2	2	1								1				
Steam smelt dissolver	P. So. 14	C13		1	1	3	1	1	1	1							1				
Black liquor cooling	P. So. 15	E5			3	1	3	3	3				1	2	1	3	3	3	1		
Condensate	P. So. 16	E6			3	1	3	3	3				1	2	1	3	3	3	1		
BL flash steam 2	P. So. 17	E7		2	3	1	3	3	3	3			1	2	1	3	3	3	1		
BL flash steam 1	P. So. 18	E8		2	3	1	3	3	3	3			1	2	1	3	3	3	1		

Figure 4-23 The connection table

The next step is to enumerate the Bridge modifications. Bridge Method has a systematic approach to identify the energy saving capacity of each modification (figure 4-24). The minimum temperature contribution of each stream is an important parameter to calculate the heat flowrate for each match.

	CU	E1	E2	E3	E4	E5	E6	E7	E8	H1	H2	H3	H4	H5	H6	H7	H8	H9	H14
HU	Saving									1.1	1.6	3.5	1.0	1.7	0.8	8	3.7	28	12
E8									**12.9**	1.1	1.6	3.5	1.1	1.6	0.8	8.0	3.4	12.9	5.6
E7								**12.4**	12.4	1.1	1.6	3.5	1.1	1.6	0.7	4.9	0.6	3.9	2.8
E6							**0.7**	0.7	0.7	0.7	0.7	0.7	0.6	0.4	0.3	0.5	0.0	0.0	0.3
E5						**4.9**	0.7	4.9	4.9	1.1	1.6	3.5	1.1	1.6	0.5	3.9	0.0	0.0	2.0
E4					**5.0**	4.4	0.7	5.0	5.0	1.1	1.6	3.5	1.1	0.0	0.0	0.2	0.0	0.0	0.0
E3				**2.3**	2.7	2.7	0.7	2.7	2.7	1.1	1.6	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E2			**2.1**	2.1	2.1	2.1	0.7	2.1	2.1	1.1	1.6	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E1		**32.5**	2.1	0.8	1.4	1.0	0.3	2.5	9.0	1.1	1.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C13	3.2	3.2	2.1	2.7	3.2	3.2	0.7	3.2	3.2	1.1	1.6	3.2	1.1	1.6	0.4	3.2	0.0	0.0	1.4
C12	4.4	4.4	2.1	2.7	4.4	4.4	0.7	4.4	4.4	1.1	1.6	3.5	1.1	1.6	0.4	3.3	0.0	0.0	1.4
C11	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.0	0.8	0.0	0.0	0.0
C10	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.5	0.0	0.0	0.0
C9	4.5	4.5	2.1	0.6	1.0	0.8	0.2	1.0	4.5	1.1	1.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C8	4.6	4.6	2.1	0.7	1.2	0.9	0.2	1.2	4.6	1.1	1.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C7	1.8	1.8	1.8	1.6	1.8	1.8	0.5	1.8	1.8	1.1	1.6	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6	11.9	11.9	2.1	1.2	2.1	1.5	0.4	3.9	9.6	1.1	1.6	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C5	19.5	20.8	2.1	0.7	1.2	0.9	0.2	2.3	8.9	1.1	1.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C4	1.8	1.8	1.8	0.3	0.3	0.3	0.2	0.3	1.8	1.1	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C3	1.0	1.0	1.0	0.2	0.2	0.2	0.2	0.2	1.0	1.0	1.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C2	1.2	1.2	1.2	0.0	0.0	0.0	0.0	0.0	1.2	1.1	1.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C1	9.0	9.0	1.6	0.0	0.0	0.0	0.0	0.0	4.8	1.1	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 4-24 The network table

The total number of Bridge modifications depends on the number of heaters, coolers and internal heat exchangers. Selecting the practical solutions among the list of all Bridge modifications should be done by a user. The energy saving capacity and the level of risk for each modification is assessed by the plant process engineer to choose the most practical options for further analysis. Tables 4-8 to 4-10 represent the list of practical Bridge modifications with one, two and three matches that are selected in this step.

Table 4-8 List of practical Bridge modifications with one match

Bridges with one match	Heat saving capacity	Qualitative weighting factor
C12H3	3.5	2
C13H3	3.2	1
C12H5	1.6	2
C13H5	1.6	3
C12H2	1.6	3
C13H2	1.6	3
C5H3	1.6	2
C12H14	1.4	3
C13H14	1.4	3
C4H3	1.2	3
C12H4	1.1	2
C13H4	1.1	3
C3H2	1.0	3

Table 4-9 List of practical Bridge modifications with two matches

Bridges with Two matches	Heat saving capacity	Qualitative weighting factor
C12E7,E7H7	4.4	2 - 1
C6E7,E7H7	3.9	2 - 1
C6E7,E7H3	3.4	2 - 3
C12E4,E4H3	3.4	2 - 3
C12E5,E5H3	3.4	1 - 2
C12E7,E7H3	3.4	2 - 1
C13E4,E4H3	3.2	3 - 3
C13E5,E5H3	3.2	3 - 3
C13E5,E5H7	3.2	1 - 1
C13E7,E7H3	3.2	3 - 3
C13E7,E7H7	3.2	3 - 1
C6E7,E7H14	2.8	2 - 1
C12E7,E7H14	2.8	2 - 1
C13E7,E7H14	2.8	3 - 1
C5E7,E7H3	2.3	2 - 3
C5E7,E7H7	2.3	2 - 1
C5E7,E7H14	2.3	2 - 1
C6E4,E4H3	2.1	2 - 3
C12E5,E5H14	2.0	2 - 1
C13E5,E5H14	2.0	3 - 1

Table 4-10 List of practical Bridge modifications with three matches

Bridges with Three matches	Heat saving capacity	Qualitative weighting factor
C12E5,E5E7,E7H7	4.4	2 - 1 - 1
C12E7,E7E8,E8H7	4.4	2 - 1 - 1
C12E7,E7E8,E8H14	4.4	2 - 1 - 1
C6E7,E7E8,E8H7	3.9	2 - 1 - 1
C6E7,E7E8,E8H14	3.9	2 - 1 - 1
C12E4,E4E7,E7H3	3.4	2 - 2 - 3
C12E7,E7E8,E8H3	3.4	2 - 1 - 3
C13E4,E4E7,E7H7	3.2	3 - 2 - 1
C13E5,E5E7,E7H3	3.2	3 - 1 - 3
C13E5,E5E7,E7H7	3.2	3 - 1 - 1
C13E7,E7E8,E8H7	3.2	3 - 1 - 1
C13E7,E7E8,E8H14	3.2	2 - 1 - 1
C12E4,E4E7,E7H14	2.8	2 - 1 - 1
C12E5,E5E7,E7H14	2.8	2 - 1 - 1

The last step of the framework aims to calculate the payback period and IRR for each modification. The energy saving cost is calculated using equation I:

$$Energy\ saving\ cost\ (USD) = 312000 \times (energy\ saving\ capacity\ (MW)) \qquad \text{(I}$$

All Bridge modifications, in this case, need a new connection and therefore a new heat exchanger. To estimate the cost of adding a exchanger, equation II is applied.

$$Cost\ of\ new\ heat\ exchnager\ (USD) = 984093 + 1127 * \left(A(m^2)\right)^{0.98} \qquad \text{(II}$$

Based on the literature, the total investment cost is the total investment cost for HEN retrofit can be estimated by using equation III:

$$Total\ investment\ cost\ (USD) = 1.3 * \sum_i^n Cost\ of\ new\ heat\ exchnager \qquad \text{(III}$$

Figures 4-25 to 4-27 represent a payback period and the internal rate of return for modifications with one, two and three matches. The energy saving capacity corresponding to each Bridge is shown by a gray line.

The modifications are sorted based on energy saving capacity the first one has the highest saving. The modification, C12H3, has the lowest payback period and highest IRR, and that makes it a very interesting retrofit project. The second modification, C13 H3, has the same payback period and very good IRR. We should keep in mind that these modifications are not all independent. For example, if we modify the network based on C12H3 Bridge, we cannot do another modification like C13H3, because the receptor of H3 exchanger is already modified.

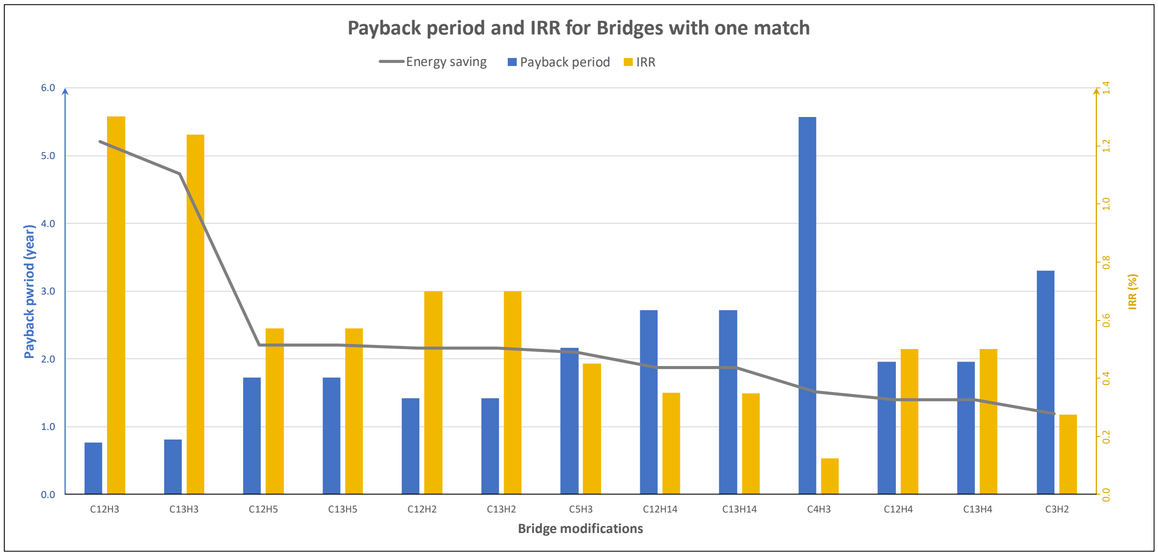

Figure 4-25 Payback period and IRR for Bridges with one match

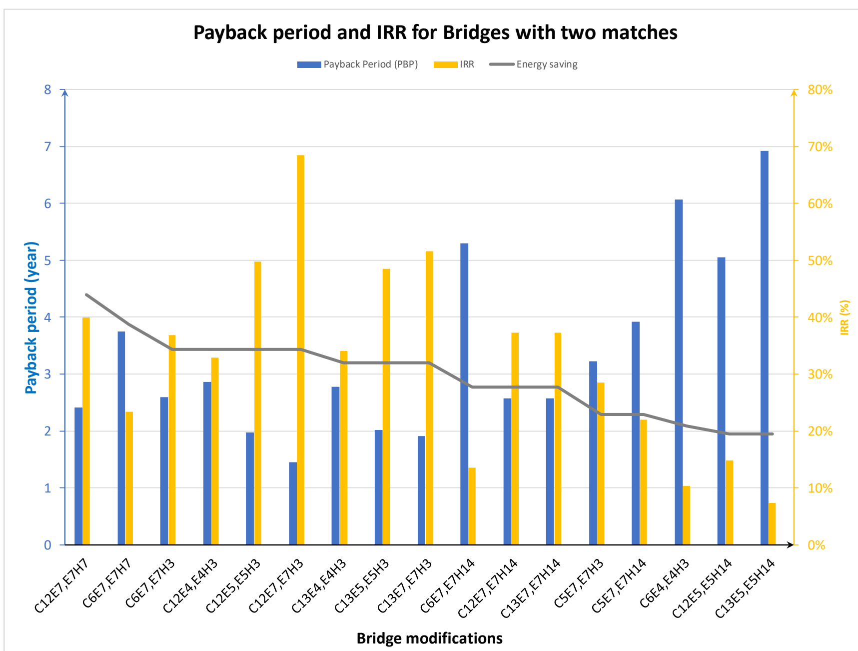

Figure 4-26 Payback period and IRR for Bridges with two matches

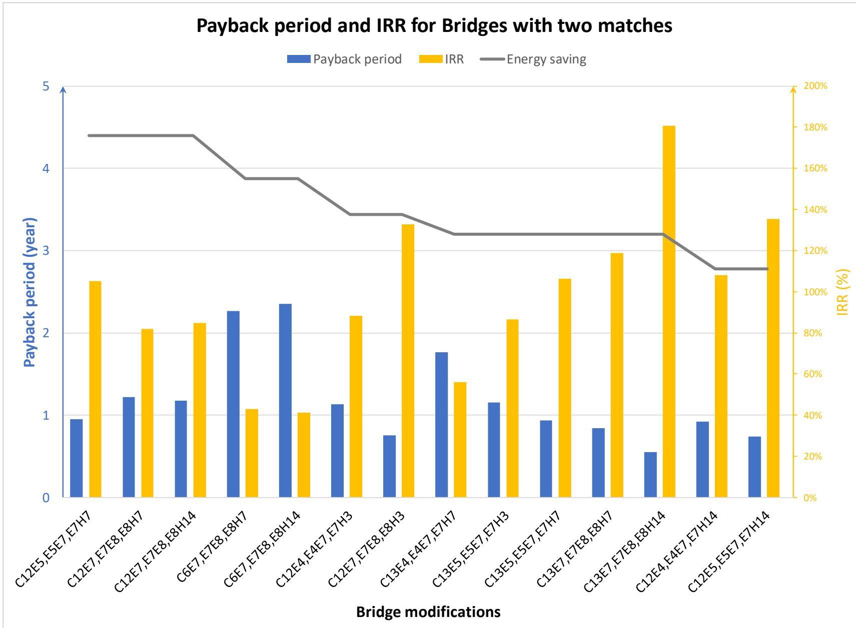

Figure 4-27 Payback period and IRR for Bridges with three matches

To select the list of economically viable modifications, first we need to prepare a sorted list of independent projects based on their IRR. The projects with IRR higher than 20% are selected in this case study. Based on the total budget, the projects with higher IRR will be selected to implement at the same time. The list of independent projects is shown in table 4-11.

Table 4-11 The list of independent retrofit projects

Pjoject	Modifications	IRR	Capital cost (MM$)	Cumulative capital cost (MM$)	Energy saving capacity (MW)	Cumulative energy saving capacity (MW)
1	C12H3	130%	0.28	0.28	3.50	3.50
2	C13H2	70%	0.24	0.52	1.60	5.10
3	C6E7,E7H7	44%	1.25	1.77	1.20	6.30
4	C7E5,E5H14	30%	1.45	3.22	1.80	8.10
5	C2E8,E8H4 - C13E3,E3E8,E8H7	23%	1.55	4.77	3.88	11.98

For a total available budget of 1.8 MM$ the first three projects can be selected and implemented together to save 6.3 MW of hot utility demand. Figure 4-28 shows the energy saving and the IRR of the retrofit projects.

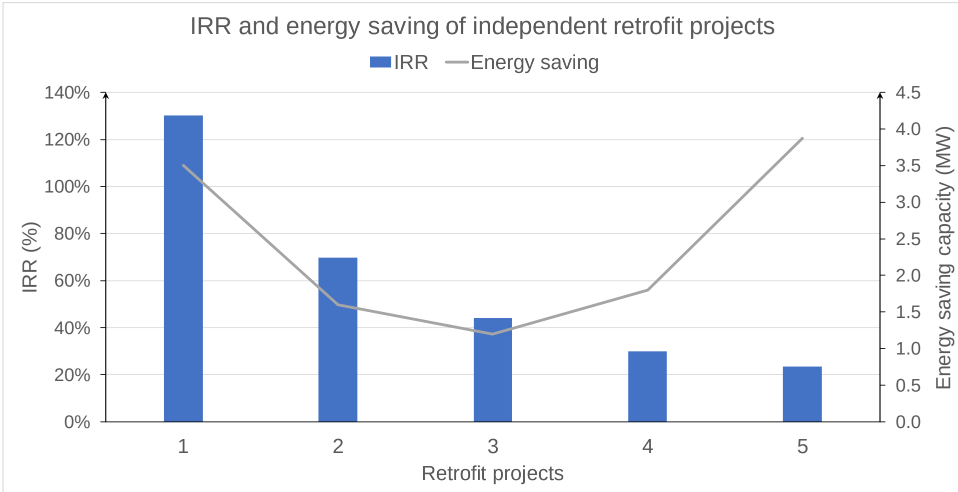

Figure 4-28 IRR and energy saving of independent retrofit projects

The first three projects can be implemented together for an investment cost of about 1.8 MM$. The forth and fifth projects has a higher energy saving capacity to compare with the second and third projects, but they are not interesting to the investors due to their low IRR.

CHAPTER 5 GENERAL DISCUSSION

The industrial sector is in charge of 24 % of total GHG emissions and almost 40% of total energy usage in the world, making it an interesting target for energy analysis. Energy use reduction in the industry is a complicated and challenging task due to several factors including the unique energy needs of different process sectors, energy use reduction constraints with cogeneration, and the essential requirement for production sites to remain competitive. Besides, energy use reduction projects are difficult to justify in industrial plants due especially to incremental savings resulting from small capital projects, and competition resulting from productivity-oriented larger projects.

However, there is a significant opportunity for radical GHG emissions reduction when considering process changes or process modernizations and energy use reduction simultaneously. Here, the systematic plant-wide energy analysis and re-profiling of a processing plant can result in a significant reduction in GHG emissions, an improvement in the project profitability, and an improvement in the long-term competitive position.

The Bridge Method is a novel approach for energy analytics of the HEN and process operations of a plant. The basis of the Bridge Method is that the flow of cascaded heat through process operations and heat exchange network (HEN) is from hot to ambient and should be decreased to reduce the external energy usage. Based on the first two laws of thermodynamics, the Bridge Method allows the user to characterize the process system energy flows across process operations and the HEN, in a manner that allows the identification of practical modifications to the energy systems.

5.1 Process operation modification

The Bridge method has graphical and numerical tools to identify the modification for HEN retrofit. In fact, the Bridge formulations were developed to enumerate the solutions to use the available heat of a cooler process source and send it to the process sink of a heater. The first objective of this project was to find a way to extend the Bridge Method and use it to identify the possible options to reduce the energy usage of process operations. The ETD represents the theoretical minimum energy consumption of a plant which is the total energy demand of process operation units. Despite HEN retrofit, reducing the energy usage of process operations does not need a modification in the whole temperature interval between hot and cold utilities. Process operations such as reactors and separation units are the core of the plant and every change in their design implies a resimulation of the whole mill to have an energy balance model.

A systematic approach has been developed in this thesis for identifying the process operations that affect the total energy demand, to identify the impact of each one, and sorting them based on their energy consumption. The list is further assessed in a user interactive decision-making procedure to select a viable modification and re-simulate the plant. Based on the type of process, different solutions are suggested in this work. The options can have an incremental energy saving like changing the operating temperature and pressure of the process to shift its corresponding ETD to the left or to the right, or major energy saving such as changing the design or using new technologies and equipment.

5.2 Sequential design decision making framework

The Bridge Method is great. However, it has never been applied in practice, which needs a decision-making framework to consider design aspects from the basic industrial process energy audit through to the final recommendation. It requires a computer-based system to manage information especially in a large-scale problem with a massive amount of data.

The next objective of this research is developing a decision-making framework for plant-wide energy analytics of industrial plants. To accomplish this objective, the steps to execute the Bridge method in practice have been identified. At each step, a decision needs to be made to produce new information and use it for the next decisions. After energy auditing and extracting all data from the simulation file, the first step is to select or refine the individual $\Delta T_{min,\ cont.}$ for each stream. This will lead to a more explicit calculation of operating and capital costs. The second step is to identify the process operation modifications, re-simulating the plant and extracting data to generate the new HEN diagram regarding each modification. To narrow down the number of Bridge modifications to practical ones, a table called the "connection table" is used to find infeasible connections and to evaluate the level of risk for each feasible connection. A number between 1 and 3 is assigned to each connection showing the level of risk, in which number 1 shows a lowest level of risk. The list of practical Bridge is evaluated in the next step to determine the energy saving capacity of each modification and finally, the payback period and IRR of each Bridge option are calculated.

Based on these steps, a sequential design decision making framework is developed. Each step of the framework is designed to find a solution to each one of the above-mentioned steps. The framework comprises a systematic and user-interactive decision-making approach, where automated design calculations are made, and user interactive open-ended decisions are taken at each step in the design process to be able to lead to a practical set of recommendations.

Open-ended decision making can not be computerized, and it allows good engineering judgment (GEJ) to be implicated in the design process. While the Bridge Method lends itself well to being formulated in computer algorithms, there are numerous open-ended decisions that need to be made from a practical perspective — for example optimizing the process operations, identifying the infeasible connections and risks associated with each connection

5.3 Bridge framework demonstration

Two Complex case studies have been analyzed using the developed framework. The first case study is the preheat train network and for the first time, an economic analysis of the Bridge modification has been done in this problem. The two most common parameters for selecting investment projects, Payback Period (PBP) and Internal Rate of return (IRR), have been used to identify economically viable solutions.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

This project was performed in the context of the energy analysis of industrial plants including both the heat exchanger network and process operations. The Bridge Method is the only approach with capability of characterizing the flowrate of transferred energy through all units in the temperature interval between the hot utility to the cooling water or ambient. It is employed to find energy saving solution using the graphical and numerical tools.

Energy analysis is a design problem. Process design decision-making is the procedure of making choices by identifying a problem, gathering information, and assessing alternative solutions. To implement the Bridge Method in practice, in should be integrated into such a design decision making system.

During this research program, a sequential design decision-making framework is developed that considers explicitly the sequential series of design decisions including (1) selection of minimum temperature difference contribution of each stream, (2) guidance for identifying potential process operation modifications, and (3) identification of Heat Exchange Network (HEN) modifications. At each step of decision-making, case-specific data are added to the framework through a graphical user interface (GUI). The management system inside the framework is responsible for managing the communication between GUI, model base, knowledge base, data base, and calculation engines. At each sequence, the results are represented on the dashboard to help users to make a decision and send that decision back to the system.

6.1 Contribution to the body of knowledge

The scientific contributions of this project from developing a sequential design decision making framework and applying it in complex case studies are as follows:

- Developing a systematic approach to identify the impact of each process operation on the total energy demand of an industrial plant
- Developing a sequential design decision making framework to implement the Bridge method in practices that considers from the basic industrial process energy audit, through to the final recommendation of economically viable solutions

- Implementing the Bridge framework in solving complex and large-scale case studies using the modified network table with economic analysis of the identified Bridges

6.2 Future work

- Developing computer-based algorithms to:
    - Generate the ETD
    - Enumerate the energy saving capacity for different combinations of Bridges
- Developing cost models to better estimate the economic return of retrofit projects and incorporating them into the Bridge framework
- Evolving the design framework considering new developments related to the Bridge Method and the Framework Architecture
- Implementing the Bridge framework for integration of a pulp and paper mill and a biorefinery
- Integrating the AI techniques into the framework for open-ended decision-making procedures.

REFERENCES

[1] I. E. A. (IEA). "CO2 Emissions Statistics." (accessed.

[2] IEA. "https://www.iea.org/reports/tracking-industry-2019." (accessed.

[3] J. J. Klemes, *Handbook of process integration (PI): minimisation of energy and water use, waste and emissions*. Elsevier, 2013.

[4] H. T. Broeck, "Multipass exchanger calculations," *Industrial & Engineering Chemistry,* vol. 30, no. 9, pp. 1041-1042, 1938.

[5] H. T. Broeck, "Economic Selection of Exchanger Sizes," *Industrial & Engineering Chemistry,* vol. 36, no. 1, pp. 64-67, 1944/01/01 1944, doi: 10.1021/ie50409a013.

[6] W. M. Nagle, "Mean temperature differences in multipass heat exchangers," *Industrial & Engineering Chemistry,* vol. 25, no. 6, pp. 604-609, 1933.

[7] R. Bowman, A. Mueller, and W. Nagle, "Mean temperature difference in design," *Trans. ASME,* vol. 62, no. 4, pp. 283-294, 1940.

[8] F. Fischer, "Mean temperature difference correction in multipass exchangers," *Industrial & Engineering Chemistry,* vol. 30, no. 4, pp. 377-383, 1938.

[9] A. P. Colburn and E. d. P. de, "Mean temperature difference and heat transfer coefficient in liquid heat exchangers," *Industrial & Engineering Chemistry,* vol. 25, no. 8, pp. 873-877, 1933.

[10] R. Bowman, "Mean temperature difference correction in multipass exchangers," *Industrial & Engineering Chemistry,* vol. 28, no. 5, pp. 541-544, 1936.

[11] M. L. Balinski, "Fixed-cost transportation problems," *Naval Research Logistics Quarterly,* vol. 8, no. 1, pp. 41-54, 1961.

[12] D. F. Rudd, "The synthesis of system designs: I. Elementary decomposition theory," *AIChE Journal,* vol. 14, no. 2, pp. 343-349, 1968.

[13] A. Masso and D. Rudd, "The synthesis of system designs. II. Heuristic structuring," *AIChE Journal,* vol. 15, no. 1, pp. 10-17, 1969.

[14] E. C. HOHMANN, JR., "OPTIMUM NETWORKS FOR HEAT EXCHANGE," Ph.D., Chemical engineering, University of Southern Callifornia, Los Angeles, USA, 1971.

[15] T. Umeda, J. Itoh, and K. Shiroko, "Heat exchanger system synthesis," *Chemical Engineering Progress,* vol. 74, no. 7, pp. 70-76, 1978.

[16] J. R. Flower and B. Linnhoff, "Thermodynamic analysis in the design of process networks," *Computers & Chemical Engineering,* vol. 3, no. 1, pp. 283-291, 1979.

[17] B. Linnhoff and J. R. Flower, "Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks," *AIChE Journal,* vol. 24, no. 4, pp. 633-642, 1978.

[18] B. Linnhoff and J. R. Flower, "Synthesis of heat exchanger networks: II. Evolutionary generation of networks with various criteria of optimality," *AIChE Journal,* vol. 24, no. 4, pp. 642-654, 1978.

[19] S. Kobayashi, T. Umeda, and A. Ichikawa, "Synthesis of optimal heat exchange systems—an approach by the optimal assingment problem in linear programming," *Chemical Engineering Science,* vol. 26, no. 9, pp. 1367-1380, 1971.

[20] N. Nishida, S. Kobayashi, and A. Ichikawa, "Optimal synthesis of heat exchange systems Necessary conditions for minimum heat transfer area and their application to systems synthesis," *Chemical Engineering Science,* vol. 26, no. 11, pp. 1841-1856, 1971.

[21] A. Ciric and C. Floudas, "A retrofit approach for heat exchanger networks," *Computers & chemical engineering,* vol. 13, no. 6, pp. 703-715, 1989.

[22] A. R. Ciric and C. A. Floudas, "A mixed integer nonlinear programming model for retrofitting heat-exchanger networks," *Industrial & engineering chemistry research,* vol. 29, no. 2, pp. 239-251, 1990.

[23] T. F. Yee, I. E. Grossmann, and Z. Kravanja, "Simultaneous optimization models for heat integration—I. Area and energy targeting and modeling of multi-stream exchangers," *Computers & chemical engineering,* vol. 14, no. 10, pp. 1151-1164, 1990.

[24] T. F. Yee and I. E. Grossmann, "Simultaneous optimization models for heat integration—II. Heat exchanger network synthesis," *Computers & Chemical Engineering,* vol. 14, no. 10, pp. 1165-1184, 1990.

[25] T. F. Yee, I. E. Grossmann, and Z. Kravanja, "Simultaneous optimization models for heat integration—III. Process and heat exchanger network optimization," *Computers & Chemical Engineering,* vol. 14, no. 11, pp. 1185-1200, 1990.

[26] H. Abbas, G. Wiggins, R. Lakshmanan, and W. Morton, "Heat exchanger network retrofit via constraint logic programming," *Computers & Chemical Engineering,* vol. 23, pp. S129-S132, 1999.

[27] K.-L. Ma, C.-W. Hui, and T. F. Yee, "Constant approach temperature model for HEN retrofit," *Applied thermal engineering,* vol. 20, no. 15-16, pp. 1505-1533, 2000.

[28] J. M. Ponce-Ortega, A. Jiménez-Gutiérrez, and I. E. Grossmann, "Simultaneous retrofit and heat integration of chemical processes," *Industrial & Engineering Chemistry Research,* vol. 47, no. 15, pp. 5512-5528, 2008.

[29] G. Athier, P. Floquet, L. Pibouleau, and S. Domenech, "A mixed method for retrofiting heat-exchanger networks," *Computers & chemical engineering,* vol. 22, pp. S505-S511, 1998.

[30] T. Gundepsen and L. Naess, "The synthesis of cost optimal heat exchanger networks: an industrial review of the state of the art," *Computers & Chemical Engineering,* vol. 12, no. 6, pp. 503-530, 1988.

[31] B. Linnhoff, "Thermodynamic analysis in the design of process networks," University of Leeds, 1979.

[32] L. March, "Introduction to pinch technology," *Targeting House, Gadbrook Park, Northwich, Cheshire, CW9 7UZ, England,* 1998.

[33] T. N. Tjoe and B. Linnhoff, "Using pinch technology for process retrofit," *Chemical Engineering,* vol. 93, no. 8, pp. 47-60, 1986.

[34] C. K. IAN, "Pinch analysis and process integration--a use guide on process integration for the efficient use of energy," ed: Oxford, UK: Butterworth-Heinemann of Elsevier, 2007.

[35] J. L. Van Reisen, J. Grievink, G. T. Polley, and P. J. Verheijen, "The placement of two-stream and multi-stream heat-exchangers in an existing network through path analysis," *Computers & chemical engineering,* vol. 19, pp. 143-148, 1995.

[36] B. Linnhoff and E. Hindmarsh, "The pinch design method for heat exchanger networks," *Chemical Engineering Science*, vol. 38, no. 5, pp. 745-763, 1983.

[37] S. Ahmad and D. Hui, "Heat recovery between areas of integrity," *Computers & chemical engineering*, vol. 15, no. 12, pp. 809-832, 1991.

[38] J. L. van Reisen, G. T. Polley, and P. J. Verheijen, "Structural targeting for heat integration retrofit," *Applied thermal engineering*, vol. 18, no. 5, pp. 283-294, 1998.

[39] N. Asante and X. Zhu, "An automated approach for heat exchanger network retrofit featuring minimal topology modifications," *Computers & chemical engineering*, vol. 20, pp. S7-S12, 1996.

[40] J.-C. Bonhivers, A. Moussavi, R. Hackl, M. Sorin, and P. R. Stuart, "Improving the network pinch approach for heat exchanger network retrofit with bridge analysis," vol. 97, no. 3, pp. 687-696, 2019, doi: doi:10.1002/cjce.23422.

[41] N. Asante and X. Zhu, "An automated and interactive approach for heat exchanger network retrofit," *Chemical Engineering Research and Design*, vol. 75, no. 3, pp. 349-360, 1997.

[42] R. Nordman and T. Berntsson, "New pinch technology based hen analysis methodologies for cost-effective retrofitting," *The Canadian Journal of Chemical Engineering*, vol. 79, no. 4, pp. 655-662, 2001.

[43] R. Nordman, *New process integration methods for heat-saving retrofit projects in industrial systems*. Chalmers University of Technology, 2005.

[44] R. Nordman and T. Berntsson, "Design of kraft pulp mill hot and warm water systems—A new method that maximizes excess heat," *Applied thermal engineering*, vol. 26, no. 4, pp. 363-373, 2006.

[45] R. Nordman and T. Berntsson, "Use of advanced composite curves for assessing cost-effective HEN retrofit I: theory and concepts," *Applied Thermal Engineering*, vol. 29, no. 2, pp. 275-281, 2009.

[46] R. Nordman and T. Berntsson, "Use of advanced composite curves for assessing cost-effective HEN retrofit II. Case studies," *Applied Thermal Engineering*, vol. 29, no. 2, pp. 282-289, 2009.

[47] J.-C. Bonhivers, M. Korbel, M. Sorin, L. Savulescu, and P. R. Stuart, "Energy transfer diagram for improving integration of industrial systems," *Applied Thermal Engineering*, vol. 63, no. 1, pp. 468-479, 2014.

[48] J.-C. Bonhivers, E. Svensson, T. Berntsson, and P. Stuart, "Comparison between pinch analysis and bridge analysis to retrofit the heat exchanger network of a kraft pulp mill," *Applied Thermal Engineering*, vol. 70, no. 1, pp. 369-379, 2014.

[49] J.-C. Bonhivers, B. Srinivasan, and P. R. Stuart, "New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 1–Concepts," *Applied Thermal Engineering*, 2014.

[50] J.-C. Bonhivers, A. Alva-Argaez, B. Srinivasan, and P. R. Stuart, "New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2 – Stepwise and graphical approach," *Applied Thermal Engineering*, vol. 119, pp. 670-686, 2017/06/05/ 2017, doi: https://doi.org/10.1016/j.applthermaleng.2015.05.085.

[51] J.-C. Bonhivers, E. Svensson, M. V. Sorin, T. S. Berntsson, and P. R. Stuart, "Energy transfer diagram for site-wide analysis and application to a kraft pulp mill," *Applied Thermal Engineering*, vol. 75, pp. 547-560, 2015.

[52] J.-C. Bonhivers, A. Moussavi, A. Alva-Argaez, and P. R. Stuart, "Linking pinch analysis and bridge analysis to save energy by heat-exchanger network retrofit," *Applied Thermal Engineering*, 2016, doi: http://dx.doi.org/10.1016/j.applthermaleng.2016.05.174.

[53] P. G. W. Keen, "Decision support systems : a research perspective," in "Report (Alfred P. Sloan School of Management. Center for Information Systems Research)," MIT, Cambridge, Massachusetts, USA., 1980.

[54] V. R. Dhole and B. Linnhoff, "Total site targets for fuel, co-generation, emissions, and cooling," *Computers & chemical engineering*, vol. 17, pp. S101-S109, 1993.

[55] J.-C. Bonhivers *et al.*, "Analysis of Heat Cascade Through Process Components to Reduce the Energy Consumption in Industrial Systems," *Process Integration and Optimization for Sustainability*, journal article August 29 2018, doi: 10.1007/s41660-018-0067-9.

[56] C. Hui and S. Ahmad, "Minimum cost heat recovery between separate plant regions," *Computers & chemical engineering*, vol. 18, no. 8, pp. 711-728, 1994.

[57] F. Maréchal and B. Kalitventzeff, "Energy integration of industrial sites: tools, methodology and application," *Applied Thermal Engineering,* vol. 18, no. 11, pp. 921-933, 1998/11/01/ 1998, doi: https://doi.org/10.1016/S1359-4311(98)00018-0.

[58] F. Marechal and B. Kalitventzeff, "Targeting the integration of multi-period utility systems for site scale process integration," *Applied Thermal Engineering,* vol. 23, no. 14, pp. 1763-1784, 2003/10/01/ 2003, doi: https://doi.org/10.1016/S1359-4311(03)00142-X.

[59] K. Matsuda, Y. Hirochi, H. Tatsumi, and T. Shire, "Applying heat integration total site based pinch technology to a large industrial area in Japan to further improve performance of highly efficient process plants," *Energy,* vol. 34, no. 10, pp. 1687-1692, 2009.

[60] H. Becker and F. Maréchal, "Energy integration of industrial sites with heat exchange restrictions," *Computers & Chemical Engineering,* vol. 37, pp. 104-118, 2012/02/10/ 2012, doi: https://doi.org/10.1016/j.compchemeng.2011.09.014.

[61] S. Bandyopadhyay, J. Varghese, and V. Bansal, "Targeting for cogeneration potential through total site integration," *Applied Thermal Engineering,* vol. 30, no. 1, pp. 6-14, 2010.

[62] P. S. Varbanov and J. í. J. Klemeš, "Total sites integrating renewables with extended heat transfer and recovery," *Heat Transfer Engineering,* vol. 31, no. 9, pp. 733-741, 2010.

[63] R. Fornell and T. Berntsson, "Process integration study of a kraft pulp mill converted to an ethanol production plant – Part A: Potential for heat integration of thermal separation units," *Applied Thermal Engineering,* vol. 35, pp. 81-90, 2012/03/01/ 2012, doi: https://doi.org/10.1016/j.applthermaleng.2011.10.010.

[64] S. W. Miller, T. W. Simpson, M. A. Yukish, L. A. Bennett, S. E. Lego, and G. M. Stump, "Preference Construction, Sequential Decision Making, and Trade Space Exploration," no. 55881, p. V03AT03A014, 2013, doi: 10.1115/DETC2013-13098.

[65] S. W. Miller, M. A. Yukish, and T. W. Simpson, "Design as a sequential decision process," *Structural and Multidisciplinary Optimization,* vol. 57, no. 1, pp. 305-324, 2018/01/01 2018, doi: 10.1007/s00158-017-1756-7.

[66] N. R. C. C. o. T. F. f. D. M. i. E. Design, *Theoretical foundations for decision making in engineering design*. National Academy Press, 2001.

[67] K. Tripathi, "Decision support system is a tool for making better decisions in the organization," *Indian Journal of Computer Science and Engineering (IJCSE)*, vol. 2, no. 1, pp. 112-117, 2011.

[68] U. R. F. Averweg, *Decision-making support systems: Theory and practice*, South Africa: Ventus, 2012.

[69] J. Xia, L. Lin, J. Lin, and L. Nehal, "Development of a GIS-Based Decision Support System for Diagnosis of River System Health and Restoration," *Water*, vol. 6, no. 10, p. 3136, 2014. [Online]. Available: http://www.mdpi.com/2073-4441/6/10/3136.

[70] M. Abd-elfattah, T. Alghamdi, and E. Amer, "Dashboard technology based solution to decision making," *International Journal of Computer Science Engineering*, vol. 4, no. 2, pp. 59-70, 2014.

[71] R. Smith, M. Jobson, and L. Chen, "Recent development in the retrofit of heat exchanger networks," *Applied Thermal Engineering*, vol. 30, no. 16, pp. 2281-2289, 2010.

[72] FRAM, "Bleached market kraft pulp mill, Reference and type mill (FRAM 09)," Stockholm, 2005.

[73] A. Moussavi, J.-C. Bonhivers, and P. R. Stuart, "Plant-wide energy analysis of industrial sites using Bridge Method: Part I – Fundamentals," *submitted to I&EC Research*, 2019.

[74] A. Moussavi and P. R. Stuart, "Plant-wide energy analysis of industrial facilities using the Bridge Method: Part II – Framework for decision support," *submitted to I&EC Research*, 2019.

[75] A. Moussavi and P. R. Stuart, "Cost analytics for energy analysis of industrial facilities using the Bridge Method," *submitted to Tappi Journal*, 2019.

[76] T. Gundersen and I. E. Grossmann, "Improved optimization strategies for automated heat exchanger network synthesis through physical insights," *Computers & chemical engineering*, vol. 14, no. 9, pp. 925-944, 1990.

[77] H. Nishimura, "A theory for the optimal synthesis of heat-exchanger systems," *Journal of Optimization Theory and Applications*, vol. 30, no. 3, pp. 423-450, 1980.

[78] S. Ahmad, "Heat exchanger networks: Cost tradeoffs in energy and capital," University of Manchester Institute of Science and Technology (UMIST), 1985.

[79] Z. Fonyo, "Diverse pinch concept for heat exchange network synthesis: the case of different heat transfer conditions," *Chemical engineering science,* vol. 46, no. 7, pp. 1623-1634, 1991.

[80] A. P. ANTON LARSSON, "Energy Efficiency Study at a Softwood Kraft Pulp Mill," 2017.

[81] R. Smith, *Chemical process: design and integration*. John Wiley & Sons, 2005.

[82] A. Simons, "Energy cost reduction in the pulp and paper industry," *Pulp and Paper Research Institute of Canada, Montreal, QC,* 1999.

[83] E. Ayotte-Sauvé, O. Ashrafi, S. Bédard, and N. Rohani, "Optimal retrofit of heat exchanger networks: A stepwise approach," *Computers & Chemical Engineering,* vol. 106, pp. 243-268, 2017.

[84] B. Linnhoff, D. R. Mason, and I. Wardle, "Understanding heat exchanger networks," *Computers & Chemical Engineering,* vol. 3, no. 1-4, pp. 295-302, 1979.

[85] J. R. Flower and B. Linnhoff, "A thermodynamic-combinatorial approach to the design of optimum heat exchanger networks," *AIChE Journal,* vol. 26, no. 1, pp. 1-9, 1980.

[86] B. Linnhoff and D. R. Vredeveld, "Pinch technology has come of age," *Chemical engineering Progress,* vol. 80, no. 7, pp. 33-40, 1984.

[87] N. Rohani, E. Ayotte-Sauvé, O. Ashrafi, and S. Bédard, "Multiple modifications in stepwise retrofit of heat exchanger networks," *Chemical Engineering Transactions,* vol. 52, pp. 313-318, 2016.

[88] M. R. Walmsley, N. S. Lal, T. G. Walmsley, and M. J. Atkins, "A modified energy transfer diagram for heat exchanger network retrofit bridge analysis," 2017.

[89] J.-C. Bonhivers, A. Alva-Argaez, B. Srinivasan, and P. R. Stuart, "New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2–Stepwise and graphical approach," *Applied Thermal Engineering,* 2015.

[90] J.-C. Bonhivers, "Nouvelle méthode d'intégration énergétique pour la rétro-installation des procédés industriels et la transformation des usines papetières," École Polytechnique de Montréal, 2013.

[91] D. E. Bell, *Decision making: Descriptive, normative, and prescriptive interactions*. cambridge university Press, 1988.

[92] M. S. S. Morton, *Management decision systems: computer-based support for decision making*. Division of Research, Graduate School of Business Administration, Harvard …, 1971.

[93] J. W. Tweedale, R. Neves-Silva, L. C. Jain, G. Phillips-Wren, J. Watada, and R. J. Howlett, *Intelligent decision technology support in practice*. Springer, 2016.

[94] V. A. W. J. Marchau, W. E. Walker, P. J. T. M. Bloemen, and S. W. Popper, *Decision Making under Deep Uncertainty*, *From Theory to Practice*. Springer, Cham, 2019.

APPENDIX A ARTICLE 1: PLANT-WIDE ENERGY ANALYSIS OF INDUSTRIAL SITES USING BRIDGE METHOD: PART I – FUNDAMENTALS

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Abstract:

Efficient use of energy is an important parameter that can help industries to increase their profitability by reducing greenhouse gas (GHG) emission, energy, water, and raw material consumption. To run a process plant, high-value energy such as steam or hot water is used by heat exchanger network and process operation units, and low-value energy such as cooling water is sent to the ambient as the lost energy. So, this is one of the main concerns of experts in the field of energy analysis during the past decades to develop a systematic approach for reducing the hot utility demand.

Recently, a novel approach called the Bridge Method has been developed for Heat Exchanger Network (HEN) retrofit. It comprises three tools, which are Energy Transfer Diagram (ETD), Network table, and Heat Exchanger Load Diagram. The ETD is helpful to characterize the energy profile of an existing industrial plant by representing the cascaded heat flow rate through each existing heat exchanger and process operation that allows identifying the necessary modifications for reducing energy usage. The Network table is a systematic approach to determine the heat saving capacity of each modification. Heat Exchanger Load Diagram (HELD) is useful to recognize an appropriate HEN configuration corresponding to each modification. The main idea behind the Bridge Method is that the flow rate of cascaded heat through the existing heat exchangers and process operations across the entire temperature range between the process sources and sinks should be reduced to decrease the external energy usage.

The objective of this artcle, which is the first part of a three-part paper, is to critically review the advanced pinch based methods and elucidate the concept of energy degradation, which provides the foundation for the process operation energy analytics. In the last section, an introduction to a sequential decision-making framework necessary to use the Bridge Method in practices is presented

Keywords: Bridge Method, plant-wide energy analysis, methodological framework, heat exchanger network retrofit

Abbreviations

ACC Advanced Composite Curves

ACLC Actual Cooling Load Curve

AHLC Actual Heat Load Curve

CCC Cold Composite Curve

CUC Cold Utility Curve

ECLC Extreme Cooling Load Curve

EHLC Extreme Heat Load Curve

ETD Energy Transfer Diagram

ETC Energy Transfer Curve

GCC Grand Composite Curve

$\dot{H}$ Enthalpy rate

$\dot{H}_{in}$ Enthalpy rate of inlet

$\dot{H}_{out}$ Enthalpy rate of outlet

HELD Heat Exchanger Load Diagram

HEN Heat Exchanger Network

HUC Hot Utility Curve

HCC Hot Composite Curve

PO Process operations

T Temperature

Ta Ambient temperature

TCLC Theoretical Cooling Load Curve

THLC Theoretical Heat Load Curve

1. Introduction:

Advancements in industrial processes offer substantial opportunities to improve plant-wide energy efficiency and increase economic profitability by tapping into new markets by staying competitive. In recent years, the focus of the forestry sector has been devoted to implementing a cogeneration system, and this will remain important as global warming is becoming a problem. On the other hand, in light of a decrease in demand in several segments of the forestry sector and the increasing importance of climate change, the pulp and paper industry is now looking for transformation into modern forest biorefineries to produce biomass-based products. One of the reasons why the forestry sector has not accelerated more quickly towards the bioeconomy is due to the high level of technology and market risk, in addition to a modest return on investment (ROI). During the biorefinery implementation, there is a return on investment due to energy system restructuring, which serves both processes. Significant opportunities in the energy reduction manifest themselves during the implementation of biorefinery strategies in pulp and paper mills that allow an improved ROI through an efficient reconfiguration of the energy profile for the incremental capital investment.

Besides, the improved energy efficiency of a well-integrated biorefinery in an existing pulp and paper mill will be crucial and environmentally preferable for a long-term competitive position. To address such complex issues, a practical and systematic methodology is required that considers retrofit situations, plant-wide integration, and utility systems. Moreover, the classical heat integration has been adopted to a far greater extent as a method in the petrochemical and chemical industries than it has in the pulp and paper industry and it has relatively limited success in this sector basically because other investments yield a higher return than incremental energy-saving projects.

An industrial plant includes three main parts: process operation units, the heat exchanger network, and utility systems. The required steam and electricity to run the plant are produced by consuming fuel in the cogeneration of heat and power (CHP) plants as a part of the utility system. Generally, high-quality energy (e.g., steam) is cascaded (degraded) through each process operation unit and heat exchanger, and low-quality energy (e.g., cooling water) is sent to the ambient as the lost energy. Due to the oil crises in the 1970s, the oil price had risen from 3 dollars per barrel to almost 40 dollars. Hence, energy experts started to find a way to reduce fuel consumption and attempts to solve the inefficient energy use problem, resulting in the development of the process integration methodology. The first development was naturally in the energy efficiency and Heat Integration (HI), and the goal was to decrease the energy usage of the industrial plant and increase the internal heat recovery. In past four decades, many approaches have been developed to reduce the hot utility demand by improving the energy management in a mill through using a systematic control and monitor of the energy in different parts of the plant, identifying equipment that are being operated based on the improper thermal efficiency and replacing them with the new equipment, defining new operating conditions for process operations by an optimization and integration of new ones into the existing mill.

The philosophy behind the Bridge Method is that the flowrate of cascaded heat through the existing heat exchangers and process operation units across the entire temperature range between the hot and cold utilities should be decreased to reduce the external energy usage.

This paper seeks to critically analyze the most used pinch-based approaches for HEN retrofit and also to elucidate the concept of cascaded energy in the Bridge Method that can be used for process operation energy analytics. We, firstly, review the existing methods for energy integration in the heat exchanger network retrofit and plant-wide energy analysis. Secondly, we explain the main tools of the Bridge Method, and finally, an introduction to the sequential decision-making framework is represented.

2. Heat exchanger network retrofit

The concept of energy integration and its vocabulary were first developed in the context of a heat exchanger network (HEN) design to reduce energy costs. The HEN often has a substantial impact on the total energy consumption of a plant. The HEN retrofit can be classified into three categories: mathematical programming approaches, thermodynamic-based approaches, and hybrid methods, resulting from the combination of the numerical optimization and the pinch method.

In this paper, we focus on the hybrid and thermodynamic-based approaches for HEN retrofit and then, the concept of the Bridge Method and its role in prioritizing process operation modifications have been explained.

2.1. Pinch method for greenfield design and retrofit

The Pinch method for the HEN greenfield design was developed in 1970s at the University of Leeds and introduced in a two-part paper [1, 2]. The idea behind it was to reduce external energy usage by increasing internal heat recovery. To identify the heating and cooling demand of a process, a visualization tool was expanded by the use of a temperature-enthalpy graph, called “composite curves”, which includes the hot and cold composite curve to represent the cumulative heat source and the cumulative heat demand across the process plant, respectively [3].

In the Pinch analysis method, the energy targets representing the maximum internal energy recovery should be set for designing the process-process heat exchangers [4]. The first step to applying the Pinch method is data extraction, which is a crucial step to provide reliable information that needs to be used in Pinch analysis. At this step, the network is represented by the set of hot and process sinks, characterized by their initial and final temperature and the total heat load of each stream [5]. The extracted data allows the representation of the hot and cold composite curves that are graphical tools to show the total heat deficit and demand of the system [6].

The next step is to select a ΔT_{min} between the hot and cold composite curves. Choosing low values for ΔT_{min} leads to larger and more costly heat exchangers, and therefore, higher investment cost while choosing high values gives us a higher hot and cold utility requirement that means a higher energy cost. So, a ΔT_{min} that minimizes the total cost should be selected [7]. A simple way to identify the pinch point is to use the problem table. Based on the selected ΔT_{min}, the hot composite curve will be shifted to the right, and the minimum external energy usage will be identified. Above the Pinch point is the heat deficit area, and below the Pinch temperature is the heat excess area [8].

Tjoe and Linnhoff used the Pinch analysis method to retrofit the HENs [9]. They proposed three rules to eliminate the cross-Pinch transfer: eliminate coolers above the Pinch, eliminate heaters below the Pinch, and eliminate the process heat exchange across the Pinch (Figure 1). It means that we are not allowed to transfer heat from a process source with the temperature above the Pinch point to the cold stream with the temperature below the Pinch point, because it leads to an increase in external energy usage. After removing the Pinch violations, the HEN will be modified. This approach allows user interaction and has served as the basis for many studies on HEN retrofitting [8].

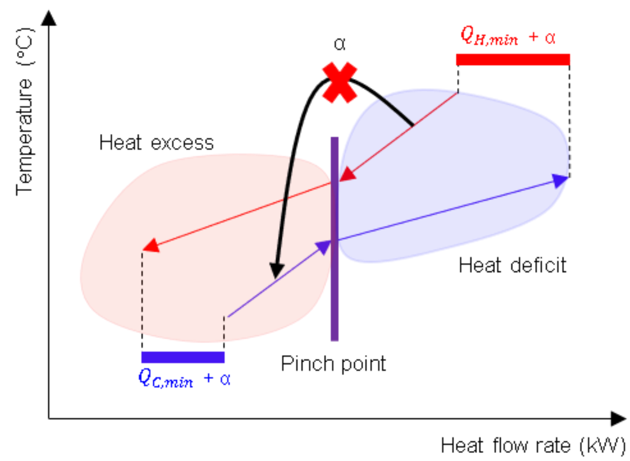

Figure 1- Forbidden heat transfer from above the pinch point to below it.

The concept behind the Pinch analysis method for greenfield design is not hard to understand, and it is a stepwise approach with user intervention to achieve more practical results. However, only streams data are considered in representing the composite curves, and there is no information about the existing HEN, and it leads to some difficulties in retrofit.

2.2. Advanced pinch-based methods

2.2.1. Path analysis and structural targeting

Since the HEN retrofit problems are complicated, many researchers attempted to find new approaches to reduce its complexity. Van Reisen et al. developed a decomposition and pre-screening method to evaluate the economic potential of subnetworks [10]. The evaluation of each subnetwork for energy savings and investments is done separately. By comparing the results, the most promising set of subnetworks is selected, and a retrofit design is made by using one of the existing procedures. Subnetworks are parts of the existing HEN that should follow two rules. They must be heat-balanced and have at least one cooler and one heater. All possible subnetworks can be generated either by the designer based on heuristics or by a computer algorithm. A path connects a cooler to a heater through at least one exchanger [11]. There is an excellent opportunity to use heat load loops and paths to relax retrofitted network and to increase compatibility with the existing network. After generating subnetworks, through a few steps, the subnets will be ranked based on energy-saving cost and investment cost. Then, the payback period will be identified for each subnetwork.

In the second stage, subnets will be sorted based on unquantifiable factors such as controllability, safety, operability, and complexity as well as feasibility. In subnetworks with a path, a designer has the opportunity to increase internal recovery by adding the area to existing exchangers. Considering the results of quantitative and qualitative studies, the critical fraction of the HEN that deserves for retrofitting can be identified [12]. Since path analysis deals with subnetworks instead of the whole network, it simplifies the problem significantly and allows engineers to do a retrofit with minimum structural changes in the HEN. However, to improve the internal heat recovery, the heat exchanger area needs to increase, and it is not always practical.

2.2.2. Network Pinch approach

Before developing the network pinch approach, methods applied for the HEN retrofit design were either pinch-based methods or mathematical programming-based methods. Pinch-based methods enable user intervention during the design process, but manual techniques are potentially time-consuming with a need to pinch expert users. On the other hand, mathematical programming-based methods have the advantage of being automated, but they are complicated and do not guarantee to find the global optimum. For covering deficiencies of Pinch-based methods and mathematical programming techniques, Asante et al. proposed a method that can solve the retrofit problems in an automated procedure and at the same time, provide proper user interaction [13]. The network pinch that is resulted from existing heat exchangers in the network. It is different from the global pinch that is driven by the existing steams and minimum temperature differences between process sources and sinks [14]. This situation means that by reducing heat recovery approaching temperature, the HEN topology faces some limitations that are independent of the area of the individual exchangers in the existing network. This method includes two main parts. The first step is the diagnosis stage to identify the best topology modification, and the second stage is an optimization stage to identify a minimum heat exchanger surface area for the selected topology modification to minimize the total cost using the non-linear programming (NLP) formulation [15].

There are some heuristics to create a new path. There is one allowed modification at that time, so it helps to achieve a robust sequential design while it is time-consuming due to executing one modification at a time.

2.2.3. Advanced composite curves

In the pinch method, composite curves and the GCC are being employed for energy analysis. Composite curves show the temperature domain of an internal heat recovery according to a specified minimum approaching temperature. They also represent the minimum external heating and cooling demand along with the highest and lowest temperature domain that utilities should be implemented for achieving the minimum required area. Although, these valuable pieces of information do not help to identify the possibilities of the HEN retrofit design because they represent the complete range of hot and cold process streams applied for both internal heat exchangers, heater and coolers without distinguishing between them. The GCC can obtain appropriate temperature for placing utilities but again, it is not possible to extract proper information about the current topology, for instance, the temperature domain that hot utilities are being operated. Also, the other deficiency of the GCC is utilizing shifted temperatures instead of actual ones.

Nordman and Berntsson developed a new method to overcome these limitations [16]. They proposed a graphical approach that includes eight composite curves that help to identify an estimation of the energy savings potential at lower investment costs that result from reducing the global temperature difference. There are four curves above the pinch point and four curves below the pinch point [17]. The four curves above the pinch point are Hot Utility Curve (HUC), Actual Heat Load Curve (AHLC), Theoretical Heat Load Curve (THLC), and Extreme Heat Load Curve (EHLC). The HUC is the composite curve of hot utilities. The AHLC, the composite curve of existing heaters in the HEN, is between the EHLC and THLC. The EHLC is the maximum temperature available to place heaters, and the THLC is the minimum temperature for placing heaters [17]. EHLC is proportional to the extreme right part of the cold composite curve in pinch analysis. In other words, if we design a network with the pinch analysis method, the heaters will be placed at the maximum available temperature that corresponds to the spaghetti arrangement of the HEN. If the AHLC and THLC are close, it means that the heaters are at low temperature, and there is an opportunity to save energy by removing this heater and placing them in higher temperatures, leading to a lower investment cost. If the AHLC and THLC are close, it means that the heaters are at low temperature, and there is an opportunity to save energy by removing this heater and placing them at a higher temperature, leading to a lower investment cost [19, 20].

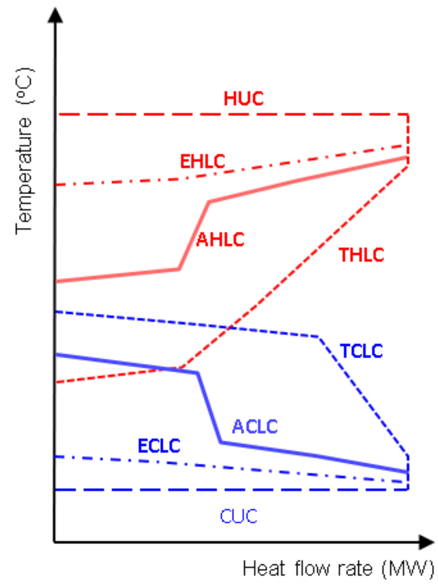

Figure 2- Advanced composite curves

The advanced composite curves give a qualitative answer more than a quantitative one and it helps to screen the solutions. Unlike pinch analysis, the information about the temperature level of the actual heaters and coolers in the existing network is represented in advanced composite curves. However, there is no information about the existing process-process heat exchangers and process operations, and it limits the identification of heat-saving opportunities.

The methods that have mentioned above are the major advances based on Pinch method, but when it comes to retrofit, having information about existing units and the effect of each unit on the total hot utility demand will give us the opportunity to do a more realistic job and find the more viable solutions. In the following section, the Bridge Method is presented that unlike previous methods gives the user a more insightful understanding of the existing HEN and process operations.

2.3. Bridge Method

Bridge Method developed by Bonhivers and Stuart based on the first two laws of thermodynamics [21]. The first law states that the energy of a system is conserved, and the second law states that the total entropy of an isolated system increases over time for an irreversible process, and the quality of energy is degraded irreversibly. In an industrial plant, high-quality energy (e.g., steam) is cascaded through all heat exchangers and process operation units to the cooling water [22]. Instead of sending heat to cooling water using coolers, there is a possibility to utilize the heat somewhere in the process. The idea behind the Bridge Method is to find a way to use this lost energy to satisfy heat demands in the plant. Bridge Method includes three powerful tools needed to characterize the existing system to determine the energy-saving projects and a convenient configuration of the final HEN. These three tools are Energy Transfer Diagram (ETD), Bridge identification and enumeration, and Heat Exchanger Load Diagram (HELD). Each tool will be explained subsequently [23, 24].

2.3.1. Energy Transfer Diagram

ETD shows the flow rate of cascaded energy through the whole temperature interval from the hot utility to the ambient as a function of T. The kinetic energy of molecules at the hot utility level is gradually transmitted more molecules with less kinetic energy until the maximum degradation of the energy at the ambient temperature. The ETD illustrates the actual flow rate of the transferred energy through a system (if the heat is not converted to other forms of energy, e.g., chemical energy).

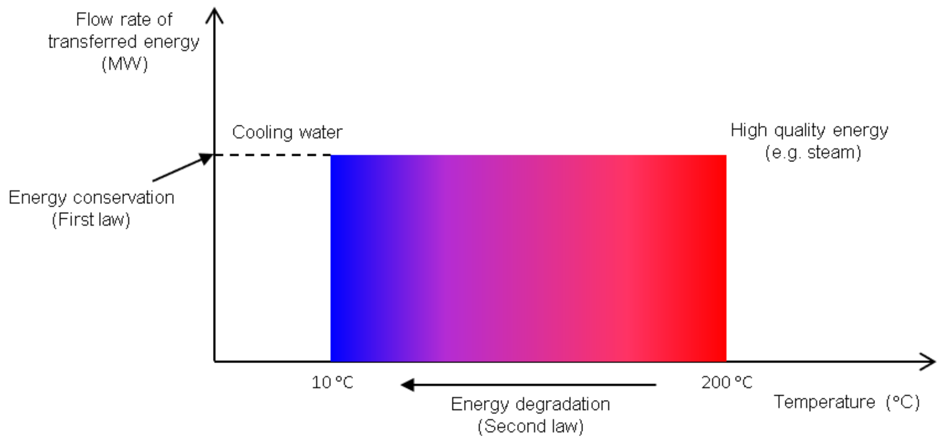

Figure 3- Energy conservation and degradation through heat exchangers and process operations

The flow rate of transferred energy through each unit in the system (heat exchanger or process operation) is the difference between the total outlet enthalpy rate and the total inlet enthalpy rate. As shown in Figure 3, cumulative enthalpy curves are shifted to the ambient temperature due to the energy degradation through each unit in the system (the total energy is constant, but the energy quality decreases).

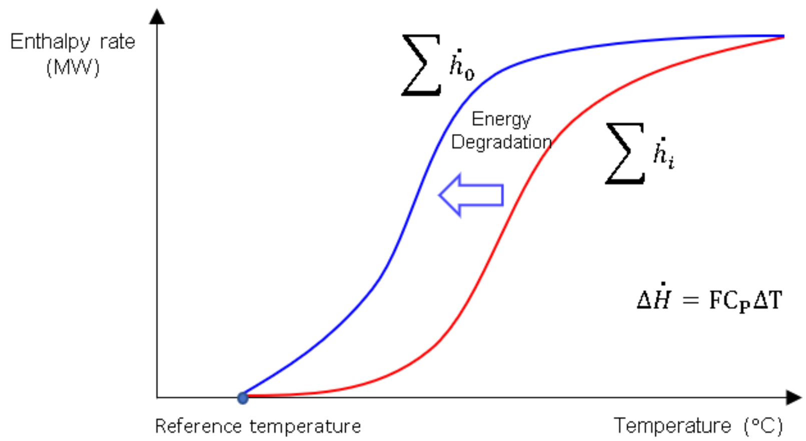

Figure 4- Energy degradation through each unit

At each temperature, T, the difference between the outlet and inlet cumulative enthalpy rate curves can be calculated as a function of temperatures, and it is called the energy transfer curve for this unit. So for each heat exchanger and process operation, the energy transfer curve that shows the energy degradation through the heat exchanger or process operation as a function of temperature can be estimated as follow:

$$ETC_{system}(T) = \sum_{out=1}^{Outlets} \dot{H}_{out}(T) \; - \; \sum_{in=1}^{Inlets} \dot{H}_{in}(T) \tag{1}$$

The ETD is composed of energy transfer curves. It means if we calculate the ETC for all internal heat exchangers, heaters, coolers, and each process operation unit and then put them together as a function of temperature, we will build the ETD. The ETD comprises two parts: the process operation and the HEN. A schematic of the ETD as shown in Figure 4, is an area that corresponds to the transferred energy through the process operations above the HEN area. The energy is degraded from the hot utility to the ambient through all units. The maximum heat capacity of the of the HEN is the minimum of the HEN curve. So, to save more energy, the process operations need to be modified. The HEN curve is the border between the process operation area and the HEN area. As mentioned earlier, the HEN area in the diagram can be decomposed into the individual heat exchangers, and the process operation area can be divided into the individual process operation units [25].

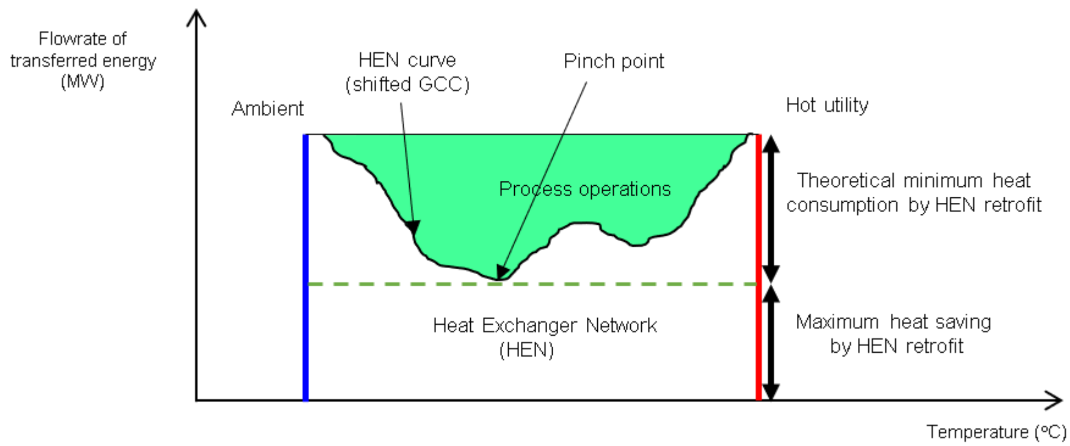

Figure 5- Energy Transfer Diagram (ETD) and linkage with GCC

The HEN curve corresponds to the Grand Composite Curve (GCC) of Pinch Analysis if the global minimum temperature difference is equal to zero, and the minimum HEN curve corresponds to the pinch point, as displayed in figure 5 [26]. Another way to illustrate the ETD is to indicate between hot and cold composite curves. The main advantage of the ETD is to characterize the existing units. Consequently, it can be used for visualization of energy-saving opportunities and analysis of HEN and process operations.

2.3.2. Process operation modification

As it was mentioned before, the ETD can help to identify process operations modifications to reduce utility consumption. The cascaded heat through four individual process operations is shown in figure 6. The maximum of the process operation curve shows the theoretical minimum heat consumption by the HEN retrofit and to reduce it further, and the process operations need to be modified. At the temperature at the maximum of the process operation curve (T), two process operations exist. Both P3 and P4 have an impact at T temperature on the total heat degradation of process operations.

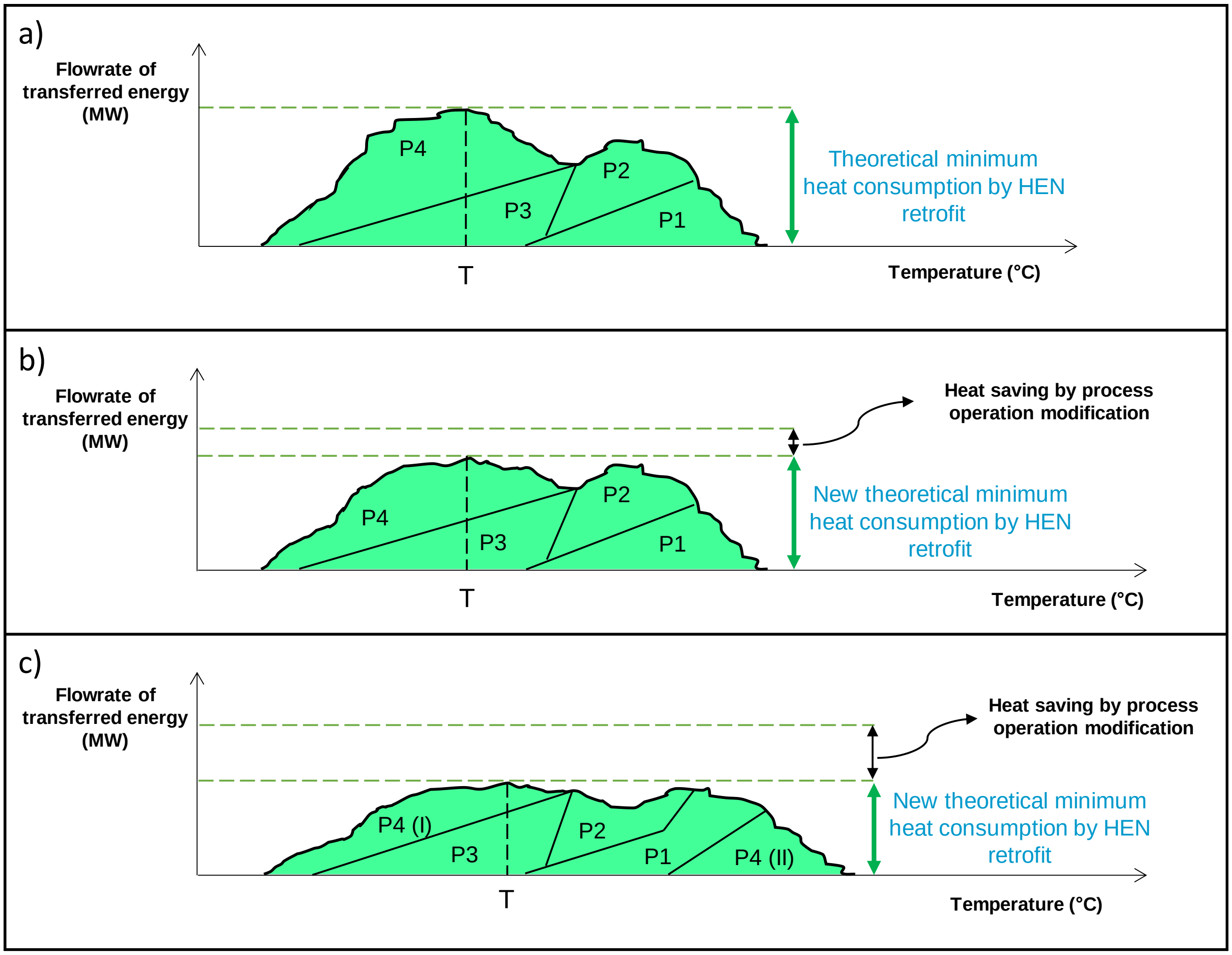

Figure 6- The heat degradation through individual process operations a) before modification, b) after modification of p4, c)after replacing p4 with new technology.

The procedure of process modification in an open-ended decision-making procedure which comprises user intervention and good engineering judgment to come to a solution. Depending on the type of operation, different solutions could be proposed. The modifications can either be incremental like optimizing the process operation or modifying the operating conditions of each process operation or using new technology which has lower hot utility demand. For example, by modifying the operating conditions around a distillation column such as temperature and pressure, we can shift the corresponding part in the ETD to the left or to the right and reduce the overall energy demand. Another example could be increasing the number of effects in the black liquor evaporation system in the pulp and paper industry to reducing the height and increasing the width of the corresponding area in the ETD. Replacing the existing technology with a new one with lower energy usage is another option. For example, using an electric evaporator or adding an infrared radiation (IR) system in the dryer can work. Figure 4.2b and 4.2c show the ETD of process operations after modifying P4 which leads to a new lower theoretical minimum heat consumption by HEN retrofit.

2.3.3. Bridge identification and enumeration

As earlier mentioned, the lost energy can be used somewhere in the process to satisfy heat demands in the plant. The set of necessary HEN modifications to utilize this lost energy (ready to transfer to the cooling water) somewhere else is called Bridge. Each Bridge includes at least one connection between process sources and process sinks, and each connection is called a match. To transfer heat through a match, the process source should be hot enough to heat the process sink, and in that case, the match would have corresponded to a heat exchanger.

As shown in Figure 7, the process sources or process sources have been divided into two categories. A part of process sources is used to satisfy a part of the process sink (II) via process-process heat exchangers and the second part which is the lost energy (I), has been sent to cooling water using coolers. Process sinks includes two parts. One part (III) is heated up by process-process heat exchangers, and the other part (IV) is heated directly by steam or hot water via heaters. The Bridge is a set of modifications to be used (I) for either (III) or (IV), and it reduces the steam or hot water consumption.

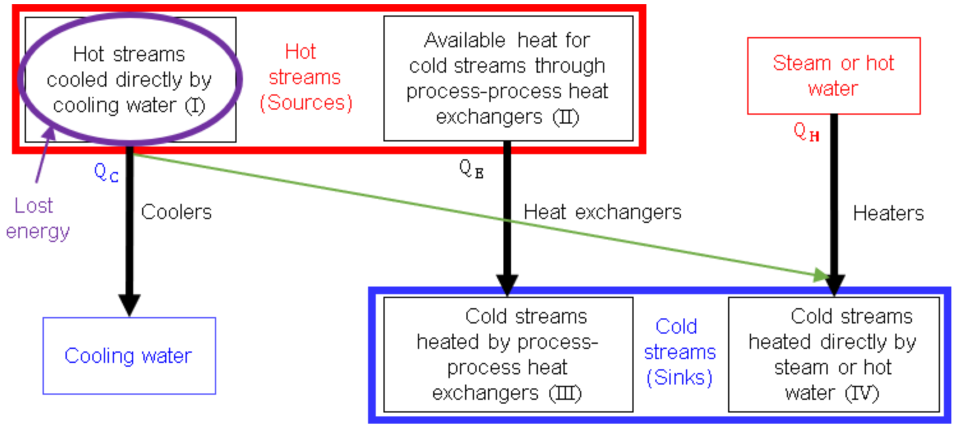

Figure 7-Bridge definition

In some cases, the match corresponds to an existing heat exchanger, and in some cases, it corresponds to a new one. Regardless of the match's feasibility and economic viability, a list of all possible ways (Bridges) to transfer the lost energy to the process sinks should be prepared. Then for each Bridge, the heat transfer capacity of each match would be calculated, and the smallest exchange capacity would be the potential heat saving capacity of that Bridge.

Bridge modifications can be enumerated by employing the first-decomposition or full decomposition network table. In the first-decomposition table, streams are decomposed into process sources and process sinks according to the existing network to provide an overall view on retrofit possibilities. In the full-decomposition table, process sources and process sinks are decomposed into temperature intervals according to the minimum temperature difference specific to each connection. This makes it possible to evaluate heat flow rates and an exchange surface area for each connection.

2.3.4. Heat exchanger load diagram

The heat exchanger load diagram (HELD) can identify a convenient exchanger configuration corresponding to Bridge modifications and for the design of new networks. The HELD includes the heat load (kW) of the process sources and the process sink s that are involved in modifications as a function of temperature. The concept of the HELD is simple, and it represents the enthalpy curve correlated to each part of a stream as a function of temperature. It shows the existing HEN and all the heat exchangers, heaters, and coolers, but both process sources and sinks, so for each unit, there is information about the temperature and heat load. HEN modifications are represented on this diagram by vertical shifts of process sources.

2.3.5. Bridge Method based approaches

Since developing the Bridge Method, few approaches have been developed to use the concept of Bridge modification to improve energy efficiency in different cases. Rohani et al. investigated or studied a step-wise approach to overcome the limitation of the network pinch approach in finding an option to enhance heat recovery. They applied the Bridge Method to identify the possibility of adding new exchangers to a network by connecting coolers and heaters. In the next stage, they implemented an MINLP model to minimize the total utility consumption. If the Bridge leads to energy-use reduction, economic optimization will be carried out. This approach can evaluate all possible connections between coolers and heaters using the concept of Bridge Method, but solving an MINLP optimization for each Bridge is time-consuming [27].

Walmsley et al. developed a modified ETD to improve the Bridge method. In the modified ETD, the heat deficit and heat surplus segments of each ETC has been shown by the use of blue and red colors for easier identification of Bridge modifications [28]. They also employed the HEN surplus/deficit table to distinguish and enumerate the Bridge modifications. This table demonstrates the heat deficit and heat excess at each shifted temperature interval for all heaters, coolers and process-process heat exchangers. This table is useful to solve simple examples but to solve the complex examples with minimum temperature difference specific to each connection, the full decomposition table is more practical to enumerate the Bridge modifications at actual temperature.

2.3.6. Case study

Figure 8 indicates a simple HEN. There are a heat exchanger, a heater, and a cooler in the system. The total hot utility consumption is equal to 2400 kW.

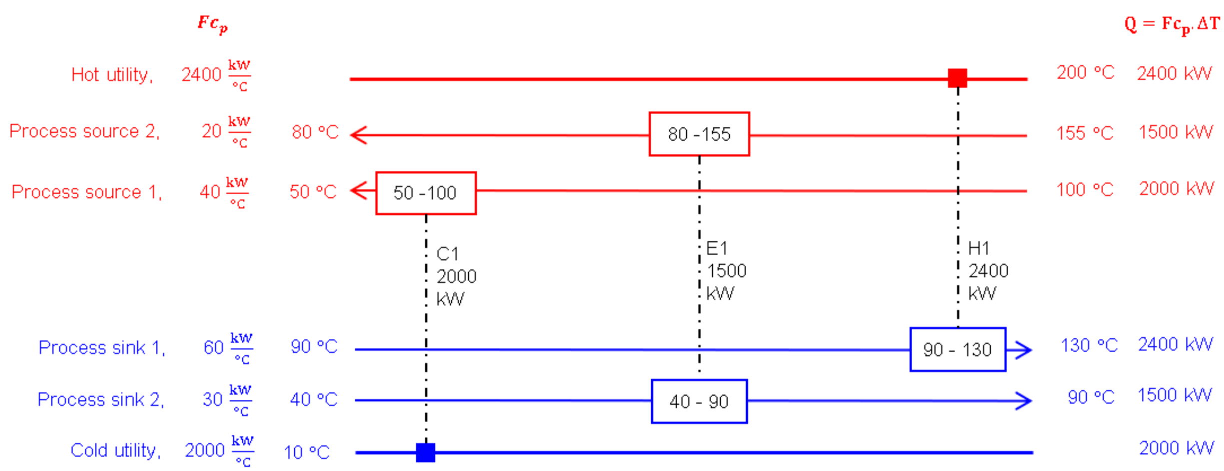

Figure 8- The existing HEN diagram

For this example, the considered ΔT_{min} is 10°C. Energy (2000 kW) has been rejected to the cooling water, and the goal of HEN retrofit is to find a way to use this energy. The corresponding ETD to the existing HEN is shown in Figure 9. It helps to characterize the existing situation, and Figure 10 illustrates the topology of the existing network. In this example, there are two possible Bridges. The first Bridge, including one match, is the connections between the process source of the cooler to the process sink of the heater and the second Bridge, including two matches (connections), are the connection between the process source of the cooler to the process sink of the heat exchanger and the connection between the process source of the heat exchanger and the process sink of the heater. For the first Bridge, the temperature of the process source ranges from

100 to 50°C, and the temperature of the process sink is between 90 and 130°C. In this case, the process source is not hot enough to heat the process sink, so it is not a possible solution. For the second Bridge, there are two matches. For the first match, the maximum available heat to transfer from the process source of the cooler to the process sink of the heat exchanger is 1500 kW and for the second match, the maximum available heat to transfer is 1100 kW. Thus, the saving capacity of the second Bridge is 1100 kW. Bridge modification presented in Figure 11, and the final HEN diagram after the modifications is shown in Figure 12. Figures 13 and 14 describe the ETD and final HELD after Bridge modification.

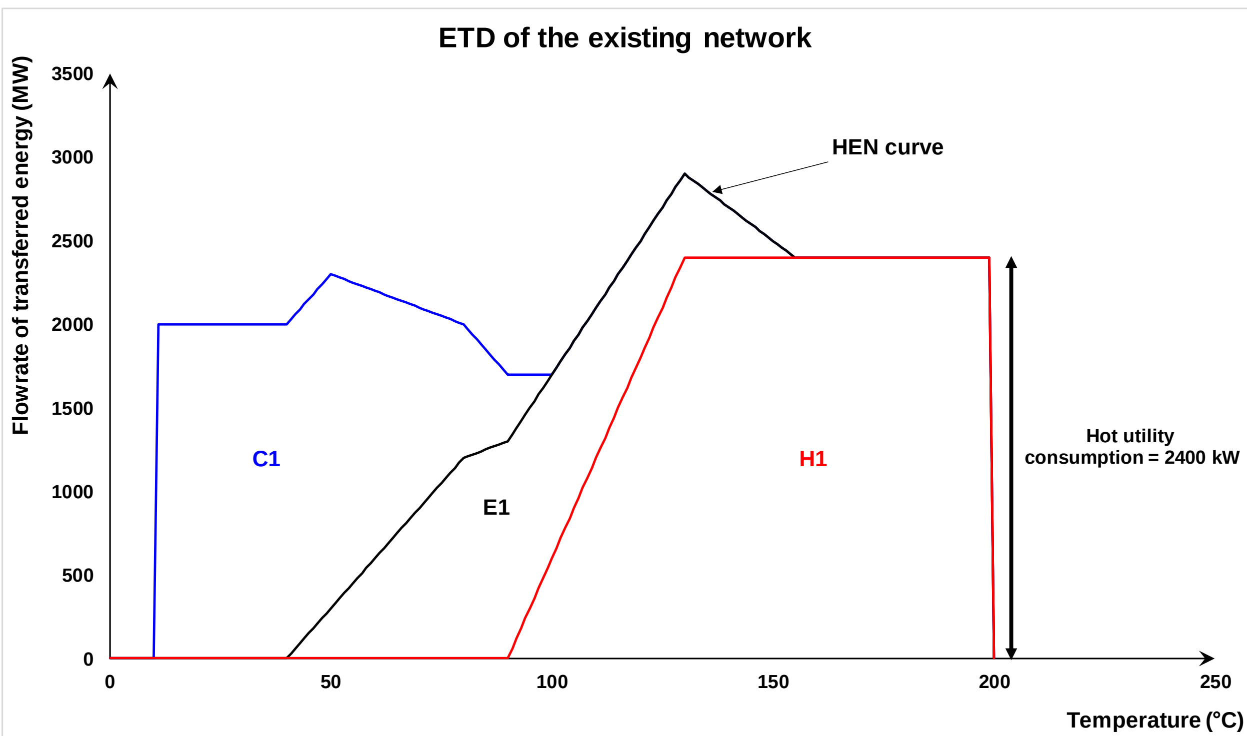

Figure 9- The ETD of the existing network

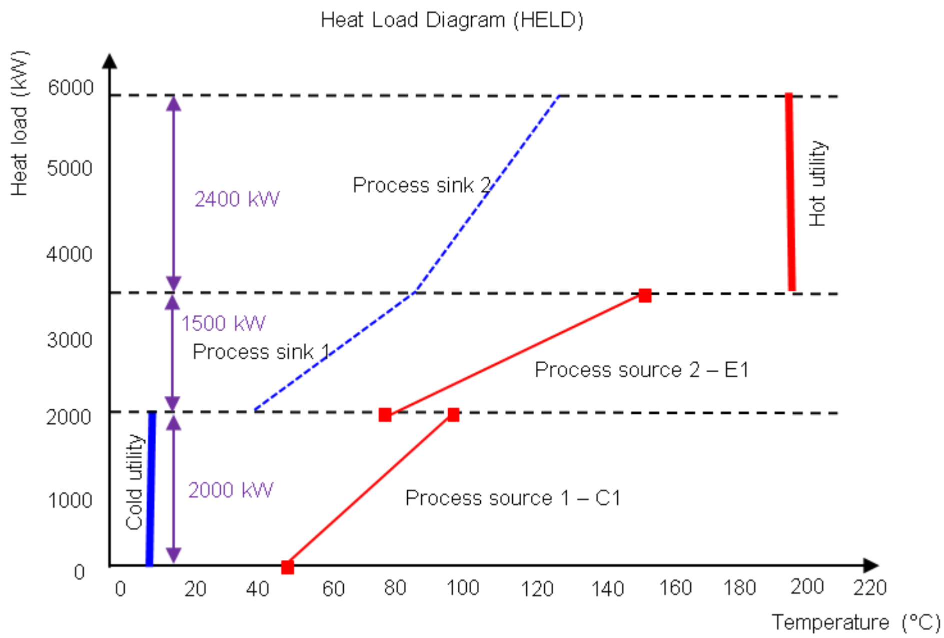

Figure 10- The HELD of the existing network

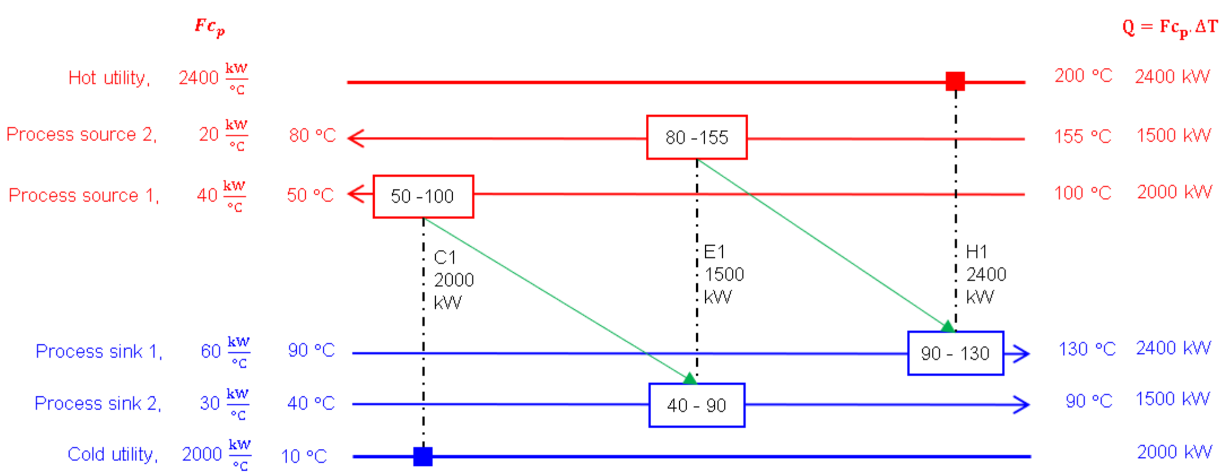

Figure 11- Bridge modification with two matches

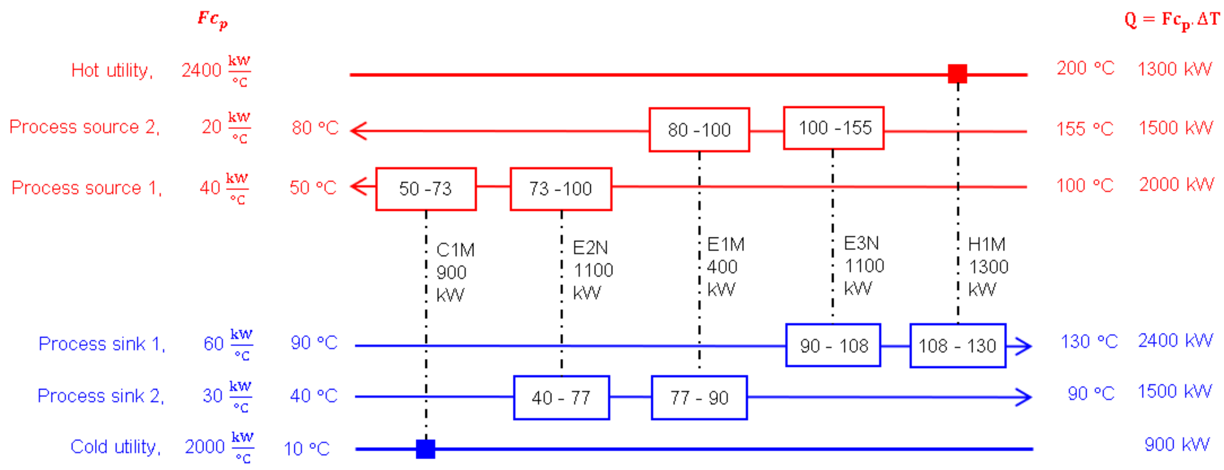

Figure 12- HEN diagram after Bridge modification

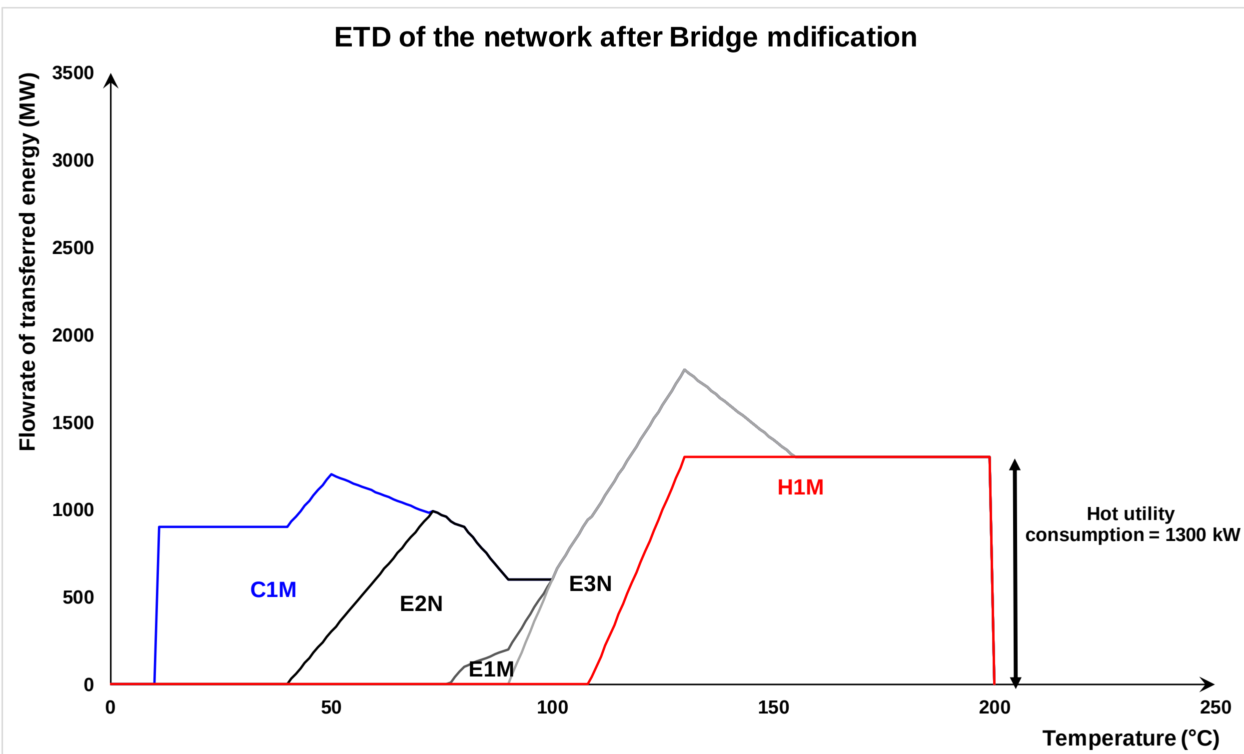

Figure 13- The ETD of the network after Bridge modification

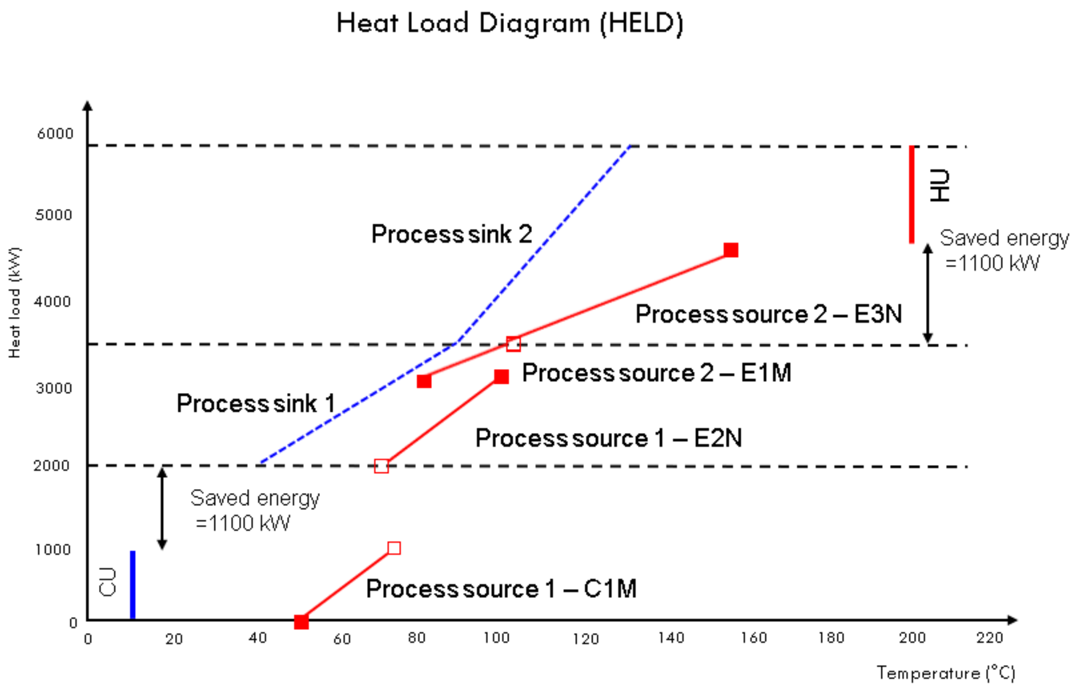

Figure 14- HELD of the network after Bridge modification

The Bridge Method can address challenges related to classical pinch analysis and advanced pinch-based methods. It is a systematic approach that helps to have a better understanding of the existing energy system by characterizing the energy profile of all units, and it helps to identify the most profitable energy projects through an algorithmic approach. However, it has not been done in practice and to apply it; there is a need for a sequential decision-making framework to be designed.

3. Introduction to a sequential decision-making framework

Bridge Method is an energy analytics methodology that considers extracting all streams. It also contemplates the energy degradation across process operations as well as the HEN. Therefore, there is an opportunity to identify energy-saving solutions.

The energy analysis is the foundation of process design and needs to be done in a practical way that considers all the constraints such as scaling, the complexity of implementations, etc.

Traditionally, the process design is conducted by a series of design steps that go from many process options to the selected one and executed in a staged manner.

Sequential open-ended decision-making (SDM) can be an integral part of a framework, and it is a practical approach that can help people to make more thoughtful decisions. It increases the chances of finding the most preferred solutions, among others. More specifically, it enables the energy analysis to concern different process configurations and site-wide options and evaluating the consequences of each energy scenario.

The open-ended decision making cannot be computerized, and it allows a good engineering judgment (GEJ) to be implicated in the design process. While the Bridge Method lends itself well to being formulated in computer algorithms, numerous open-ended decisions should be made from a practical perspective. For example, modifying the process operations, identifying infeasible connections or assessing the corresponding risk for each modification are all the activities that need to be supervised by expert users. Different qualitative and quantitative parameters should be considered to deal with these open-ended decisions.

4. Conclusion

The concept of the Bridge Method was presented as a stepwise approach to reduce energy usage. This new approach has relative benefits to the classical pinch analysis and advanced pinch-based energy analysis methods. The classical pinch analysis is a well-known approach in process integration. It helps to have an estimation of energy-savings capacity, but the point is that removing cross-pinch transfers can not necessarily reduce energy usage. The use of this method allows energy and process experts to identify all possible solutions to save energy. It includes three powerful tools to characterize and modify the energy profile of an industrial system. So, energy usage can be decreased by reducing the flowrate of cascaded heat by utilizing all heat exchangers and process operation units.

To apply the Bridge Method in practice, the design of a sequential decision-making framework is necessary to assess different scenarios of the energy use reduction for users (stakeholders) and then to be benefited from the framework. During the decision-making process, the user intervention can help to make a more realistic and feasible decision, and it helps to identify the short-term and long-term energy projects during the biorefinery implementation.

References

1. Linnhoff, B. and J.R. Flower, Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks. AIChE Journal, 1978. 24(4): p. 633-642.

2. Linnhoff, B. and J.R. Flower, Synthesis of heat exchanger networks: II. Evolutionary generation of networks with various criteria of optimality. AIChE Journal, 1978. 24(4): p. 642-654.

3. Linnhoff, B., Thermodynamic analysis in the design of process networks. 1979, University of Leeds.

4. Linnhoff, B., D.R. Mason, and I. Wardle, Understanding heat exchanger networks. Computers & Chemical Engineering, 1979. 3(1-4): p. 295-302.

5. Flower, J.R. and B. Linnhoff, A thermodynamic-combinatorial approach to the design of optimum heat exchanger networks. AIChE Journal, 1980. 26(1): p. 1-9.

6. Linnhoff, B. and D.R. Vredeveld, Pinch technology has come of age. Chemical engineering Progress, 1984. 80(7): p. 33-40.

7. March, L., Introduction to pinch technology. Targeting House, Gadbrook Park, Northwich, Cheshire, CW9 7UZ, England, 1998.

8. IAN, C.K., Pinch analysis and process integration--a use guide on process integration for the efficient use of energy. 2007, Oxford, UK: Butterworth-Heinemann of Elsevier.

9. Tjoe, T.N. and B. Linnhoff, Using pinch technology for process retrofit. Chemical Engineering, 1986. 93(8): p. 47-60.

10. Van Reisen, J.L., et al., The placement of two-stream and multi-stream heat-exchangers in an existing network through path analysis. Computers & chemical engineering, 1995. 19: p. 143-148.

11. Linnhoff, B. and E. Hindmarsh, The pinch design method for heat exchanger networks. Chemical Engineering Science, 1983. 38(5): p. 745-763.

12. van Reisen, J.L., G.T. Polley, and P.J. Verheijen, Structural targeting for heat integration retrofit. Applied thermal engineering, 1998. 18(5): p. 283-294.

13. Asante, N. and X. Zhu, An automated approach for heat exchanger network retrofit featuring minimal topology modifications. Computers & chemical engineering, 1996. 20: p. S7-S12.

14. Bonhivers, J.-C., et al., Improving the network pinch approach for heat exchanger network retrofit with bridge analysis. 2019. 97(3): p. 687-696.

15. Asante, N. and X. Zhu, An automated and interactive approach for heat exchanger network retrofit. Chemical Engineering Research and Design, 1997. 75(3): p. 349-360.

16. Nordman, R. and T. Berntsson, New pinch technology based hen analysis methodologies for cost-effective retrofitting. The Canadian Journal of Chemical Engineering, 2001. 79(4): p. 655-662.

17. Nordman, R., New process integration methods for heat-saving retrofit projects in industrial systems. 2005: Chalmers University of Technology.

18. Nordman, R. and T. Berntsson, Design of kraft pulp mill hot and warm water systems—A new method that maximizes excess heat. Applied thermal engineering, 2006. 26(4): p. 363-373.

19. Nordman, R. and T. Berntsson, Use of advanced composite curves for assessing cost-effective HEN retrofit I: theory and concepts. Applied Thermal Engineering, 2009. 29(2): p. 275-281.

20. Nordman, R. and T. Berntsson, Use of advanced composite curves for assessing cost-effective HEN retrofit II. Case studies. Applied Thermal Engineering, 2009. 29(2): p. 282-289.

21. Bonhivers, J.-C., et al., Energy transfer diagram for improving integration of industrial systems. Applied Thermal Engineering, 2014. 63(1): p. 468-479.

22. Bonhivers, J.-C., et al., Comparison between pinch analysis and bridge analysis to retrofit the heat exchanger network of a kraft pulp mill. Applied Thermal Engineering, 2014. 70(1): p. 369-379.

23. Bonhivers, J.-C., B. Srinivasan, and P.R. Stuart, New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 1–Concepts. Applied Thermal Engineering, 2014.

24. Bonhivers, J.-C., et al., New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2 – Stepwise and graphical approach. Applied Thermal Engineering, 2017. 119: p. 670-686.

25. Bonhivers, J.-C., et al., Energy transfer diagram for site-wide analysis and application to a kraft pulp mill. Applied Thermal Engineering, 2015. 75: p. 547-560.

26. Bonhivers, J.-C., et al., Linking pinch analysis and bridge analysis to save energy by heat-exchanger network retrofit. Applied Thermal Engineering, 2016.

27. Rohani, N., et al., Multiple modifications in stepwise retrofit of heat exchanger networks. Chemical Engineering Transactions, 2016. 52: p. 313-318.

28. Walmsley, M.R., et al., A modified energy transfer diagram for heat exchanger network retrofit bridge analysis. 2017.

29. Dhole, V.R. and B. Linnhoff, Total site targets for fuel, co-generation, emissions, and cooling. Computers & chemical engineering, 1993. 17: p. S101-S109.

30. Bonhivers, J.-C., et al., Analysis of Heat Cascade Through Process Components to Reduce the Energy Consumption in Industrial Systems. Process Integration and Optimization for Sustainability, 2018.

31. Hui, C. and S. Ahmad, Minimum cost heat recovery between separate plant regions. Computers & chemical engineering, 1994. 18(8): p. 711-728.

32. Maréchal, F. and B. Kalitventzeff, Energy integration of industrial sites: tools, methodology and application. Applied Thermal Engineering, 1998. 18(11): p. 921-933.

33. Marechal, F. and B. Kalitventzeff, Targeting the integration of multi-period utility systems for site scale process integration. Applied Thermal Engineering, 2003. 23(14): p. 1763-1784.

34. Matsuda, K., et al., Applying heat integration total site based pinch technology to a large industrial area in Japan to further improve performance of highly efficient process plants. Energy, 2009. 34(10): p. 1687-1692.

35. Becker, H. and F. Maréchal, Energy integration of industrial sites with heat exchange restrictions. Computers & Chemical Engineering, 2012. 37: p. 104-118.

36. Fornell, R. and T. Berntsson, Process integration study of a kraft pulp mill converted to an ethanol production plant – Part A: Potential for heat integration of thermal separation units. Applied Thermal Engineering, 2012. 35: p. 81-90.

APPENDIX B ARTICLE 2: PLANT-WIDE ENERGY ANALYSIS OF INDUSTRIAL FACILITIES USING THE BRIDGE METHOD: PART II – FRAMEWORK FOR DECISION SUPPORT

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Abstract:

Heat integration is a practical approach for increasing the long-term competitiveness of industry through a reduction in energy usage and significantly is crucial for radical greenhouse gas (GHG) emissions reduction from industrial sites. In the last few years, a novel approach called the Bridge Method had been developed for Heat Exchanger Network (HEN) retrofit. It is a systematic method with a well-defined procedure that lends itself well to the solution using a computer algorithm and graphical user interface. It is a stepwise approach that needs user intervention and employing a decision-making framework to make it practical.

The objective of this paper, which is the second part of a three-part article, is to demonstrate the developed sequential design decision-making framework for applying the Bridge Method in practice. The framework comprises a systematic and user interactive decision-making approach, where design calculations are made, and decisions are taken at different points in the design process - leading to recommendations for energy optimization. The developed framework explicitly considers the selection of ΔT_{min} contribution of each stream ($\Delta T_{min,cont.}$), guidance for identifying potential process operation modifications, and identification of the Heat Exchange Network (HEN) modification. The framework is demonstrated through a concretizing example, which led to a 46% decrease in hot utility consumption.

Keywords: Bridge Method, heat exchanger network retrofit, plant-wide energy analysis, sequential decision-making framework

Abbreviations

$\dot{E}$	Flowrate of cascaded heat
EEP	Energy Efficiency Program
ES	Energy Specialist
ETD	Energy Transfer Diagram
ETC	Energy Transfer Curve
$\dot{H}$	Enthalpy rate
$\dot{H}_{in}$	Enthalpy rate of inlet
$\dot{H}_{out}$	Enthalpy rate of outlet
HELD	Heat Exchanger Load Diagram
HEN	Heat Exchanger Network
HUC	Hot Utility Curve
PO	Process operations
PES	Plant Energy Superintendent
PPE	Plant Process Engineer
P. Si.	Process sink
P. So.	Process source
T	Temperature
Ta	Ambient temperature
$T_{h_{Source}}$	Hot end temperature of the process source stream
$T_{c_{Source}}$	Cold end temperature of the process source stream
$T_{h_{Sink}}$	Hot end temperature of the process sink stream
$T_{c_{Sink}}$	Cold end temperature of the process sink stream

1. Introduction:

1.1 Problem Context

The industrial sector CO_2 emissions reached almost one-quarter of global emissions in 2017 and became the third-largest GHG emitter [1]. Moreover, radical GHG emissions reduction by industries is an especially difficult and complicated challenge due to a number of factors including the unique energy needs of different process sectors, energy use reduction constraints with cogeneration, and the essential requirement for production sites to remain competitive.

Over the last decades, several approaches were developed to reduce the energy usage of industrial plants to reduce GHG emissions and increase profitability. Pinch Analysis has been implemented for decades to identify site-wide opportunities for energy use reduction in greenfield [2, 3] and retrofit designs [4]. It has been incorporated in all kinds of different contexts considering fouling and pressure drop and has been applied in practice. The graphical tools in pinch analysis are based on stream data and do not include information about the existing process operations and heat exchanger, which are crucial in the context of retrofit.

In the past few years, a novel energy analysis approach called the Bridge Method had been developed by Bonhivers and Stuart [5-8]. This method has the ability to characterize the energy degradation through the whole system, including the process operations and, therefore, can address critical issues such as site-wide energy integration, non-isothermal mixing, process operation modifications, etc. However, applying Bridge Method in practice has never been done before.

Applying in practice means integrating design and the Method. The engineering design is a sequence of tasks, and each task must be done to have a duly diligent design that does not have errors and omissions. Each one of these tasks can imply a lot or a little work, depending on risks and whether it is essential to the design.

In the first section of this paper, the Bridge Method and the concept of a sequential decision making process to incorporate the Bridge Method are presented. Bridge Method brings a whole new set of opportunities that have to be brought into the design process practically.

1.2 Literature review

To define a sequential design decision-making framework, first, the philosophy behind the Bridge Method and its advantages over the conventional pinch-based methods are presented. Second, the literature pertinent to engineering design and decision support system framework is represented.

1.2.1. Bridge Method

A detailed review of the Bridge Method is presented in part I of this paper. The Bridge Method extracts all process stream data (unlike other methods) and employs what we call the Energy Transfer Diagram (ETD) to describe the flow rate of transferred energy through temperature intervals from the hot utility to ambient [5]. Figure 1 is a schematic of an ETD, illustrating how energy degrades across process operations and the HEN. The ETD helps to identify heat savings possible by HEN retrofit, including the consideration of minimum temperature driving forces in each heat exchanger. Energy degradation through process operations can be interpreted to identify opportunities to increase the maximum possible savings. Understanding the impact of each unit in degrading the energy can help to determine the possible energy-saving projects [9]. According to this method reducing the hot utility usage in an existing HEN implies decreasing the flowrate of transferred heat through exchangers or process operations in the entire temperature interval between the hot utility and the ambient [5].

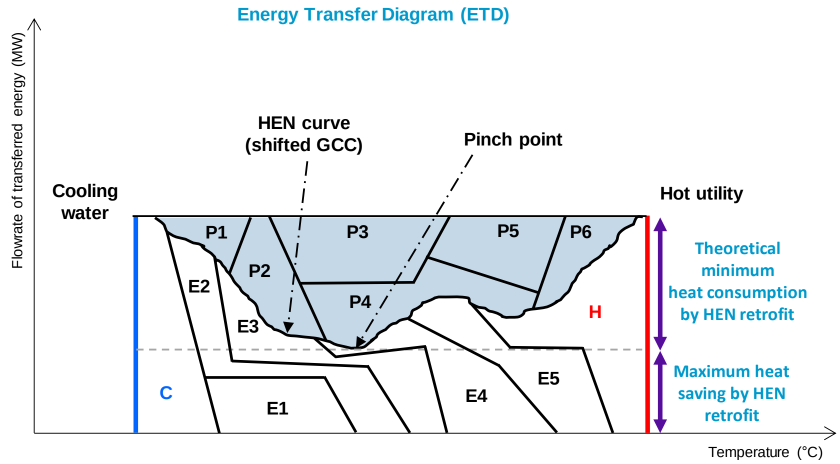

Figure 1- Schematic of an energy transfer diagram including the heat exchanger network and process operations

The set of necessary HEN modifications to use the lost energy (ready to transfer to the cooling water) somewhere else is called Bridge. Each Bridge includes at least one connection between process sources and sinks, and each connection is called a match. Each modification starts with the cooler supplier and ends with the heater receptor. To enumerate the possible Bridge modifications, the first decomposition network table is used to identify the energy saving capacity of each match. The Bridge Method can address critical issues such as non-isothermal mixing, plant-wide analysis, stream splitting, process operations, and HEN topology. It can be executed in practice by designing a state-of-the-art framework that systematically considers the design process with inputs from plant process engineers, energy specialists, etc.

1.2.2. Engineering design as a sequential decision-making process

The plant-wide energy analytics is, at its foundation, an engineering design where the design statement is to reduce energy use consumption in heat exchangers and process operations, and it needs to be done in a practical way that considers all the constraints such as scaling, pressure drop, the complexity of implementations, etc.

Traditionally, engineering design is conducted by a series of design steps that go from many options to the selected one and executed in a staged manner (order of magnitude analysis, pre-feasibility analysis, feasibility analysis, definition engineering, detailed engineering) and finally construction [10]. Sequential decision-making in engineering design refers to a procedure whereby from a set of possible design options, the user sequentially triages the options to include more insight, better data, and with these, reduces risk. As the decision-making process moves forward, the user learns more about the system and can make a better decision [11].

To design a sequential decision-making process, the objective at each design step needs to be identified. Each sequence is designed to fulfill a specific objective, and to do that, it comprises a set of activities, and at the end of each sequence, a decision is made, and it is used as new information in the next sequence to proceed the next decision.

Figure 2 shows a generic single-step design decision-making process which is influenced by sets of controlled and uncontrolled conditions [12]. The controlled conditions are generally in control of decision-makers such as fundamental and stochastic models necessary to calculate the decision metrics, product, and process design to create a new product, and design practices, and good engineering judgment (GEJ). The uncontrolled conditions comprise the fuel price or product price, legal and business consideration, and government regulation (energy contract of the mill).

To make a decision, some information needs to be added as an input such as design objective, data and design constraints, and knowledge. Decision objectives are the identified goals that are needed to be attained or accomplished through decision making [13]. The design constraints include safety, cost, timing, and manufacturability. Decision metrics represent the quantitative measures such as graphs, tables, or numbers used to help decision-makers for assessing risks, comparing results, and finally make a better decision.

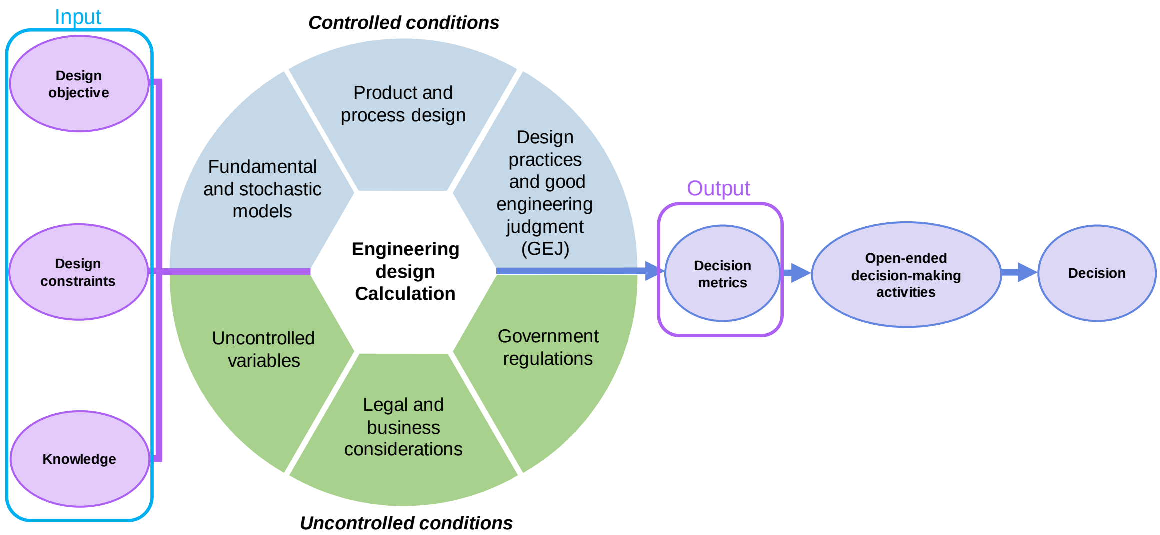

Figure 2- Generic single-step decision-making process in engineering design

As mentioned before, the design process in engineering is a series of sequences and therefore, decisions in earlier steps are interdependent to the later decisions. A schematic of a generic sequential decision-making process is shown in figure 3.

The necessary activities to make a decision can be categorized into two groups. The first group is the activities that can be done automatically by a computer through algorithms without any user intervention. The second group is the activities that need to be done by expert users to find solutions for open-ended decisions. In each sequence, the objective, case-related data and constraints, and necessary knowledge should be known. These data will be employed for calculating and generating necessary decision metrics such as graphs and tables, using the computer algorithm as an output.

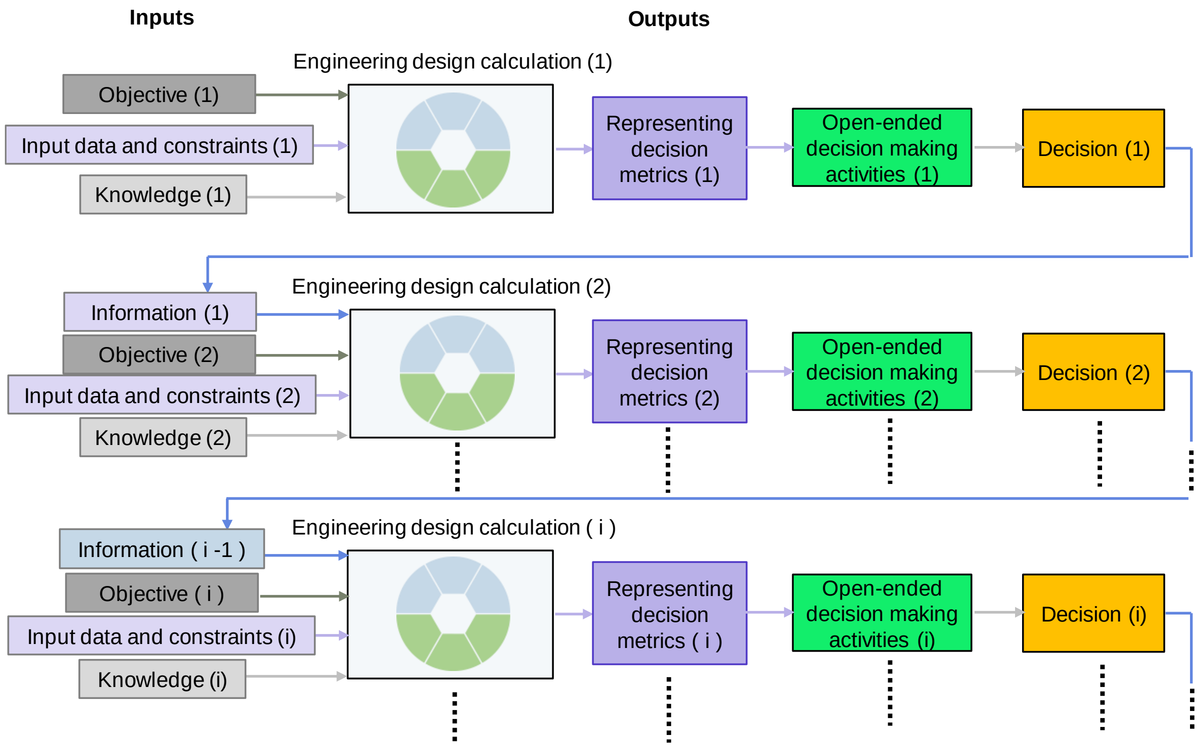

Figure 3- The structure of a sequential decision-making process

Then, decision-makers use outputs along with their knowledge and experiences to select appropriate options and make a decision, which may take days or months. The new decision at each sequence will be used in the next sequence as new information to narrow down the options and help to come to the final decision.

To make an effective decision-making process, especially for a complex problem with a massive amount of data, we need a computer-based system to input necessary data, utilize them to calculate decision metrics, and represent the results to the user. In the next section, the need for a computer-based information system is explained.

1.2.3. Framework for a decision support system

The Bridge Method is a systematic approach that lends itself well into a computer algorithm but implementing it into practice requires a computer-based information system (CBIS) to interact with the user and help to organize information and provide better decisions. When a vast amount of information is involved, the Decision Support System (DSS) as an interactive, adjustable, and versatile type of CBIS is the best choice to make the complex decision-making process with high consistency [14]. It can get the data from different sources, provide reports and presentations using textual and graphical tools that suit the user's needs. Besides, it can perform sophisticated computations, assessments using computer-based algorithms for optimization and solving problems [15].

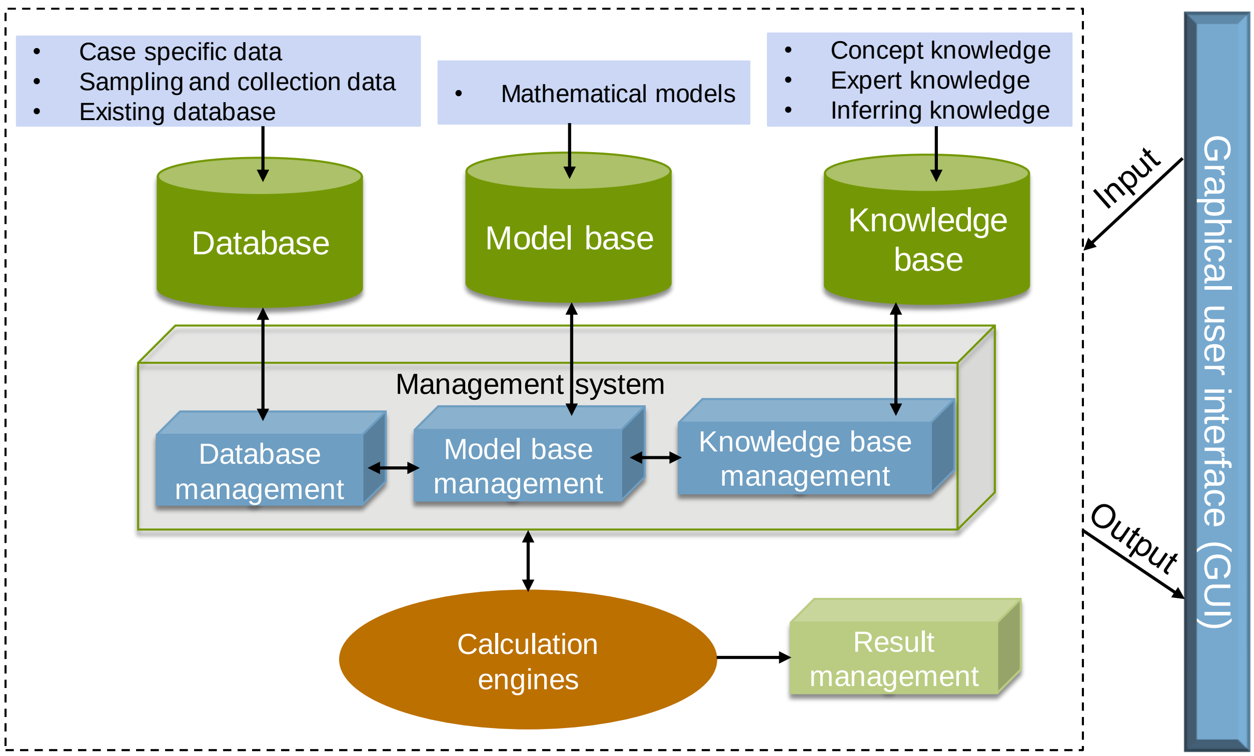

Figure 4- Architecture of a decision support system inspired by Xia et al. [18]

Over the last 50 years, DSS has been evolved from a simple management decision system [16] to a data-driven and knowledge-driven DSS in the past few years [17, 18]. An architecture of a DSS is presented in figure 4 [19]. A DSS commonly includes a Graphical User Interface (GUI), model base, knowledgebase, database, calculation engine, and management system. The GUI is a front-end tool for data input and output results [19]. It has a module to ask the user to input the information and to transfer this information to the management system. It also includes an output module, known as “dashboard”, to visualize results for further analysis [20]. The database is an organized collection and storage of information that generally is relevant to the problem. In addition, the results of the analysis and assessment of the case study are stored in the database. The model base is a place to store all necessary models to support the process of decision-making. The knowledgebase is a base which the human expertise, heuristic knowledge, concept knowledge, expert knowledge, and inferential knowledge, are efficiently stored and accessed. The calculation and data analysis engine, also known as “calculation engine,” is responsible for evaluating and calculating parameters and indicators. The management system includes the database management module, the model base management module, and the knowledge base management module. These management modules allow the user to create a new database and append, modify, delete, and browse the data, models, or knowledge. The GUI can communicate with a database, model base, knowledgebase, and calculation engine through the management system.

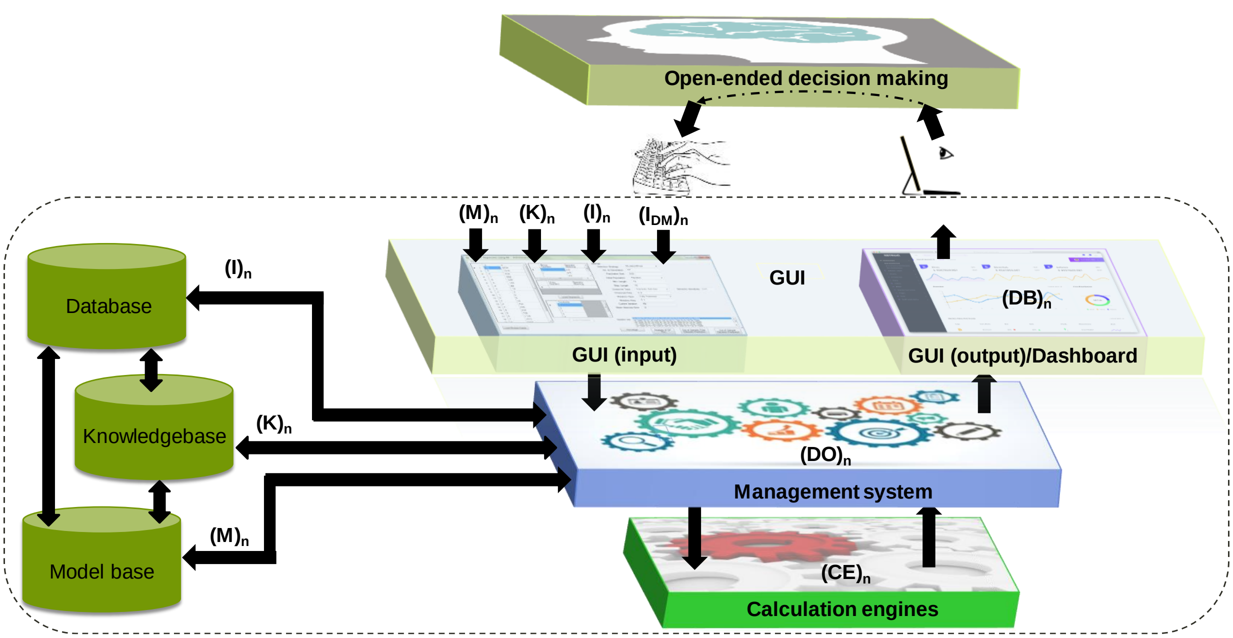

Figure 5- Overall Architecture of DSS for a sequential decision support system

Figure 4 shows the proposed architecture of DSS to use for a sequential design decision-making process. The GUI includes input modules and the output modules or dashboard. First, the decision objective (DO) in each step should be identified. The case-relevant data or new knowledge or models are added through the GUI and will be stored in the knowledge base or the model base through the management system. The management system also includes the list of the decision objectives in an execution priority order. Based on this list, at each sequence, the GUI asks the necessary information relevant to the specific decision objective. This information is sent to the calculation engine to calculate and generate tables, graphs, or texts to be represented in the dashboard. These visualized decision metrics help the user for assessing further and doing activities to make an appropriate decision.

The new decision needs to be added to the existing information, and it will be used in the next sequence of decision making. Some elements such as GUI, dashboard, and calculation engine in the overall architecture of DSS can be coupled with the sequential decision-making framework. Figure 5 represents a schematic of a sequential decision-making framework with demonstrating some of those elements. The necessary knowledge and models in each sequence can be extracted from the knowledge base or model base or can be directly added to the system through GUI by the user. Making a decision in each sequence leads to new information that will add to the system by decision-makers through GUI. This Framework benefits both from the calculation power of the computer for sophisticated algorithms and human knowledge and expertise to bring it to a viable decision at each sequence.

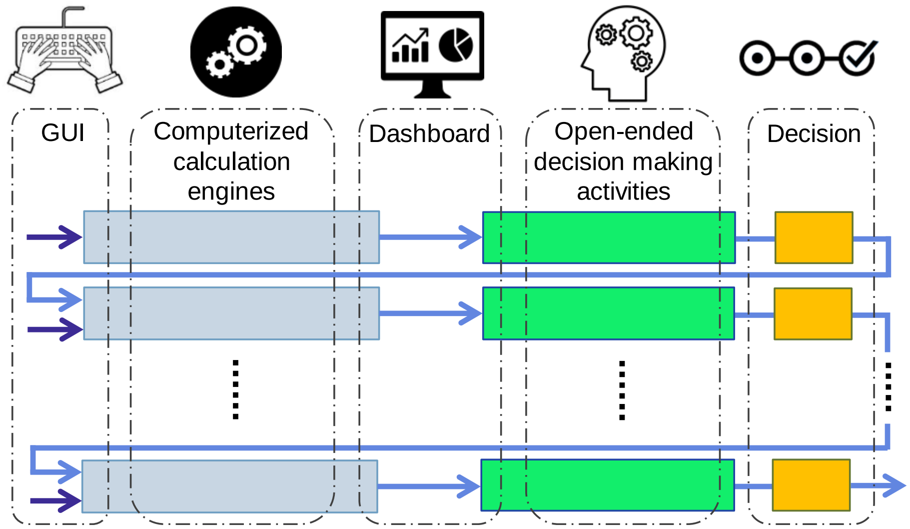

Figure 6- Sequential design decision-making framework

To incorporate the sequential design decision-making framework for the Bridge method, we need to dissect the Bridge Method and identify the activities that need to be done in each sequence.

2. Dissection of the Bridge Method

The Bridge Method like any other energy analytics approaches needs energy-related data. The first step of all these approaches is to extract data from a validated and verified simulation file, however, in most cases, there is no such simulation available for the plant. The first step in our methodology is to do energy auditing. In Bridge Method, there is an opportunity to extract all data from a simulation file and then use them to characterize the energy degradation through heat exchangers and process operations.

The first step in the Bride method is to identify the global ΔT_{min} or ΔT_{min} contribution of each stream ($\Delta T_{min,cont.}$) that is necessary to identify the maximum heat saving capacity in the ETD. In pinch-based approaches, this parameter is identified by a rough estimation of investment and energy cost for different minimum temperature differences and plotting the total cost versus ΔT_{min} to find the optimum ΔT_{min} with minimum total cost. In the Bridge Method, there is an opportunity to use minimum temperature contribution specific to each stream.

In an industrial plant, we have a mixture of liquid and vapor streams which have a different heat transfer coefficient. So, in these cases, using the same ΔT_{min} for all streams is not correct [21-23]. The actual temperature of process source and sink streams can be shifted by the individual $\Delta T_{min,cont.}$ using Eq. 1 and Eq. 2.

$$For\ process\ source\ stream\ (i): T_i^* = T_i - \Delta T_{min,cont,i} \quad (1)$$

$$For\ process\ sink\ stream\ (j): T_j^* = T_j + \Delta T_{min,cont,j} \quad (2)$$

Whereas, T_i^* and T_i are the shifted and existing T for process source i, and T_j^* and T_j are the shifted and existing T for process sink j, and $\Delta T_{min,\ cont,i}$ and $\Delta T_{min,\ cont,j}$ are the individual ΔT_{min} contribution of process source stream i and process sink j, respectively. It means that to connect stream i and stream j, the ΔT_{min} will be $\Delta T_{min,cont,i} + \Delta T_{min,cont,j}$.

The Bridge Method has the ability to consider individual ΔT_{min} contribution for each stream., So, the first step will be its identification for each stream as a function of heat transfer coefficient where few correlations have been developed to calculate it [24, 25]. There are also some databases which can help to identify the individual ΔT_{min} contribution based on heuristics [26]. These data can be used by an expert user to make a decision and determine an appropriate value for each stream.

The Bridge Method has the ability to represent the cascaded energy through process operations, which is pertinent to the energy degradation in each unit. The heat cascade through process operations has an impact on the minimum hot utility consumption because process sources in a HEN come from operations, and process sinks in a HEN are inlets to the process operations. According to the onion diagram, the design starts from process operation and moves outward to the heat exchanger network and utilities [27]. So, a process operation modification should be done before the HEN retrofit design.

Calculating and generating the ETD for the process operations alone can be done through a computer algorithm. As it was mentioned in part I of this paper, the energy demand of the process operations can be decreased by reducing the maximum of the process operation curve. First, the temperature of the maximum of the process operation curve should be identified. At this temperature, the process operations that have an impact should be listed for further analysis. The modification of the process operations is an open-ended decision-making problem and it needs expert users to do the feasibility study for a possible modification. After that, for potential modification opportunities, a re-simulation process should be done, and all data should be extracted for the next steps.

In an industrial plant, there are many process-process heat exchangers, heaters, and coolers, and therefore, many Bridge modifications could be formulated. To reduce the search space and save time, the infeasible connections must be identified and removed from the network table before the Bridge enumeration step. A table can be generated by computer to take into account all connections between process source and process sink streams. Some connections are thermodynamically infeasible and automatically can be identified by the computer, but the forbidden or restricted connections should be identified by someone like the plant process engineer (PPE). For the rest of the connections, it is possible to rank them based on the associated risk such as complexity and safety. These are the unquantitative parameters that can help to find viable Bridge modifications.

The fourth step is to enumerate the practical Bridge modification and calculate the energy saving capacity of each one using the computer algorithms. In practice, the solutions with less than five modifications are more likely to be selected for implementation, so the Bridge modifications with four matches or less can be selected by the user for further analysis.

The fifth step is to calculate the investment cost and payback period for each modification, and it can be done by a computer algorithm. A cost model should be developed to consider the investment cost for each Bridge modification. This model helps to define the list of modifications that meet the payback period, and for each modification, the level of risk that is identified in the previous step will be represented. This list can be sorted by the amount of saving energy or the risk (unquantitative parameter). Then expert users can do a detailed analysis for each bridge and calculate the more precise investment cost by considering the type and number of new heat exchangers need for each modification, the cost of adding area or relocating the heat exchangers.

In conclusion, five steps need to be considered to identify the most viable Bridge modifications in the conceptual design step:

1. Identification of individual ΔT_{min} contribution for each stream,
2. Identification of possible process operation modification opportunities,
3. Identification infeasible stream connections,
4. Identification of practical Bridge modifications,
5. Identification of economically viable Bridge modifications,

The next section presents each sequence of the decision-making framework incorporating these five steps.

3. Sequential design decision-making framework for Bridge Method

Before the framework execution for the Bridge Method, an energy auditing step is necessary to extract required energy-relevant data for the framework. Figure 6 shows a schematic of the developed energy auditing process. Before starting an energy analysis project, having the senior management commitment to reduce energy consumption and GHG emissions is crucial. The mill manager must be the primary motivator of the project as evidenced by attending the meeting, giving priority to energy matters, choosing an energy champion and identifying the hurdle rate(minimum return on investment) for the energy project. The energy champion is the leader of the energy projects with enough authority and skill to set up the initial program and to implement the first few phases.

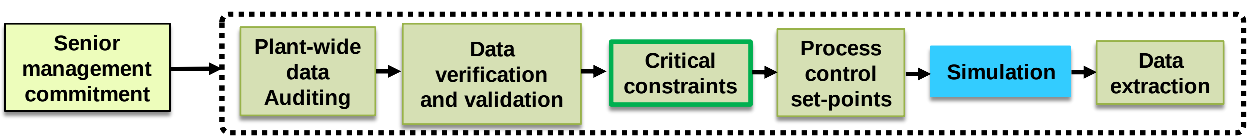

Figure 7- Energy auditing to identify some energy projects that have obvious savings before the design decision-making framework

To do the energy auditing, a multi-disciplinary team should be built because of a wide variety of experience and skills that are required to understand all aspects of energy utilization in the plant. Team members should include a key representation from management, technical, engineering, operations, and maintenance departments.

The next step is to do a plant-wide data auditing for the industrial processes that normally have a large and complex steam generation and distribution system. In this step, the operating data have to be validated and verified to use them for the overall mass and energy balance of the plant. The critical constraints, particularly for the cogeneration system, such as boilers and turbines constraints including energy contract, the minimum and maximum fuel usage of boilers and the minimum steam flowrate of turbine inlet should be considered. The next step is to take a look at the process control set-points and tuning them, which can lead to an energy saving with zero or near-zero capital cost. After that, a steady state simulation must be done by applying the verified data from the previous step to calculate the energy and mass balance and produce a process flow diagram that is well balanced [28]. The extracted data from the simulation then will be used in the developed sequential decision-making framework.

The first step of the framework is to determine the $\Delta T_{min,\ cont.}$ specific to each stream. It can be the same for all streams, or it can be specific to each stream. Therefore, the objective of the first sequence of the framework, represented in figure 7, is to identify the individual ΔT_{min} contribution for all streams.

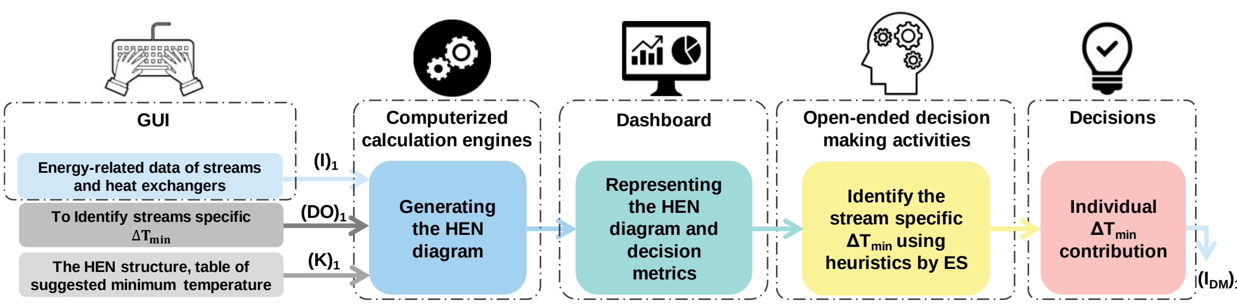

Figure 8- identification of the individual ΔTmin contribution for streams

In this step, the user needs to input Energy-related data of streams and heat exchangers through the GUI. They are necessary to generate the existing HEN, including the hot and cold streams and existing exchangers. These case-specific data include initial and final temperature, mass flowrate and heat load for each stream, hot and cold utility temperature and heat load for each heater and cooler, placement of every exchanger with the initial and final temperature of the hot-end and the cold-end. Also, some information such as the knowledge to generate the HEN diagram and the list of suggested values for individual ΔT_{min} contribution for different types of streams will be used as inputs and will be sent to the calculation engine through the management system.

The calculation engine will generate the HEN diagram and represents a table that includes suggestions for stream specific ΔT_{min} according to the composition and phase of each process stream. Then the HEN diagram will be demonstrated on the dashboard with the table of suggested ΔT_{min}.

In the open-ended decision-making part, an energy specialist can accept the suggested values or refine them by employing his or her knowledge and expertise. The final ΔT_{min} for each stream will be added through the GUI and will store in the database.

The objective of the next sequence in the framework is to identify the process operation modifications. The Bridge Method will be useful hereby indicating the energy degradation through each process operation in the ETD. Figure 8 shows the sequence of the identification of process operations.

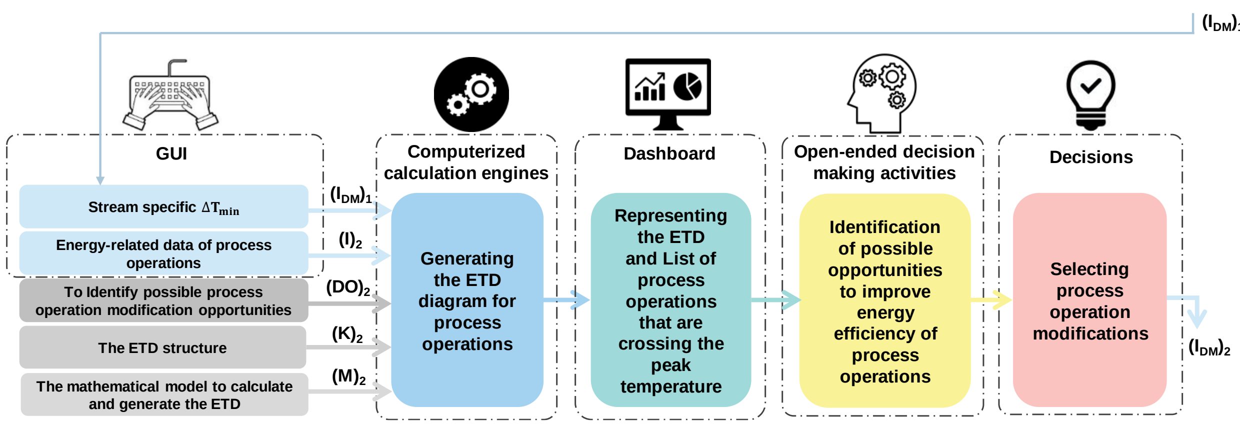

Figure 9- Identification of opportunities for the possible process operations modification

To calculate the ETD, the energy-related data for all process operations such as the list of process operations with input and output temperature, mass flowrate, heat load, and exothermic or endothermic reactions will be added to the framework by the user. Besides, the ETD structure and the mathematical formulation to calculate the ETD, stored in the knowledge base and model base respectively, it will be sent to the calculation engine through the management system. The energy transfer curve of a system is the difference between the sum of the outlet enthalpy rate curves and the sum of the inlet enthalpy rate curves (Eq. 3).

$$ETC_{Process\ operation}(T) = \sum_{out=1}^{Total\ outlets} \dot{H}_{out}(T) - \sum_{in=1}^{Total\ inlets} \dot{H}_{in}(T) \quad (3)$$

The ETD is the combination of the ETCs of all process operations. Accordingly, the maximum of the ETD will show the maximum hot utility consumption by process operations. To reduce that, the cascaded heat through the process operations that have an impact on the maximum of the curve should be reduced [9]. By calculating the temperature of the maximum of the ETD, and detecting the process operations, that have an impact on the ETD at that temperature, the potential process operation modification can be identified. The ETD and the list of identified process operations will be represented on the dashboard, and we need to answer the question of the most viable opportunities for the process operation modification. The next step is to assess the list of process operations by Plant Process Engineer (PPE) and Plant Energy Superintendent (PES) using Good Engineering Judgement (GEJ), to find possible opportunities and improve the energy efficiency of process operations that merit for their examination. After that, they need to confirm the operational viability of each modification. For each modification, we need to re-simulate the system and extract the data for the Bridge modification. All following sequences of the framework should be executed for each potential process operation modification.

Figure 9 represents the next sequence of the framework, which is the identification of infeasible stream connections. Before calculating the Bridge modification, the infeasible connections need to be determined. The infeasible connection means a connection that is thermodynamically impossible, or it is categorized as the forbidden connection. The extracted data for each modification will be added to the system through the GUI. The Connection table will help to recognize the infeasible connections. The columns in this table are assigned to the process sinks, and the rows represent the heat source. So each cell in this table belongs to a connection between hot and cold streams. This table will be generated by the calculation engine and will reveal on the dashboard. Identification of infeasible stream connections will be done by the plant process engineer using the energy data and Good Engineering Judgment (GEJ).

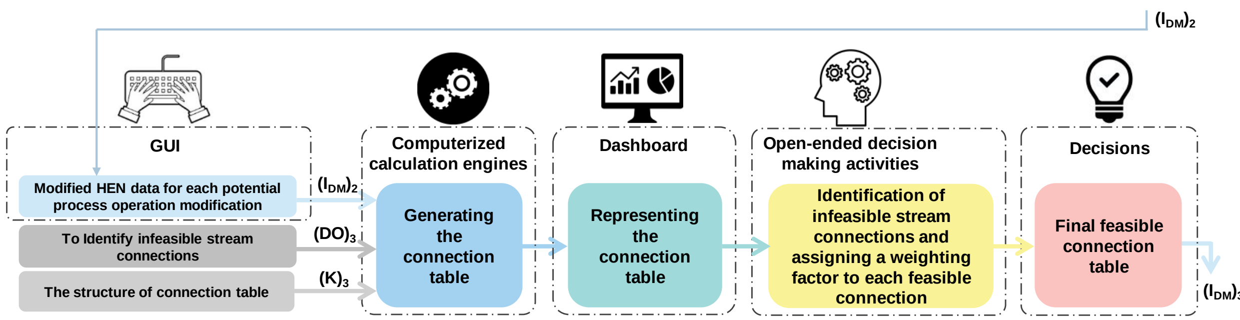

Figure 10- Identification of infeasible stream connections

To identify a viable solution, many parameters should be considered. These can be categorized into qualitative and quantitative parameters. In heat exchanger network retrofit, the qualitative parameters are safety, complexity, operability, and controllability and the quantitative parameters are the cost of the heat exchanger equipment and external utilities [29]. To consider the qualitative parameters, the plant process engineer and plant energy superintendent can identify very interesting connections, interesting connections, and less interesting connections using the GEJ.

The very interesting connections are the existing connections that there is no need for piping and construction, and they can be assigned by number 3. The new connections that are close together, and without any concern about their risk or complexity are categorized as the interesting connections and assigned by number 2. The connections that are far from each other, or there is a topology restriction, or with other complexity or controllability issues are categorized as the less interesting connections, and assigned by number 1. These numbers are the weighting factors, and the higher number means a more interesting connection.

For all feasible connections, the qualitative assessment needs to be done, and a number should be assigned to each connection. The list of weighted feasible connections will be added to the system by the user through the GUI.

Figure 10 shows the next sequence of the framework to identify the practical Bridge modifications. The Bridge Method has a tool named the network table to enumerate the Bridges. Each cell in this table belongs to a feasible connection between process sources and process sinks. Equation 2 illustrates the potential heat transfer capacity for each connection. The calculation engine will generate the list of all possible Bridges with a maximum of three matches, and it will calculate the average weighting factor for each Bridge. Then the sorted list of Bridges based on the energy-saving capacity along with their average weighting factor will be displayed on the dashboard. This list will give the decision-makers a nice starting point for further assessment of Bridge modifications. Besides, the modifications with more than five matches are more likely to be impractical.

$$Potential\ heat\ transfer\ capacity = Max\left(Min\left(FCp_{Source} \times \left(T_{h_{Source}} - Max\left(T_{c_{Source}}, T_{c_{Sink}} + \Delta T_{Source} + \Delta T_{Sink}\right)\right), FCp_{Sink} \times \left(Min\left(T_{h_{Source}} - \Delta T_{Source} - \Delta T_{Sink}, T_{h_{Sink}}\right)\right)\right), 0\right) \quad (2)$$

As a result, some modifications need new heat exchangers and disposing areas or using smaller heat exchangers that may lead to an investment cost of modifications and therefore making them impractical choices. The decision-makers then have to make a tradeoff between energy saving capacity and the weighting factor based on their experience and GEJ. The list of practical Bridge modifications will then be added to the system through the GUI.

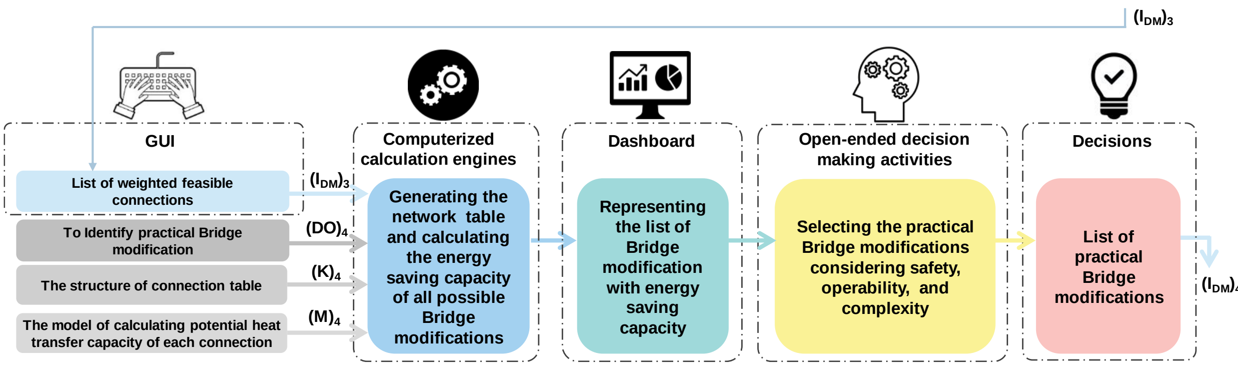

Figure 11- Identification of practical Bridge modifications

Figure 11 is the last sequence in the framework to identify economically the viable Bridge modifications. The input of this sequence is the list of practical Bridge modification with the energy saving capacity and the weighted factor, that represents the complexity, controllability, operability, and risk for each connection.

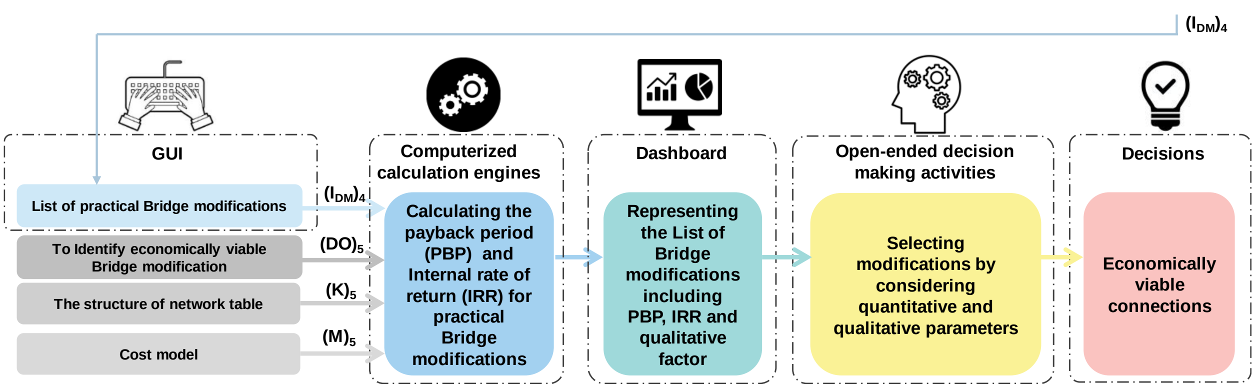

Figure 12- Identification of viable Bridge modifications economically.

To meet the minimum payback period that was determined by the manager at the beginning of the energy analysis project, the payback period for each modification has to be identified. To calculate the investment cost, we need a model to consider the cost of adding area, purchasing new exchangers, relocating them, and the cost of piping and pumping. After calculating the investment cost, the payback period can be calculated for each Bridge modification, and it will be represented on the dashboard. So, for each modification, the payback period, a quantitative parameter and the weighting factor, a qualitative parameter is identified. Based on the GEJ and trading off between the two parameters for each solution, the decision-makers can come to a list of 10 to 20 economically viable modifications for each potential process operation modification.

4. Case study

The same case study from the previous study is used in this paper to use the framework and find the solution. It is a simple HEN with one heater, one cooler, and one exchanger. The first sequence in the framework is to generate the HEN diagram and to identify $\Delta T_{min,cont.}$ for each stream. For each process source (P. So.) and each process sink (P. Si.), the initial and final temperature, the heat load, and the composition will be added to the framework by the user. The energy-related data are shown in table 1.

Table 1- Energy-related data of all streams

Stream	Inial temperature T_i (°C)	Final temperature T_f (°C)	Load Q (MW)	Composition
P. So. 1	100	80	1500.0	Clean water
P. So. 2	155	50	1000.0	Clean water
P. Si. 1	90	130	2400.0	Clean water
P. Si. 2	40	90	1500.0	Clean water

The compositions of all streams are clean water, and therefore according to the existing knowledge, the suggested stream specific temperature for all streams will be equal to 5 °C. Table

2 shows the compositions and ΔT_{min} for all streams that are extracted from the existing knowledge base.

Table 2- The suggested individual ΔT_{min} contribution.

Stream	Composition	Suggested stream specific ΔTmin (°C)
P. So. 1	Clean water	5.0
P. So. 2	Clean water	5.0
P. Si. 1	Clean water	5.0
P. Si. 2	Clean water	5.0

Then the HEN diagram will be generated with all energy-related information, composition and suggested ΔT_{min} for each stream (figure 12).

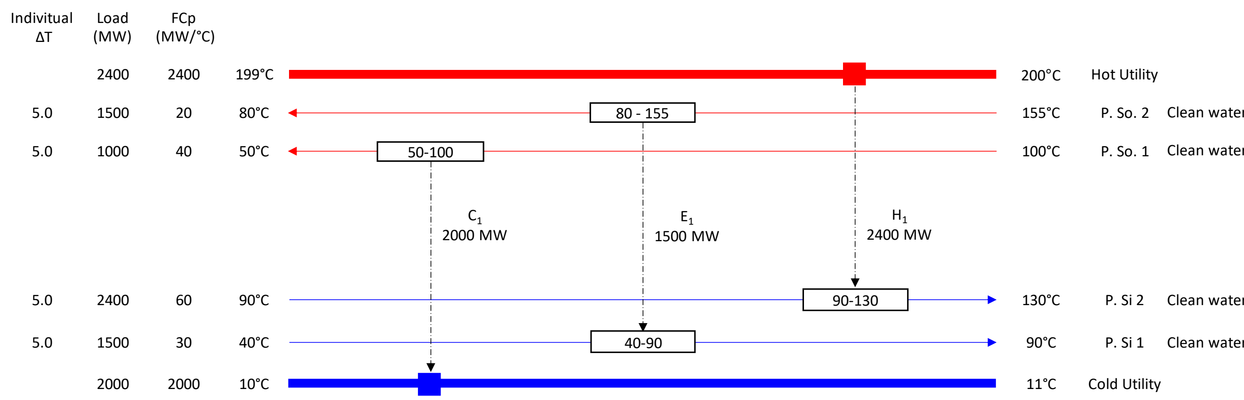

Figure 13- The existing HEN diagram.

The objective of the next sequence in the framework is to generate the connection table and help the decision-makers to identify the infeasible connections and to assign a weighting factor to the feasible connections. As it is mentioned before, the connection table shows all possible modifications, and each cell represents a connection between a process source and a process sink. In a real case, the decision-makers need to carefully evaluate each connection and consider the complexity, safety, and operability of adding or modifying the connection and assign a number to that, but in this case, the connection between process sink 1 and process source 2 already exists, and there is no need for new piping, and we can assign the highest number to that. We assumed that the rest of the connections are interesting, and we assigned number 2 to all of them. The output of decision-making activities, that is a piece of new information, should be added to the system through the GUI. Figure 13 exhibits the procedure whereas the decision-makers should do some offline assessment and fill out the table. The next sequence is to enumerate the Bridge modifications. By using Equation (2), the network table will automatically generate by the calculation engine. Table 3 shows the calculated values for each connection.

Table 3- Identification of the feasible connections and considering the qualitative parameters for each connection

Dashboard

		P. Si 1 E1	P. Si 2 H1
P. So. 1	C1		
P. So. 2	E1		

Offline assessment by the decision makers →

GUI (Input), I_{DM}

		P. Si 1 E1	P. Si 2 H1
P. So. 1	C1	2	2
P. So. 2	E1	3	2

In this example, there are two possible Bridges. The first Bridge that includes one match is the connections between the process source of the cooler to the process sink of the heater and the second Bridge includes two matches (connections) that are the connection between the process source of the cooler to the process sink of the heat exchanger and the connection between the process source of the heat exchanger and the process sink of the heater. For the first Bridge, the temperature of the process source ranges from 100 to 50°C, and the temperature of the process sink is between 90 and 130°C. In this case, the process source is not hot enough to heat up the process sink, and it is not a possible solution. For the second Bridge, there are two matches. For the first match, the maximum available heat to transfer from the process source of the cooler to the process sink of the heat exchanger is 1500 kW, and for the second match, the maximum available heat to transfer is 1100 kW. So, the saving capacity of the second Bridge is 1100 kW.

Table 4- Network table to enumerate the Bridge modifications

								Process sink 1	Process sink 2
							CU	E1	H1
						ΔT/2		5	5
						Th		90	130
						Tc		40	90
						FCp		30	60
ΔT/2	Th	Tc	FCp						
					HU		Saving		2400
5	155	80	20	Process source 2	E1			1500	1100
5	100	50	40	Process source 1	C1		2000	1500	0.0

So, only one Bridge modification is available for this example with the energy saving capacity of 1100 kW. The final modification will lead to adding two new exchangers and reducing area of three existing exchangers. Having a cost model helps to calculate the investment cost and therefore have a payback period for each modification.

5. Conclusion

In this study, we propose a sequential design decision-making framework, developed for using the Bridge Method in practice. The framework comprises a systematic and user interactive decision-making approach, where design calculations are made, and decisions are taken at different points in the design process, leading to a set of recommendations for plant-wide energy optimization. Also, a critical review of the classical heat integration approaches in the literature has been performed, along with elucidating the concept of the bridge method and the need for a decision-making framework to make it useful in practice.

The framework considers explicitly the sequential series of design decisions including (1) selection of $\Delta T_{min,cont.}$needed for heat transfer, (2) guidance for identifying potential process operation modifications, and (3) identification of Heat Exchange Network (HEN) modifications. At each step of decision-making, case-specific data are added to the framework through a graphical user interface (GUI). The management system inside the framework is responsible for managing the communication between GUI, model base, knowledge base, database, and calculation engines. At each sequence, the results are represented on the dashboard to help users to make a decision and send that decision back to the system.

Once the framework is operational, opportunities present themselves to employ the power of the Bridge Method implemented into a computer algorithm. The present work can be further advanced by developing a cost model to calculate the payback period for each modification considering the complexity, safety, maintenance, and risk – exploiting the framework to the extent practical and enable better decision-making based on cost/return data.

References:

[1] I. E. A. (IEA). "CO2 Emissions Statistics." (accessed.

[2] B. Linnhoff and J. R. Flower, "Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks," AIChE Journal, vol. 24, no. 4, pp. 633-642, 1978.

[3] B. Linnhoff and J. R. Flower, "Synthesis of heat exchanger networks: II. Evolutionary generation of networks with various criteria of optimality," AIChE Journal, vol. 24, no. 4, pp. 642-654, 1978.

[4] T. N. Tjoe and B. Linnhoff, "Using pinch technology for process retrofit," Chemical Engineering, vol. 93, no. 8, pp. 47-60, 1986.

[5] J.-C. Bonhivers, M. Korbel, M. Sorin, L. Savulescu, and P. R. Stuart, "Energy transfer diagram for improving integration of industrial systems," Applied Thermal Engineering, vol. 63, no. 1, pp. 468-479, 2014.

[6] J.-C. Bonhivers, B. Srinivasan, and P. R. Stuart, "New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 1–Concepts," Applied Thermal Engineering, 2014.

[7] J.-C. Bonhivers, A. Alva-Argaez, B. Srinivasan, and P. R. Stuart, "New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2–Stepwise and graphical approach," Applied Thermal Engineering, 2015.

[8] J.-C. Bonhivers, "Nouvelle méthode d'intégration énergétique pour la rétro-installation des procédés industriels et la transformation des usines papetières," École Polytechnique de Montréal, 2013.

[9] J.-C. Bonhivers et al., "Analysis of Heat Cascade Through Process Components to Reduce the Energy Consumption in Industrial Systems," Process Integration and Optimization for Sustainability, journal article August 29 2018, doi: 10.1007/s41660-018-0067-9.

[10] S. W. Miller, T. W. Simpson, M. A. Yukish, L. A. Bennett, S. E. Lego, and G. M. Stump, "Preference Construction, Sequential Decision Making, and Trade Space Exploration," no. 55881, p. V03AT03A014, 2013, doi: 10.1115/DETC2013-13098.

[11] S. W. Miller, M. A. Yukish, and T. W. Simpson, "Design as a sequential decision process," Structural and Multidisciplinary Optimization, vol. 57, no. 1, pp. 305-324, 2018/01/01 2018, doi: 10.1007/s00158-017-1756-7.

[12] N. R. C. C. o. T. F. f. D. M. i. E. Design, Theoretical foundations for decision making in engineering design. National Academy Press, 2001.

[13] D. E. Bell, Decision making: Descriptive, normative, and prescriptive interactions. cambridge university Press, 1988.

[14] K. Tripathi, "Decision support system is a tool for making better decisions in the organization," Indian Journal of Computer Science and Engineering (IJCSE), vol. 2, no. 1, pp. 112-117, 2011.

[15] U. R. F. Averweg, Decision-making support systems: Theory and practice, South Africa: Ventus, 2012.

[16] M. S. S. Morton, Management decision systems: computer-based support for decision making. Division of Research, Graduate School of Business Administration, Harvard …, 1971.

[17] J. W. Tweedale, R. Neves-Silva, L. C. Jain, G. Phillips-Wren, J. Watada, and R. J. Howlett, Intelligent decision technology support in practice. Springer, 2016.

[18] V. A. W. J. Marchau, W. E. Walker, P. J. T. M. Bloemen, and S. W. Popper, Decision Making under Deep Uncertainty, From Theory to Practice. Springer, Cham, 2019.

[19] J. Xia, L. Lin, J. Lin, and L. Nehal, "Development of a GIS-Based Decision Support System for Diagnosis of River System Health and Restoration," Water, vol. 6, no. 10, p. 3136, 2014. [Online]. Available: http://www.mdpi.com/2073-4441/6/10/3136.

[20] M. Abd-elfattah, T. Alghamdi, and E. Amer, "Dashboard technology based solution to decision making," International Journal of Computer Science Engineering, vol. 4, no. 2, pp. 59-70, 2014.

[21] T. Gundersen and I. E. Grossmann, "Improved optimization strategies for automated heat exchanger network synthesis through physical insights," Computers & chemical engineering, vol. 14, no. 9, pp. 925-944, 1990.

[22] H. Nishimura, "A theory for the optimal synthesis of heat-exchanger systems," Journal of Optimization Theory and Applications, vol. 30, no. 3, pp. 423-450, 1980.

[23] S. Ahmad, "Heat exchanger networks: Cost tradeoffs in energy and capital," University of Manchester Institute of Science and Technology (UMIST), 1985.

[24] Z. Fonyo, "Diverse pinch concept for heat exchange network synthesis: the case of different heat transfer conditions," Chemical engineering science, vol. 46, no. 7, pp. 1623-1634, 1991.

[25] C. K. IAN, "Pinch analysis and process integration--a use guide on process integration for the efficient use of energy," ed: Oxford, UK: Butterworth-Heinemann of Elsevier, 2007.

[26] A. P. ANTON LARSSON, "Energy Efficiency Study at a Softwood Kraft Pulp Mill," 2017.

[27] R. Smith, Chemical process: design and integration. John Wiley & Sons, 2005.

[28] A. Simons, "Energy cost reduction in the pulp and paper industry," Pulp and Paper Research Institute of Canada, Montreal, QC, 1999.

[29] T. Gundepsen and L. Naess, "The synthesis of cost optimal heat exchanger networks: an industrial review of the state of the art," Computers & Chemical Engineering, vol. 12, no. 6, pp. 503-530, 1988.

APPENDIX C ARTICLE 3: COST ANALYTICS FOR ENERGY ANALYSIS OF INDUSTRIAL FACILITIES USING THE BRIDGE METHOD

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Abstract:

Using a practical method for energy use reduction in industrial plants is crucial to have an economic and environmental impact. In the last few years, a novel approach called the Bridge Method had been developed for site-wide energy analysis of industrial processes. Recently, a sequential decision-making framework has been developed to use the Bridge Method in practice. A core element of the framework is an appropriate cost model that can provide a precise estimate of capital expenditure and therefore definitive solutions for the heat-exchanger network (HEN) retrofit. In this paper, the application of the Bridge Method will be demonstrated to select economically viable modifications. After enumerating the Bridge modification with two and three matches, a simplified cost model is used to calculate the payback period and internal rate of return for each solution to find the most attractive ones. As a case study, the preheating of crude oil in the crude oil distillation system has been analyzed, which led to reducing the cascaded energy through all heat exchangers by about 20% by adding two new heat exchangers, with a five-month payback period.

Keywords: Bridge method, HEN retrofit, decision-making framework, cost analysis.

For the past few decades, different approaches have been developed to address issues in heat-exchanger network retrofit, but finding practical and economically viable modifications is still a challenge. Recently, a novel energy analysis technique called the Bridge Method was developed to identify modifications for energy use reduction. To use the Bridge Method in practice, a sequential design decision-making framework has been developed to address the complex issues of energy management in existing and new processes which is presented in part II of this paper. To identify the most viable Bridge modifications using the framework, a cost model is needed to calculate the payback period and the internal rate of return (IRR) for each modification. In this paper, the approaches that are utilized in mathematical-programming-based and thermodynamic based methods to consider cost are reviewed, and the last to steps of the Bridge framework is demonstrated by energy analysis of a complex case study to identify the economically viable Bridge modifications.

1. Bridge framework

To evaluate the profitability of HEN retrofit projects, a cost model is needed for estimating the total investment and operating costs. Over the past decades, many approaches developed for HEN retrofit with emphasis on optimizing the total cost of the projects. Recently we have developed a novel approach called Bridge Method in which for the first time, all process stream data are extracted from the process model to generate what we call the Energy Transfer Diagram (ETD) to characterize the flowrate of transferred energy as a function of temperature from the hot utility to ambient [1]. A sequential design decision making framework is developed and presented in a previous paper to implement the Bridge Method in practice, which is called the Bridge framework. The Generall structure of this framework is shown in figure 1.

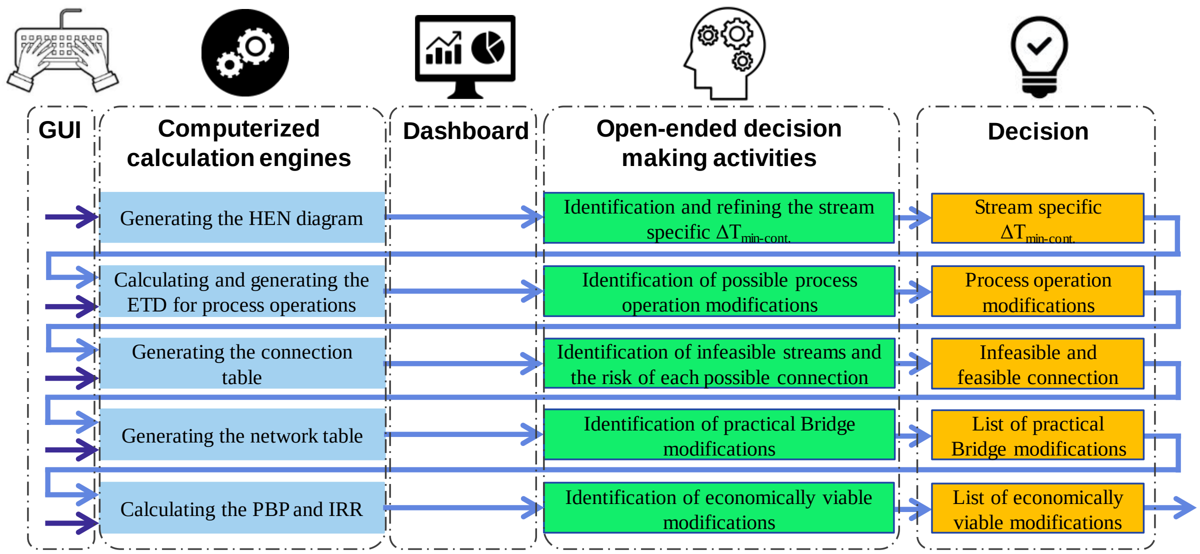

Figure 1- The Generall structure of the Bridge framework

As it is shown in this figure, the last step of the framework is to economically analysis of the practical Bridge modifications. The Bridge Method Framework employs a user-interactive sequential decision-making approach, where (1) automated design calculations are made by a computerized calculation engine, and (2) certain open-ended decisions are taken in the design process leading to a practical set of recommendations. A cost model can be used by calculation engines to calculate the payback period and the internal rate of return of each project and are interpreted by expert users to prepare the list of economically viable modifications.

2. Heat exchanger selection and design criteria

Different types of exchangers such as shell-and-tube or plate are used in the industry [2]. The engineer selects a heat exchanger based on essential criteria such as the composition and phase of the fluid, operating pressures, energy load, and cost. Usually, a heat exchanger has a wide range of operating conditions, and therefore the flexibility is normally high, especially for shell-and-tube or plate exchangers [3]. Shell-and-tube heat exchangers are extremely flexible, easy to repair, and can operate at high pressure and temperature. However, they need a large area for installation and are more expensive. On the other hand, plate heat exchangers are less expensive and perfect for high turbulence and low minimum approach temperature. However, they operate at low temperatures and pressure and are not suitable for corrosive fluids. For a given heat load, other parameters such as construction material, flow rate, flow regime, pressure drop, maintenance, inspection, cleaning, extension and repair possibilities, and mounting arrangement must also be considered [4].

In the following sections, the mathematics-based and thermodynamic-based approaches are reviewed to show how cost estimation for heat-exchanger network retrofit has been handled in these approaches.

3. Mathematics-based approaches for HEN retrofit

A sequential mathematical approach has been developed for optimal HEN design by formulating the HEN design problem using a two-step approach [5]. The HEN is divided into an Interior system representing the process-process heat exchangers and exterior system representing heaters and coolers, and the objective function was fixed costs of the interior and exterior systems and the operating cost of the exterior system. For considering the investment cost of heat exchangers, the following correlation is used:

$$C_{Ei}(USD) = 55.46 \times A_i^{\beta'}$$

Where β` is between 0.6 and 1.0. For the energy cost, they used a simple equation which is:

$$Energy\ cost\ (USD) = 2.5 \times \left(Q(kcal/h)\right)^{0.7}$$

A year later, the same group at the Tokyo Institute of Technology, developed an algorithm to provide an efficient structure for HEN with minimum heat transfer area. They studied the necessary conditions to have an optimal HEN structure [6].

Ciric and Floudas developed a two-stage approach for HEN retrofit [7]. The objective function in this study is to minimize total investment cost, including the cost of new heat exchangers, additional area cost, and piping cost. The first stage comprises five steps, which start with selecting a heat recovery approach temperature (HRAT) either randomly from a reasonable range of values or using a targeting procedure for good estimation. In the second step, the minimum utility cost regarding the selected HRAT and the pinch point is selected. In the third step, all possible modifications including purchasing a new heat exchanger, repiping or rearranging the existing exchanges, will be considered to create a retrofit model by categorizing the possible modifications into six groups and assigned a cost for each group. They defined an objective function, which is the sum of costs in all categories, and they used nonlinear programming to minimize the objective function. The first group is the matches that will not change during the modification and therefore, the piping cost of this category is zero. The second group is the exchangers that need to be relocated, but there is no need for piping, and only the cost of labor for removing the existing heat exchanger and installing the new heat exchanger will be considered. The third group represents a situation in which one of the streams of the existing heat exchanger needs to be replaced by another stream, and the cost of piping for one stream will be considered. In the fourth group, the existing exchanger needs two new streams, and therefore, the cost of piping for two streams must be considered. In the fifth group, a new heat exchanger must be purchased to replace the existing exchanger, and there is no need for re-piping. In the last group, a new heat exchanger needs to be purchased and for both streams, the cost of piping should be considered to form an MILP formulation for the first stage.

During the second stage which is an optimization stage, the information from the first stage is used to create a superstructure containing all possible configurations and then a nonlinear programming problem (NLP) is used to optimize the heat exchanger orders with corresponding matches to find a network with minimum investment cost. One year later, Ciric and Floudas used an MINLP approach, which was the combination of two stages in the previous work to optimize the network structure [8].

Yee and Grossmann presented a systematic approach for pre-screening and optimizing a heat-exchanger network for retrofit in a three-part article [9-11]. The pre-screening stage was employed to identify the economic feasibility of the retrofit for different HRATs to evaluate potential savings for a specific payback period. The selected modifications were sent to the optimization stage and optimized using an MINLP model to minimize total cost.

Abbas et al. [12] used a set of heuristics to develop a novel approach to solve the retrofit problem using constraint logic programming (CLP). While developing heuristics, they considered few steps such as the heat load shifting from utilities to the process-process heat exchangers, reducing criss-cross exchanges by repiping or stream splitting and adding a new heat exchanger. To calculate the payback period, a cost model was developed considering the cost of moving equipment, piping and new area. The method was tested by solving the case study [7] and the payback period was 25% better than the original study.

Ponce-Ortega et al. [14] developed a model for solving HEN retrofit problems that considered the interaction between the HEN retrofit and process modifications simultaneously. They considered the utility cost and the total investment cost of the exchangers and piping. They mentioned that the cost of relocating the existing exchanger is usually higher than that of connecting new streams to a heat exchanger.

Athier et al. [15] developed an approach for automatic determination of optimum HEN retrofit considering the purchase of new exchangers or reallocating existing exchangers, adding area, and stream splitting. This approach is a two-level procedure; in the first level, they used a simulated annealing (SA) procedure to generate network topology modifications within the feasibility constraints. An estimate of the re-piping cost and investment cost for reassignment and placing new heat exchangers were made at this level. At the second level, the required additional area and the new heat exchanger for each modification were optimized by an NLP algorithm. The investment cost was determined by using simplified cost formulations for new and existing exchangers.

To obtain a cost-optimal HEN retrofit design, existing constraints such as forbidden matches, restricted matches, types of streams, pressure drop, and distances should be considered. Some of the constraints can be reflected in the cost model by a quantitative parameter such as piping cost, pumping cost, equipment cost, and hot utility. Besides, qualitative parameters such as safety, operability, and flexibility should also be taken into account [16].

The mathematics-based approaches mainly use grass-roots techniques, although with some extension or modification for HEN retrofitting. In addition, all the methods use grass-roots techniques for optimization, which involve optimizing the utility demand, the number of units, and the exchanging area. For retrofit design, different levels of heat recovery may require significantly different modifications, and the capital expenses must be restricted to the specified payback period. Hence, the simultaneous consideration of energy and modification costs appears necessary.

4. Thermodynamic-based methods for HEN retrofit

Since the Pinch Method was developed in the late 1970s, developing a systematic procedure to identify the cheapest operable and safe heat-exchanger network (HEN) design with respect to annualized energy and capital costs has been the main concern in the heat integration domain. To find a cost-effective solution, various parameters such as physical distance between streams (piping), pressure drop (pumping), material requirements, the type of heat exchanger, auxiliary equipment (valves), fouling, and maintenance should be considered. Most of the approaches developed in the past four decades have aimed to minimize heat-exchanger area and hot utility usage by performing a targeting procedure and finding a global ΔT_{min} , together with its corresponding minimum utility demands [17].

Tore and Linnhoff introduced the Pinch Method for HEN retrofit and used a simple cost model to calculate the investment cost, which was a function of the area added to the heat exchangers [18], as presented as follow:

$C_E=8600+670A^{0.83}$ $\quad 10 < A <300\ m^2$

$C_E=252A$ $\quad A>300\ m^2$

For each global ΔT_{min} less than the existing value, the utility demand, and required area were calculated, the results were compared with the existing demand and area, and the energy saving cost and the added area was calculated. The results were presented as a saving/investment plot, and for the preferred payback period, the appropriate global ΔT_{min} was identified. This approach, with its simplified cost model, in some cases, led to an inaccurate assumption of investment cost. For example, in some cases, there were needs for pumps, which are expensive, but due to the simplified model, they were not considered as an investment cost.

The targeting procedure in the Pinch method to find an appropriate global ΔT_{min} was later improved by considering the pressure drop to obtain a more accurate cost model [19]. In this method, a relation between ΔP and heat-transfer coefficients was introduced to enable a more precise calculation. In this approach, the temperature driving forces between the streams were the main factor for project cost analysis, and other parameters such as piping and heat-exchanger type were not considered, although these in many cases have a greater financial impact on a retrofit project.

Carlsson et al. [17] proposed a retrofit approach to finding the HEN retrofit project by considering various parameters such as heat-exchanger type, pressure drop, thermal fouling, and maintenance costs. This approach used a computer-based model to find near-optimum HENs, which included a user interface to set feasible constraints taking relevant parameters into account and an option to conduct sensitivity analysis. This tool used metrics to provide some information about the nature of the existing network, such as complex matches, economically feasible matches, and the impact of global ΔT_{min} on network complexity. These metrics, in fact, calculate the cost of each match between process sources and sinks, considering the information about existing heat exchangers, piping, pumps, distances between streams, and material requirements for specific streams. This method then became the basis for Chalmers University to develop a new software environment called the Matrix.

Van Reisen et al. [20] proposed a method for decomposition and pre-screening of a HEN, called path analysis. This method selects and evaluates parts of an existing HEN, celled subnetworks, while the remaining network remains unchanged. The subnetworks can be generated either by the designer or by a computer algorithm by following two rules. The first rule is that each subnetwork must include at least one heater and one cooler. The second rule is that each subnetwork should be energy-balanced. This approach can lead to modifications with minimum structural changes and less piping costs.

The main focus of thermodynamic-based approaches is on developing a user interactive approach with visualization tools to determine a more practical solution for HEN retrofit and they often use a simple cost model to compare the modifications.

5. Economic analysis using the Bridge Framework

Most of the Pinch-based approaches use a cost-estimation procedure to find attractive energy-saving projects. In most of these methods, at the beginning of energy analysis, a cost formulation, which is a function of the exchanger area, is employed to select retrofit projects with the desired payback period. In the Bridge method, there is no need to consider cost at the beginning of the procedure because, after the Bridge enumeration step, the topology for each modification is specified [21, 22]. Therefore, the investment cost can then be considered in more detail, including the type of exchanger and maintenance.

The objective of this paper is to perform an economic analysis using the Bridge Method and the Bridge framework through solving a complex and large-scale case study with temperature-dependent specific heat capacity for all streams. We used a simplified cost model to compare the results.

6. Case study

For the case study, the existing preheat train, which is the first stage of preheating crude oil in a crude oil distillation system, has been analyzed [23]. Tables 1 and 2 provide information about process sources and sinks. The existing HEN, represented in Figure 1, contains 27 exchangers with a total area of 4000 m^2, and the hot utility consumption of the existing network is 89MW [24].

Table 1- Process source data.

Stream name	Stream No.	Inial T	Final T	Load	FCp	Total Load
		T_i (°C)	T_f (°C)	Q (MW)	(MW/°C)	Q (MW)
Bott Cool 1	Process source 9	339	299	9.6	0.240	50.5
		299	259	9.2	0.229	
		259	219	8.7	0.218	
		219	179	8.2	0.206	
		179	139	7.7	0.193	
		139	100	7.0	0.180	
Pump-Ar 1	Process source 8	298	268	12.8	0.428	12.8
Bott Cool 3	Process source 7	282	242	3.9	0.099	20.3
		242	202	3.7	0.093	
		202	162	3.5	0.087	
		162	122	3.2	0.081	
		122	82	3.0	0.075	
		82	42	2.8	0.069	
		42	40	0.2	0.082	
Bott Cool 2	Process source 6	257	217	1.1	0.029	5.2
		217	177	1.1	0.027	
		177	137	1.0	0.025	
		137	97	0.9	0.024	
		97	57	0.9	0.022	
		57	50	0.1	0.021	
Pump-Ar 2	Process source 5	250	210	14.4	0.360	17.9
		210	200	3.5	0.347	
Bott Cool 4	Process source 4	189	149	1.8	0.046	6.2
		149	109	1.7	0.043	
		109	69	1.6	0.039	
		69	40	1.1	0.037	
Pump-Ar 3	Process source 3	170	150	11.2	0.559	11.2
Cond Duty 4	Process source 2	100	77	47.9	2.081	47.9
Dist Cool 4	Process source 1	77	40	1.3	0.036	1.3

In this case study, a minimum temperature contribution equal to 5°C for all streams was selected. It was assumed that there were no constraints on connecting streams. This means that all matches were feasible, and Bridge modifications with two and three matches were chosen to identify the solutions. Types of heat exchangers and pressure drops were not considered in this example.

Table 2- Process sink data.

Stream name	Stream No.	Inial T	Final T	Load	FCp	Total Load
		T_i (°C)	T_f (°C)	Q (MW)	(MW/°C)	Q (MW)
Feed PreH 1	Process sink 3	25	65	12.5	0.312	154.5
		65	105	13.6	0.339	
		105	145	14.7	0.367	
		145	166	8.0	0.383	
		166	185	9.2	0.484	
		185	225	20.1	0.503	
		225	265	21.1	0.527	
		265	305	21.8	0.545	
		305	345	22.3	0.558	
		345	365	11.3	0.564	
Reb Duty 3	Process sink 2	271	282	8.8	0.798	8.8
Reb Duty 4	Process sink 1	182	189	6.6	0.946	6.6

Figure 3 shows the existing network before the retrofit. The temperature of the hot and cold utilities are 400°C and 10°C respectively. The heat-transfer coefficients for all streams, the hot utility, and the cold utility were assumed to be constant and equal to 1 kW/°C.m^2, 2 kW/°C.m^2, and 2.5 kW/°C.m^2 respectively.

Table 3- Data of existing heaters

Heat exchanger	P.Si. No.	P. So. No.	P.Si. initial temperature	P.Si. final temperature	Total load
			T_i (°C)	T_f (°C)	Q (MW)
H1	1	HU	182.0	189.0	6.6
H2	2	HU	271.0	282.0	8.8
H3	3	HU	231.0	365.0	73.5

Table 4- Data of existing coolers

Heat exchanger	P.So. No.	P. Si. No.	P.So. initial temperature	P.So. final temperature	Total load
			T_i (°C)	T_f (°C)	Q (MW)
C1	1	CU	77.0	40.0	1.3
C2	2	CU	100.0	77.0	47.9
C3	9	CU	106.0	100.0	1.1
C4	4	CU	125.0	40.0	3.3
C5	5	CU	170.0	150.0	11.2
C6	6	CU	209.0	200.0	3.1
C7	7	CU	228.0	50.0	4.3
C8	8	CU	281.0	40.0	20.2

Table 5- Data of existing heat exchangers

Heat exchanger	P.So. No.	P. Si. No.	P.So. inial temperature	P.So. final temperature	P. Si. inial temperature	P. Si. final temperature	Load
			T_i (°C)	T_f (°C)	T_i (°C)	T_f (°C)	Q (MW)
E1	4	3	189.0	125.0	36.0	49.0	2.05
E2	4	3	189.0	125.0	40.0	46.0	0.89
E3	9	3	223.5	106.0	46.0	114.0	11.42
E4	9	3	224.0	106.0	49.0	119.0	11.52
E5	5	3	250.0	209.0	114.0	154.0	7.47
E6	5	3	250.0	209.0	119.0	158.0	7.33
E7	6	3	257.0	228.0	154.0	158.0	0.89
E8	8	3	273.0	268.0	25.0	36.0	1.74
E9	7	3	282.0	281.0	158.0	159.0	0.11
E10	8	3	298.0	268.0	25.0	40.0	2.37
E11	8	3	298.0	273.0	214.0	231.0	8.76
E12	9	3	339.0	223.5	158.0	213.0	13.25
E13	9	3	339.0	224.0	159.0	214.0	13.19

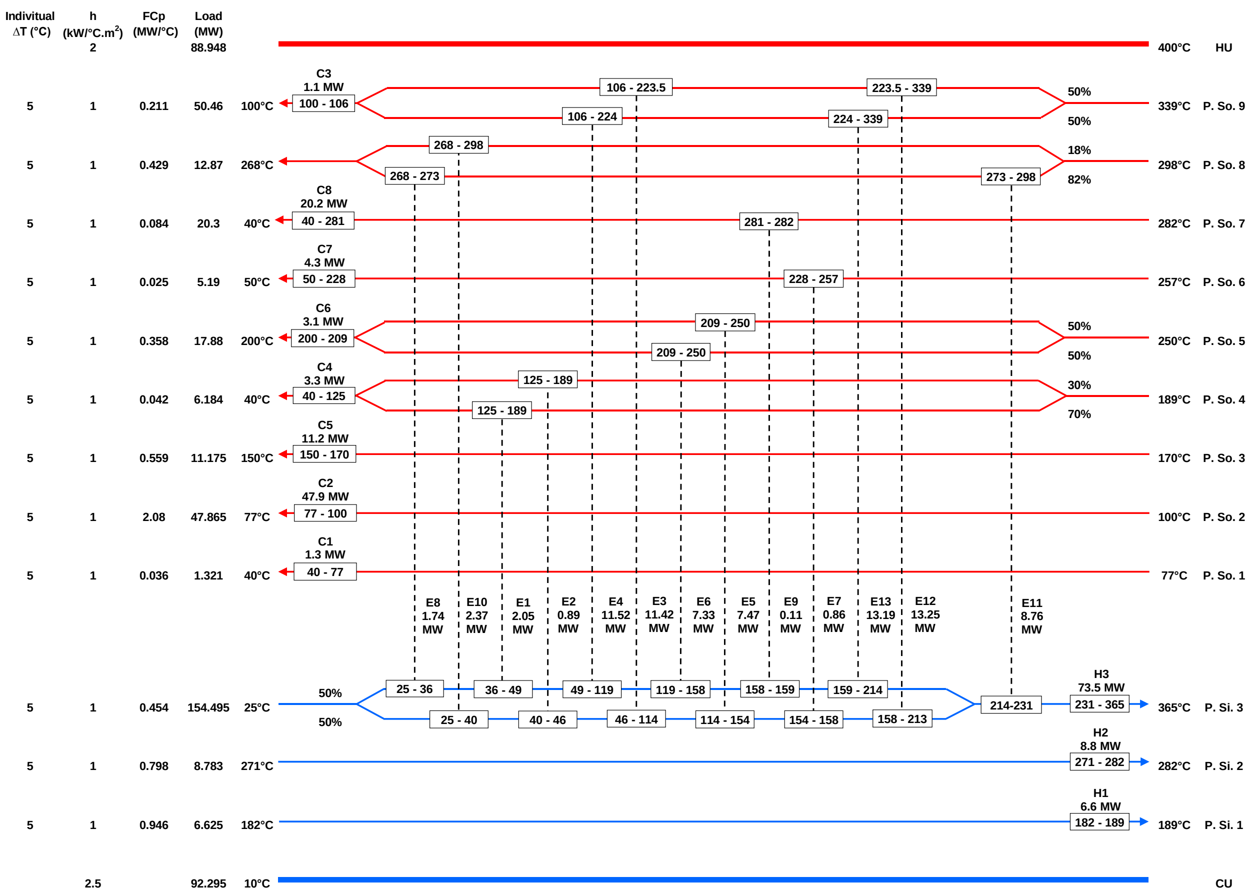

Figure 2- Initial Heat Exchanger Network (HEN).

Before the Bridge Method is used, a number should be assigned to all heaters, coolers, and heat exchangers. For coolers and process-process exchangers, the exchanger with the lowest hot-end temperature at the process source will be assigned the lowest number, which is 1, and so on. For the heaters, the exchanger with the lowest hot-end temperature at the process sink is H1. In Figure 2, all exchangers are designated based on the Bridge Method.

The next step is to build the ETD across the temperature interval between the hot utility temperature (400°C) and the ambient temperature (10°C). The ETD is used to identify the maximum energy-saving capacity of a network, which is the minimum of the HEN curve [1]. The minimum of the HEN curve in this case study is 50 MW, which means that it is impossible to save more than 50 MW of energy by modifying the existing HEN. Figure 2 represents the ETD of the existing network before the retrofit. In this example, the focus is on HEN modification, and information about the process operations part is not illustrated. ETD can help identify the Bridge modifications using a set of downward arrows.

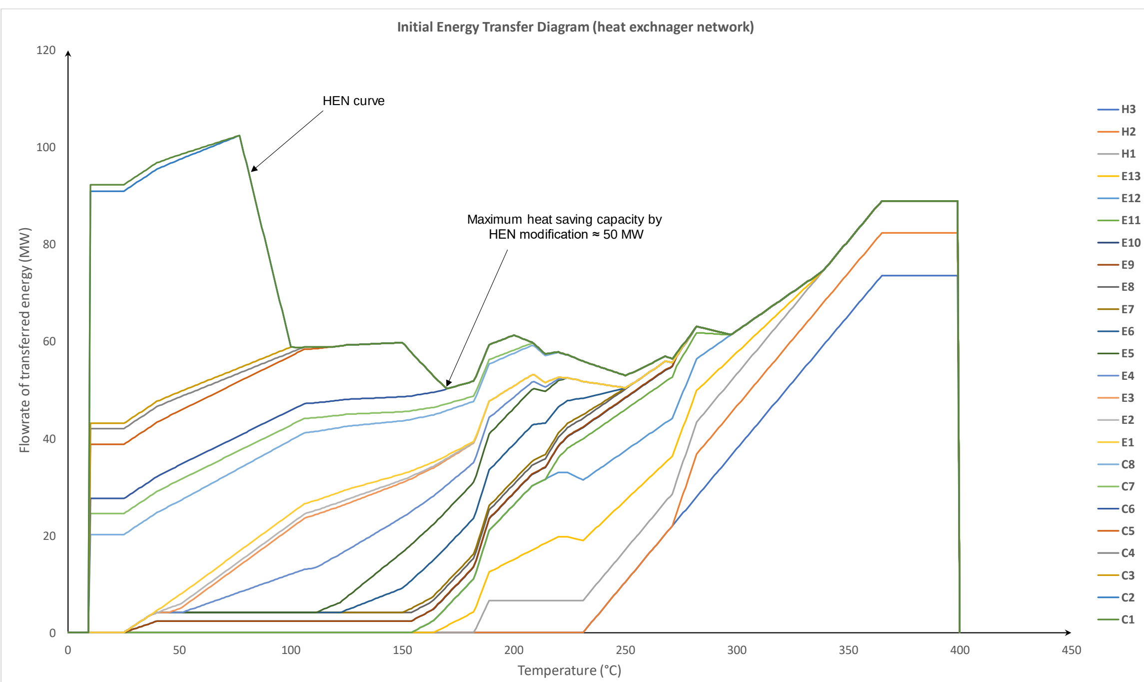

Figure 3- ETD of the existing HEN

A Bridge is a set of matches, with each match corresponding to a new heat exchanger or the addition of area to an existing exchanger. In practice, energy projects with up to five modifications are normally considered in heat-exchanger networks, which is equivalent to Bridge modifications with up to four matches. Besides, in reality, there are connection constraints and forbidden matches that must be considered, and therefore some Bridge modifications are not feasible.

In the fourth step of the framework, a list of Bridge modifications and their energy saving capacity are prepared.

Table 6- Network table

	CU	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	H1	H2	H3
HU																	
E13														13.19	6.62	6.12	10.34
E12													13.25	12.19	6.62	6.12	10.34
E11												8.76	8.79	8.79	6.62	5.98	8.79
E10											2.37	2.32	2.32	2.32	2.32	1.31	2.32
E9										0.11	0.08	0.08	0.08	0.08	0.08	0.08	0.08
E8									1.74	0.22	1.76	1.76	1.76	1.76	1.76	0	1.76
E7								0.86	0.73	0.22	0.73	0.73	0.73	0.73	0.73	0	0.40
E6							7.33	0.94	2.62	0.22	3.54	4.65	7.34	7.34	6.62	0	1.61
E5						7.47	7.34	0.94	2.62	0.22	3.54	4.65	7.34	7.34	6.62	0	1.61
E4					11.52	9.21	8.93	0.94	2.62	0.22	3.54	0	6.33	5.28	3.38	0	0
E3				11.42	12.40	9.21	8.93	0.94	2.62	0.22	3.54	0	6.28	5.22	3.32	0	0
E2			0.89	0.81	0.81	0.81	0.72	0.37	0.81	0.20	0.81	0	0.32	0.19	0	0	0
E1		2.05	1.180	1.88	1.88	1.88	1.68	0.85	1.88	0.22	1.88	0	0.74	0.44	0	0	0
C8		3.05	1.180	9.21	15.47	9.21	8.93	0.94	2.62	0.22	3.54	4.79	9.83	8.99	6.62	0	3.36
C7		3.05	1.180	2.68	4.18	2.68	2.40	0.94	2.62	0.22	3.54	0.10	1.60	1.35	0.90	0	0
C6		3.05	1.180	3.22	3.22	3.22	3.22	0.94	2.62	0.22	3.22	0	3.22	3.22	3.22	0	0
C5		3.05	1.180	9.21	11.18	9.21	8.28	0.94	2.62	0	3.54	0	1.42	0	0	0	0
C4		3.05	1.180	0.17	2.69	0.17	0	0	2.62	0	3.54	0	0	0	0	0	0
C3		1.27	1.180	0	1.27	0	0	0	1.27	0	1.27	0	0	0	0	0	0
C2		3.05	1.180	0	8.50	0	0	0	2.62	0	3.54	0	0	0	0	0	0
C1		1.08	0.972	0	0.58	0	0	0	1.33	0	1.33	0	0	0	0	0	0

Table 6 shows the network table which is used to calculate the energy saving capacity of each Bridge modification. In this table, the process sources are placed in the first column, and the process sinks are placed in the first row. Each cell shows the maximum transferable energy between a process source and a process sink. For example, to enumerate C1H1, one should look at the cell at the intersection between C1 and H1, which is 0. Tables 7 and 8 present the list of Modifications with one and two matches.

Table 7- List of Bridge modifications with one match

Bridges with one match	Heat saving capacity (MW)
C8H1	6.6
C8H3	3.4
C6H1	3.2

Table 8- List of Bridge modifications with two matches

Bridges with one match	Heat saving capacity (MW)
C8E12,E12H3	9.8
C8E13,E13H3	9.0
C5E5,E5H1	6.6
C5E6,E6H1	6.6
C8E5,E5H1	6.6
C8E6,E6H1	6.6
C8E12,E12H1	6.6
C8E13,E13H1	6.6
C8E12,E12H2	6.1
C8E13,E13H2	6.1

The fifth step of the Bridge Framework is to calculate the payback period and internal rate of return (IRR) for practical Bridge modification. To calculate the energy cost, the following cost model is used [25]:

Energy cost (USD) = 312000 ×(Q(kW))

The following equations are employed to calculate the investment cost regarding a new heat exchanger of adding the area to an existing exchanger:

Cost of new exchanger (including the cost of piping and installation) = 188186 + 2254×A

Cost of adding the area to an existing heat exchanger = $2254 \times A^{0.68}$

To calculate the IRR, the interest rate was set to 10% for ten years. The payback period and IRR of the most interesting Bridge modifications are shown in Tables 9 and 10.

Table 9- Payback period and IRR for Bridges with one match

Bridges with one match	energy saving (MW)	Capital cost ($)	Energy saving cost ($/year)	Parback period (Year)	IRR
C8H1	6.6	1,253,866	2,032,954	0.6	165%
C8H3	3.4	1,247,392	1,031,520	1.2	84%
C6H1	3.2	1,391,668	989,154	1.4	72%

The economic analysis results for Bridges with one match are presented in figure 4. The first modification which is C8H1, the payback period is less than a year, and the IRR is higher than the other two projects. C8H3 and C6H1 modifications can be done together because they are independent projects. For this group (C8H3, C6H1), the payback period is 1.3 year and the IRR is 78% and it can lead to 6.6 MW of energy saving.

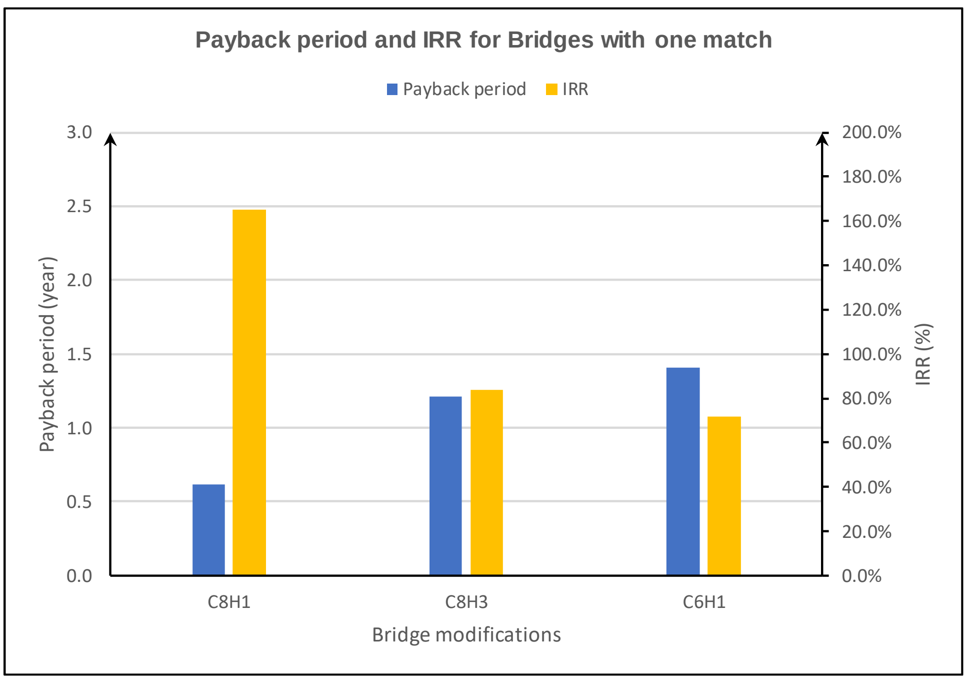

Figure 4- Payback period and Internal Rate of Return for Bridge modifications with one match

Table 10- Payback period and IRR for Bridges with two matches

Bridges with two matches	energy saving (MW)	Capital cost ($)	Energy saving cost ($/year)	Parback period (Year)	IRR
C8E12,E12H3	9.8	2,702,622	3,017,196	0.9	112%
C8E13,E13H3	9.0	2,747,938	2,759,316	1.0	100%
C5E5,E5H1	6.6	2,822,255	2,032,954	1.4	72%
C5E6,E6H1	6.6	2,937,297	2,032,954	1.4	69%
C8E5,E5H1	6.6	2,436,231	2,032,954	1.2	83%
C8E6,E6H1	6.6	2,442,316	2,032,954	1.2	83%
C8E12,E12H1	6.6	2,295,505	2,032,954	1.1	88%
C8E13,E13H1	6.6	2,298,489	2,032,954	1.1	88%
C8E12,E12H2	6.1	2,258,101	1,878,533	1.2	83%
C8E13,E13H2	6.1	2,260,570	1,878,533	1.2	83%

Figure 5 shows the results of Bridges with two modifications. It is safe to say that all modifications have an acceptable IRR with payback periods lower than 1.5 years. It shows that (C8E12, E12H3) is the most interesting modification and it can be done at the same time with (C5E5, E5H1) or (C5E6, E6H1) modification to save more energy.

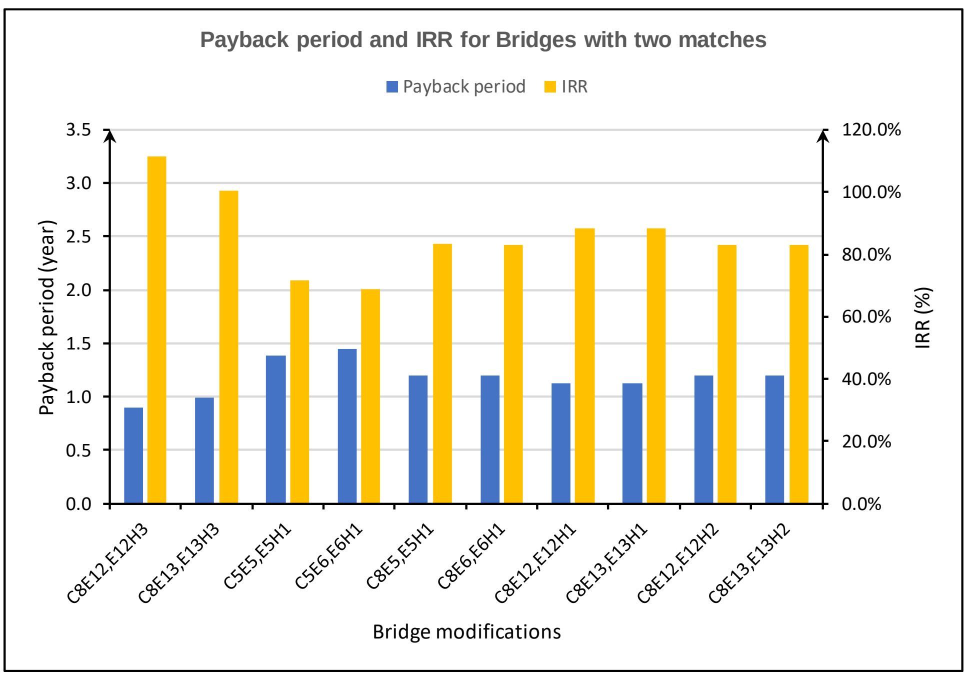

Figure 5- Payback period and Internal Rate of Return for Bridge modifications with two matches

7. Conclusions

The economic analysis of HEN retrofit solutions using the Bridge Method and Bridge framework has been demonstrated using a complicated problem. The Bridge Method can specify the topology of each retrofit modification, which helps to have a more precise cost estimate by considering different parameters. From a numerous number of retrofit options, a list of economically viable retrofit solutions can be selected based on decision metrics such as payback period and IRR in addition to close interaction of expert users during the open-ended decision making process. These metrics are providing useful information for evaluating retrofit projects and to identify the most viable modifications with good heat-saving potential. This method has been implemented to analysis a preheat train of the crude oil distillation system, which led to 13 Bridges with one and two matches and with a maximum energy saving of 16.4 MW which is more than 30% of current HEN energy usage.

References

1. Bonhivers, J.-C., et al., Energy transfer diagram for improving integration of industrial systems. Applied Thermal Engineering, 2014. 63(1): p. 468-479.

2. Roetzel, W. and F. Nicole, Mean temperature difference for heat exchanger design—a general approximate explicit equation. Journal of Heat Transfer, 1975. 97(1): p. 5-8.

3. Svensson, E., et al., Design of Heat Exchanger Networks with Good Controllability. 2018, Technical Report.

4. Doldán, O.B., M.J. Bagajewicz, and J. Cerdá, Designing heat exchanger networks for existing chemical plants. Computers & chemical engineering, 1985. 9(5): p. 483-498.

5. Kobayashi, S., T. Umeda, and A. Ichikawa, Synthesis of optimal heat exchange systems—an approach by the optimal assingment problem in linear programming. Chemical Engineering Science, 1971. 26(9): p. 1367-1380.

6. Nishida, N., S. Kobayashi, and A. Ichikawa, Optimal synthesis of heat exchange systems Necessary conditions for minimum heat transfer area and their application to systems synthesis. Chemical Engineering Science, 1971. 26(11): p. 1841-1856.

7. Ciric, A. and C. Floudas, A retrofit approach for heat exchanger networks. Computers & chemical engineering, 1989. 13(6): p. 703-715.

8. Ciric, A.R. and C.A. Floudas, A mixed integer nonlinear programming model for retrofitting heat-exchanger networks. Industrial & engineering chemistry research, 1990. 29(2): p. 239-251.

9. Yee, T.F., I.E. Grossmann, and Z. Kravanja, Simultaneous optimization models for heat integration—I. Area and energy targeting and modeling of multi-stream exchangers. Computers & chemical engineering, 1990. 14(10): p. 1151-1164.

10. Yee, T.F. and I.E. Grossmann, Simultaneous optimization models for heat integration—II. Heat exchanger network synthesis. Computers & Chemical Engineering, 1990. 14(10): p. 1165-1184.

11. Yee, T.F., I.E. Grossmann, and Z. Kravanja, Simultaneous optimization models for heat integration—III. Process and heat exchanger network optimization. Computers & Chemical Engineering, 1990. 14(11): p. 1185-1200.

12. Abbas, H., et al., Heat exchanger network retrofit via constraint logic programming. Computers & Chemical Engineering, 1999. 23: p. S129-S132.

13. Ma, K.-L., C.-W. Hui, and T.F. Yee, Constant approach temperature model for HEN retrofit. Applied thermal engineering, 2000. 20(15-16): p. 1505-1533.

14. Ponce-Ortega, J.M., A. Jiménez-Gutiérrez, and I.E. Grossmann, Simultaneous retrofit and heat integration of chemical processes. Industrial & Engineering Chemistry Research, 2008. 47(15): p. 5512-5528.

15. Athier, G., et al., A mixed method for retrofiting heat-exchanger networks. Computers & chemical engineering, 1998. 22: p. S505-S511.

16. Gundepsen, T. and L. Naess, The synthesis of cost optimal heat exchanger networks: an industrial review of the state of the art. Computers & Chemical Engineering, 1988. 12(6): p. 503-530.

17. Carlsson, A., P.-A. Franck, and T.J.C.E.P. Berntsson, Design better heat exchanger network retrofits. 1993. 89(3).

18. Tjoe, T.N. and B. Linnhoff, Using pinch technology for process retrofit. Chemical Engineering, 1986. 93(8): p. 47-60.

19. Polley, G., M. Panjeh Shahi, and F. Jegede, Pressure drop considerations in the retrofit of heat exchanger networks. Transactions of the Institute of Chemical Engineers, 1990. 68.

20. Van Reisen, J.L., et al., The placement of two-stream and multi-stream heat-exchangers in an existing network through path analysis. Computers & chemical engineering, 1995. 19: p. 143-148.

21. Bonhivers, J.-C., B. Srinivasan, and P.R. Stuart, New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 1–Concepts. Applied Thermal Engineering, 2014.

22. Bonhivers, J.-C., et al., New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2 – Stepwise and graphical approach. Applied Thermal Engineering, 2017. 119: p. 670-686.

23. Gadalla, M., M. Jobson, and R. Smith, Optimization of existing heat-integrated refinery distillation systems. Chemical Engineering Research and Design, 2003. 81(1): p. 147-152.

24. Smith, R., M. Jobson, and L. Chen, Recent development in the retrofit of heat exchanger networks. Applied Thermal Engineering, 2010. 30(16): p. 2281-2289.

25. Ayotte-Sauvé, E., et al., Optimal retrofit of heat exchanger networks: A stepwise approach. Computers & Chemical Engineering, 2017. 106: p. 243-268.

APPENDIX D ARTICLE 4: PLANT-WIDE ENERGY ANALYSIS OF INDUSTRIAL FACILITIES USING THE BRIDGE METHOD: PART III – FRAMEWORK APPLICATION

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Abstract:

The industrial sector is among the largest GHG emitters. In past decades, several methods have been developed for the energy-use reduction of heat exchanger networks. In the last few years, a novel method called the Bridge Analysis has been developed for Heat Exchanger Network (HEN) retrofit. It is a systematic method distinct in approach to classical pinch analysis, with a well-defined procedure that lends itself well to the solution using a computer algorithm and graphical user interface. In this method, all energy-related process data is used to characterize the existing process configuration, which helps to identify the necessary modifications to reconfigure the energy-use profile of an industrial mill. To make Bridge analysis practical to be employed in industry, a sequential decision-making framework has been developed which is presented in part II of this paper. The objective of this article is to apply the developed framework for energy analytics of a complex problem considering both the process operation and the HEN, to find the economically viable retrofit projects. A model of an energy-efficient Scandinavian pulp mill is analyzed to demonstrate steps of the Bridge framework. The energy saving capacity of this

problem is 61MW, and by applying the framework, a list of practical Bridge modifications has presented.

Keywords: Bridge Method, heat exchanger network retrofit, plant-wide energy analysis, sequential decision-making framework

Abbreviations

$\dot{E}$	The flowrate of cascaded heat
ECLC	Extreme Cooling Load Curve
EEP	Energy Efficiency Program
EHLC	Extreme Heat Load Curve
ES	Energy Specialist
ET	Energy Transfer Diagram
ETC	Energy Transfer Curve
GCC	Grand Composite Curve
$\dot{H}$	Enthalpy rate
$\dot{H_{in}}$	Enthalpy rate of inlet
$\dot{H_{out}}$	Enthalpy rate of outlet
HELD	Heat Exchanger Load Diagram
HEN	Heat Exchanger Network
HUC	Hot Utility Curve
HCC	Hot Composite Curve
PO	Process operations
PES	Plant Energy Superintendent
PPE	Plant Process Engineer
P. Si.	Process sink
P. So.	Process source
T	Temperature

Ta	Ambient temperature
TCLC	Theoretical Cooling Load Curve
THLC	Theoretical Heat Load Curve
$T_{h_{Source}}$	Hot end temperature of the process source stream
$T_{c_{Source}}$	Cold end temperature of the process source stream
$T_{h_{Sink}}$	Hot end temperature of the process sink stream
$T_{c_{Sink}}$	Cold end temperature of the process sink stream

1. Introduction

Today, the industry sector has been accounted for nearly 40% of total final energy use. According to the International Energy Agency (IEA), the industrial sector will soon overtake transportation to become the second-largest greenhouse gas (GHG) emitter after power generation [1]. Moreover, the IEA has identified radical GHG emissions reduction by the industry as an especially difficult and complex challenge due to a number of factors including the unique energy needs of different process sectors, energy use reduction constraints with cogeneration, and the essential requirement for production sites to remain competitive [2]. The energy use reduction projects have been difficult to justify in industrial plants due especially to incremental savings resulting from small capital projects and competition resulting from productivity-oriented larger projects such as capacity increase. However, there is a substantial opportunity for radical GHG emissions reduction when considering significant process changes and energy use reduction simultaneously. Here, the systematic site-wide energy analysis and re-optimization of the energy profile of a processing plant can result in a significant reduction in GHG emissions, an improvement in the project profitability, and an improvement in a long-term competitive position. In the past few years, a novel energy analysis approach called Bridge Method has been developed by Bonhivers and Stuart, for energy analysis of industrial processes [3]. The basis of the Bridge Method is that the flow of cascaded heat through process operations and heat exchange network (HEN) is from hot to ambient and should be decreased to reduce the external energy usage [4]. Based on first two laws of thermodynamics, Bridge Method allows the user to characterize the system energy flows across process operations and the HEN, in a manner that allows the identification of practical modifications to the energy systems [5, 6]. To implement the Bridge method in practice, it has been integrated into a sequential design decision-making framework that considers design aspects from the basic industrial process energy audit, through to the economically viable retrofit projects. A detailed description of the Bridge Method and its framework has been presented in Part I and II of this paper. The aim of this article, which is part III of the article, is to demonstrate some parts of the developed framework through solving a complex case study.

To address the energy analytics of a complex problem using the Bridge framework, a summary of the Bridge Method and the developed sequential design decision-making framework is presented. Then the challenges in solving a complicated problem using the conventional approaches are reviewed.

2. Bridge Method

Bridge Method is an energy analytics methodology, which considers extracting all streams. It is based on first two laws of thermodynamics and helps to characterize the energy degradation across process operations as well as HEN in the temperature interval between hot and cold utility

[3]. It is a systematic method to find energy saving modifications by connecting a cooler supplier to a heater receptor through new or existing heat exchangers. It includes three tools, which are the Energy Transfer Diagram (ETD), the network table, and Heat Exchanger Load Diagram [7].

The ETD shows the cascaded heat as a function of temperature between the hot and cold utilities. The cascaded heat through each unit in the system (heat exchanger or process operation) is the difference between the total outlet and inlet enthalpy rates [5]. The network table can be used to enumerate the maximum heat saving capacity of each Bridge modification regarding the ΔT_{min} between streams. In this table, streams are decomposed into suppliers and receptors according to the existing HEN to provide an overall view on retrofit possibilities. Each row corresponds to a supplier, and each column corresponds to a receptor. The HELD is a graphical tool to identify Bridge modifications visually [8]. It represents the heat transfer constraints and possibilities visually by plotting the enthalpy change of each process sources and sinks as a function of temperature [6]. It improves clarity and helps to identify modifications in retrofit situations; it is also helpful for HEN greenfield design.

The Bridge Method as an energy analysis approach, at its foundation, is a process design and needs to be done in a practical way that considers all the constraints such as thermal fouling, the complexity of implementations, etc. To address design issues in practice and find the economically viable modifications, a decision-making framework is needed to couple computer-aided calculations with the expertise of energy specialists and process engineers in open-ended process assessments to narrow down to practical and profitable retrofit projects.

3. Sequential design decision-making framework:

A decision-making framework has been developed to make thoughtful, case-specific decisions by managing case-specific information and evaluating different options [part II]. It increases the probabilities of selecting the most preferred solution. More specifically, it enables energy analysis with respect to comparing different process configurations and site-wide options and assessing the consequences of each energy scenario. The framework includes different sequences and each sequence comprises both calculation engines using computer algorithms and open-ended decision-making parts. A decision is made in each sequence, which adds new information to the problem and helps to make the next decision.

Open-ended decision making cannot be computerized, and it allows good engineering judgment (GEJ) to be implicated in the design process. While the Bridge Method lends itself well to being formulated in computer algorithms, there are numerous open-ended decisions that need to be made from a practical perspective. For example, modifying the process operations, identifying infeasible connections or assessing the corresponding risk for each modification are all the activities that need to be done by expert users. Different qualitative and quantitative parameters need to be considered to deal with these open-ended decisions. Figure 1 shows a summary of the sequential decision-making structure to implement the Bridge Method. After energy auditing and extracting all data from the simulation file, the first thing to do in the framework is to select or refine the individual ΔT_{min} contribution for each stream. This will lead to a more explicit calculation of the operating and capital costs. The HEN diagram will be generated in this step using a calculation engine, and in the open-ended decision-making part, an energy specialist is needed to refine and select an appropriate value for $\Delta T_{min\text{-}cont.}$ of all streams.

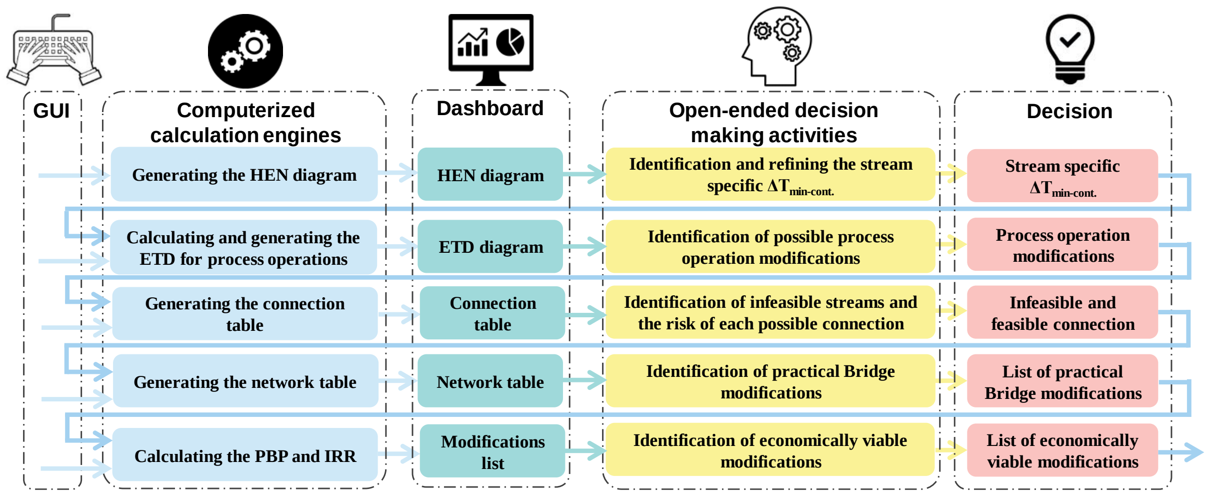

Figure 1- The sequential decision-making framework incorporating the Bridge Method

The $\Delta T_{min\text{-}cont.}$ then is used in the next sequence, among other necessary inputs to calculate and generate the ETD of the process operations through a calculation engine. The maximum of the process operation curve in the ETD shows the maximum hot utility consumption by process operations, and to reduce that, the cascaded heat through the process operations that have an impact in the maximum of the curve should be reduced. By calculating the temperature of the maximum of the ETD and detecting the process operations which have an impact on the ETD at that temperature, the potential process operation modification can be identified. This list will be assessed by Plant Process Engineer (PPE) and Plant Energy Superintendent (PES) using GEJ to find possible opportunities to improve the energy efficiency of process operations that merit for their examination through an open-ended decision-making procedure.

The third step is to identify the infeasible connections for the HEN retrofit. Infeasible connection means a connection that is thermodynamically impossible, or it is categorized as the forbidden connection. This is useful to narrow down the searching space for identifying the practical Bridge modifications. A table called the “connection table” is generated by a calculation engine to show all connections between process sources and sinks. The columns in this table are assigned to the process sinks, and the rows represent the heat source. So, each cell in this table belongs to a connection between process sources and process sinks. The level of risk associated with each feasible connection can be shown qualitatively. The feasible connections are ranked based on qualitative parameters such as complexity and safety which reflect the risk associated with each connection. A number between 1 and 3 is assigned to each connection showing the level of risk, in which number 1 shows a low level of risk. Identification of infeasible stream connections and selecting the low, medium and high-risk connections will be done by the plant process engineer using the energy data and Good Engineering Judgment (GEJ).

The fourth step is to enumerate and select the practical Bridge modifications. The detailed approach to enumerate the Bridges has been explained in the previous paper. The sorted list of Bridges based on the energy-saving capacity with their risk level will be used in a decision-making procedure for further assessment of the Bridge modifications. Besides, the modifications with more than five matches are more likely to be impractical.

The fifth step is to identify economically viable Bridge modifications. The input of this sequence is the list of practical Bridge modifications with the energy saving capacity and the risk level associated with each connection. To meet the minimum payback period that was defined by the manager at the beginning of the energy analysis project, the payback period for each modification has to be identified. The payback period can be estimated from dividing the investment cost by saving energy cost. To calculate the investment cost, we need a model to consider the cost of adding a new area, new exchangers, reallocating the existing exchangers, and the cost of piping and pumping. Several studies have been done to develop a cost model for HEN retrofit. After calculating the investment cost, the payback period can be calculated for each Bridge modification, and it will be represented on the dashboard. So, for each modification, the payback period, which is a quantitative parameter and the risk level, which is a qualitative parameter is identified. Based on the GEJ and trading off between the two parameters for each solution, the decision-makers can come to a list of 10 to 20 economically viable modifications for each potential process operation modification.

4. Demonstrating the Bridge framework

For demonstrating the developed methodology in solving a complicated case including the process operation, a Scandinavian kraft pulp mill model is used in this thesis [9]. The mill produces 1000 ADt/day of bleached market kraft pulp from 2065 t/day of softwood. Figure 2 shows the simplified representation of the FRAM kraft pulp mill fiber line and chemical recovery system [10, 11].

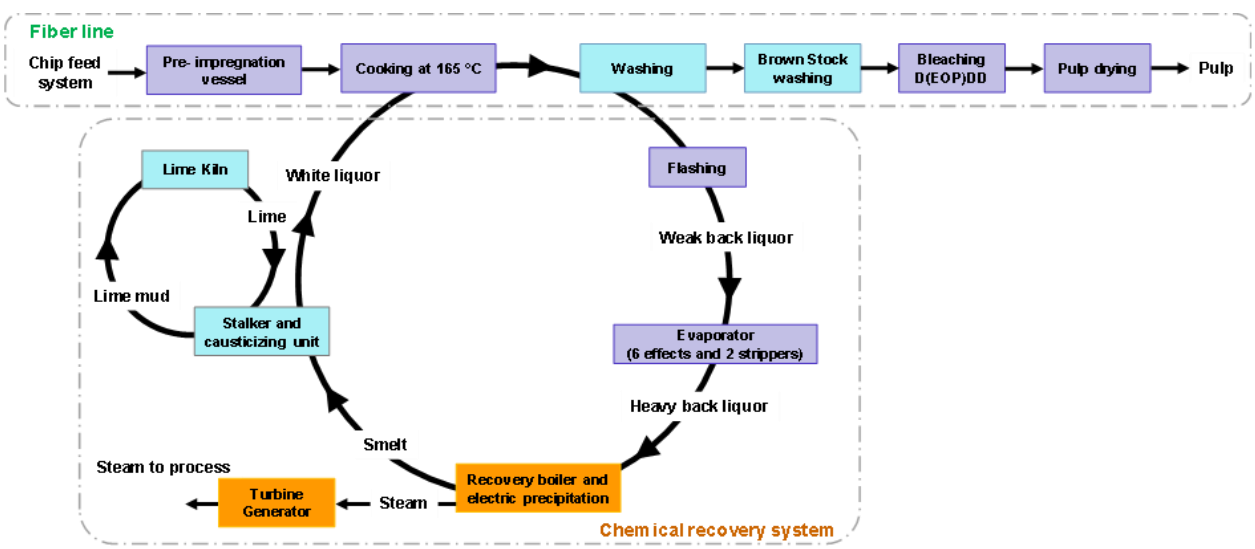

Figure 2- Simplified representation of the FRAM kraft pulp mill fiber line and chemical recovery system

The continues cooking is performed at relatively high alkalinity at 165 °C. The continues digester system includes two flash systems. The first flash supplies steam to the chip bin for impregnation and preheating, while the steam from the second flash is utilized for hot water production. The digester is followed by a brown stock washing system. The bleach plant includes four steps in the sequence D(EOP)DD that gives 90% brightness.

The evaporation is a six-effect system using low and medium pressure steams to give 73% solids content in the heavy liquor. LP steam is used at the first effect, and steam evaporated from this effect is used to the next effect, and so on until the sixth effect from which heat is evacuated through a surface condenser to freshwater for the production of warm water. The evaporation system is the largest energy user in the mill.

Table 1- Process sources data

Stream name	Stream No.	Inial T T_i (°C)	Final T T_f (°C)	Load Q (MW)	Heat transfer coefficient h (W/m^2.K)
General cooling	P. So. 1	40	35	9.0	1000
Chemical preparation	P. So. 2	48	47	1.2	1000
Excess condensate	P. So. 3	60	39	1.0	1000
Pulp dryer effluent	P. So. 4	60	39	1.8	1000
Surfac condenser	P. So. 5	61	60	52.0	6000
D1-stage effluent	P. So. 6	66	39	11.9	1000
D1-stage filtrate	P. So. 7	69	66	1.8	1000
D0-stage effluent	P. So. 8	75	39	7.3	1000
D0-stage filtrate	P. So. 9	75	68	2.1	1000
EOP-stage effluent	P. So. 10	85	39	9.5	1000
Stripper second condsenser	P. So. 11	90	89	0.5	4000
Digester bottom	P. So. 12	90	89	0.8	1000
Stripper condenser	P. So. 13	100	99	4.4	6000
Steam smelt dissolver	P. So. 14	100	99	3.2	6000
Black liquor cooling	P. So. 15	105	93	4.9	1000
Condensate	P. So. 16	107	75	0.7	1000
BL flash steam 2	P. So. 17	109	107	12.4	8000
BL flash steam 1	P. So. 18	128	127	12.9	8000

The HEN of this case study includes 40 units, i.e. 13 coolers, 19 heaters, and eight internal heat exchangers. The $\Delta T_{min,\ cont.}$ for each stream is also indicated. The hot utility consumption before retrofit is equal to 147 MW [10, 12]. The case-specific data that are needed in the first step of the framework are shown in tables 1 to 5. All these data should be added to the framework through GUI and will be used to generate the existing HEN diagram.

Table 2- Process sinks data

Stream name	Stream No.	Inial T T_i (°C)	Final T T_f (°C)	Load Q (MW)	Heat transfer coefficient h (W/m^2.K)
Building heating (LP)	P. Si. 1	21	22	1.1	3000.0
Wood yard	P. Si. 2	18	30	1.6	1000.0
WW50	P. Si. 3	18	50	32.5	3000.0
Mak up boiler water	P. Si. 4	18	75	5.6	3000.0
WW 75	P. Si. 5	50	75	9.4	3000.0
WW 85	P. Si. 6	50	85	19.0	3000.0
White liquor - imp. (MP)	P. Si. 7	85	105	12.0	2000.0
Wood chips	P. Si. 8	7	120	20.9	-
Air heating (LP)	P. Si. 9	95	120	3.7	100.0
Circulation air (LP)	P. Si. 10	95	124	28.0	100.0
Stripper (LP)	P. Si. 11	150	151	6.4	-
BL evap (LP)	P. Si. 12	150	151	52.0	-
Rest (LP)	P. Si. 13	150	151	6.6	-
Hi-Heat (MP)	P. Si. 14	128	160	7.8	1000.0
White liquor - digester (MP)	P. Si. 15	85	165	12.0	2000.0
Digester circ. (MP)	P. Si. 16	165	170	1.9	1000.0
MP to oxygen stage	P. Si. 17	200	201	2.3	-
MP to bleach plant	P. Si. 18	200	201	6.0	-
MP to rest	P. Si. 19	200	201	2.2	-

Table 3-- Coolers energy data

Heat exchanger	P.So. No.	P. Si. No.	P.So. initial temperature T_i (°C)	P.So. final temperature T_f (°C)	Load Q (MW)
C1	1	CU	35.0	40.0	9.0
C2	2	CU	47.0	48.0	1.2
C3	3	CU	39.0	60.0	1.0
C4	4	CU	39.0	60.0	1.8
C5	5	CU	60.0	60.4	19.5
C6	6	CU	39.0	66.0	11.9
C7	7	CU	66.0	69.0	1.8
C8	8	CU	39.0	61.0	4.6
C9	10	CU	39.0	61.0	4.5
C10	11	CU	89.0	90.0	0.5
C11	12	CU	89.0	90.0	0.8
C12	13	CU	99.0	100.0	4.4
C13	14	CU	99.0	100.0	3.2

Table 4- Heaters energy data

Heat exchanger	P.So. No.	P. Si. No.	P. Si. inial temperature T_i (°C)	P. Si. final temperature T_f (°C)	Load Q (MW)
H1	HU	1.0	21.0	22.0	1.1
H2	HU	2.0	18.0	30.0	1.6
H3	HU	4.0	40.0	75.0	3.4
H4	HU	5.0	72.0	75.0	1.0
H5	HU	6.0	82.0	85.0	1.7
H6	HU	7.0	85.0	105.0	0.8
H7	HU	8.0	77.0	120.0	8.0
H8	HU	9.0	95.0	120.0	3.7
H9	HU	10.0	95.0	124.0	28.0
H10	HU	11.0	150.0	151.0	6.4
H11	HU	12.0	150.0	151.0	52.0
H12	HU	13.0	150.0	151.0	6.6
H13	HU	14.0	128.0	160.0	7.8
H14	HU	15.0	85.0	165.0	12.0
H15	HU	16.0	165.0	170.0	1.9
H16	HU	17.0	200.0	201.0	2.3
H17	HU	18.0	200.0	201.0	6.0
H18	HU	19.0	200.0	201.0	2.2

Table 5- Process - process heat exchangers energy data

Heat exchanger	P.So. No.	P. Si. No.	P.So. inial temperature T_i (°C)	P.So. final temperature T_f (°C)	P. Si. inial temperature T_i (°C)	P. Si. final temperature T_f (°C)	Load Q (MW)
E1	5	3	60.4	61.0	18.0	50.0	32.5
E2	9	4	68.0	75.0	18.0	40.0	2.1
E3	8	5	61.0	75.0	50.0	69.0	2.7
E4	10	5	61.0	85.0	50.0	74.0	5.0
E5	15	6	93.0	105.0	50.0	82.0	4.9
E6	16	5	75.0	107.0	50.0	75.0	0.7
E7	17	6	107.0	109.0	50.0	82.0	12.4
E8	18	8	127.0	128.0	7.0	77.0	12.9

The calculation engine uses the input data and the knowledge of creating the HEN diagram and generates the existing HEN diagram which is shown in figure 3. For streams with the liquid phase, the ΔT_{min} contribution is between 3 to 5 °C according to the literature and for gas streams, it goes up to 10 to 15 °C. Selecting a suitable value for each stream is not easy and needs an expert engineer to decide which one is more appropriate. In this case, the simulation of the mill was done using the $\Delta T_{min\text{-}cont.}$ for each stream which is shown in table 6.

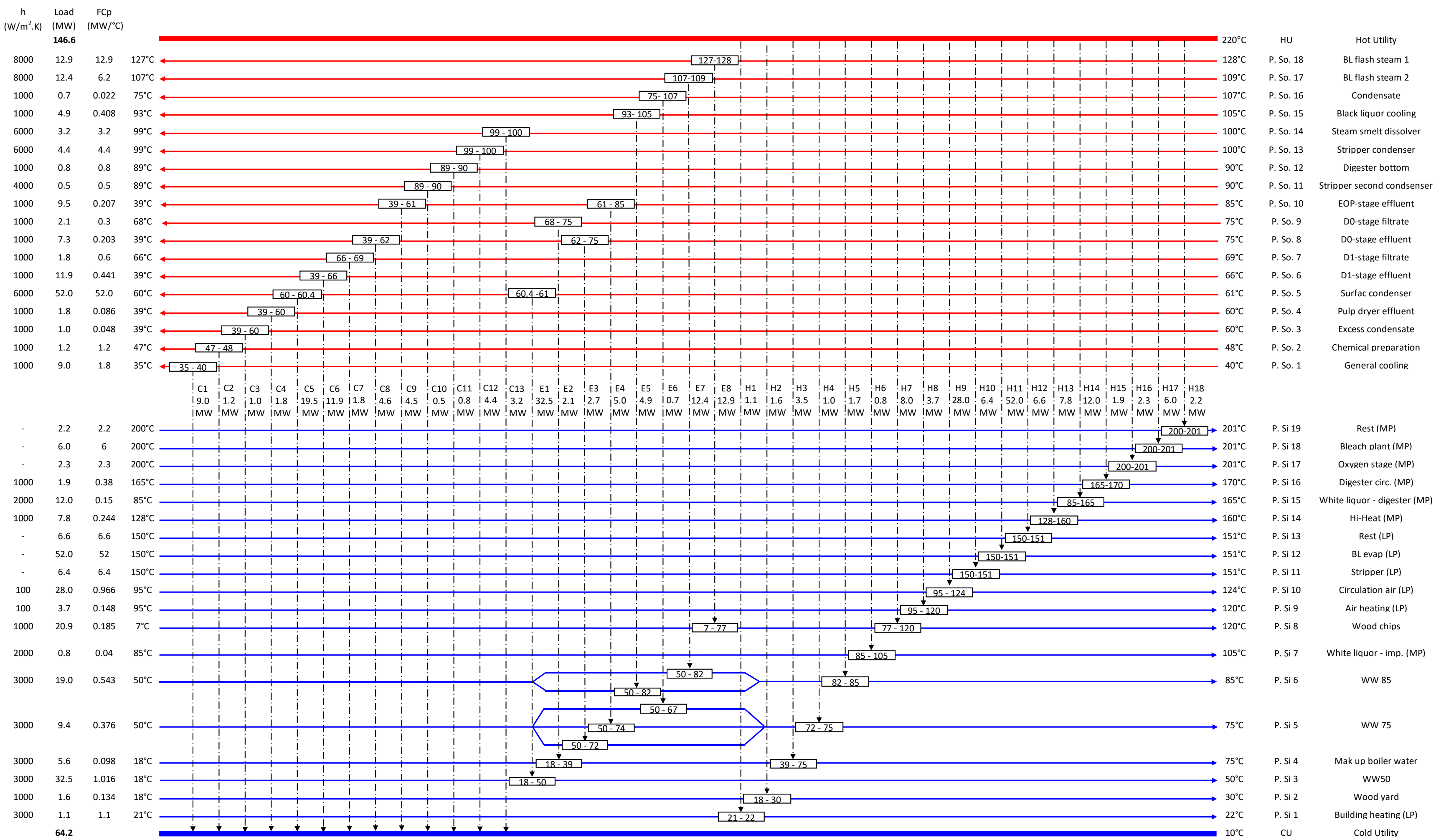

Figure 3- Existing HEN diagram

Table 6- The $\Delta T_{min\text{-}cont.}$ for each stream

Stream No.	Min ΔT contribution $\Delta T_{min\text{-}cont.}$ (°C)	Stream No.	Min ΔT contribution $\Delta T_{min\text{-}cont.}$ (°C)
P. So. 1	3.5	P. Si. 1	8.0
P. So. 2	3.5	P. Si. 2	4.0
P. So. 3	3.5	P. Si. 3	2.5
P. So. 4	3.5	P. Si. 4	2.5
P. So. 5	2.0	P. Si. 5	2.5
P. So. 6	3.5	P. Si. 6	2.5
P. So. 7	3.5	P. Si. 7	3.5
P. So. 8	3.5	P. Si. 8	3.5
P. So. 9	3.5	P. Si. 9	8.0
P. So. 10	3.5	P. Si. 10	8.0
P. So. 11	4.0	P. Si. 11	0.5
P. So. 12	3.5	P. Si. 12	0.5
P. So. 13	2.0	P. Si. 13	0.5
P. So. 14	2.0	P. Si. 14	3.5
P. So. 15	3.5	P. Si. 15	3.5
P. So. 16	3.5	P. Si. 16	3.5
P. So. 17	2.0	P. Si. 17	0.5
P. So. 18	2.0	P. Si. 18	0.5
-	-	P. Si. 19	0.5

Values of $\Delta T_{min\text{-}cont.}$ should be added to the system. The second step of the framework is to find opportunities for potential process operation modifications. A Simplified process diagram was presented in the previous chapter. The data related to input and output of pre-impregnation vessel (PO1), digester (PO2), the first and the second flash system, the bleaching plant, pulp dryer, evaporator, and stripper are added to the framework. The calculation engine uses these case-specific data to calculate the ETD of the process operations. The calculation engine must first analyze each process operation individually and then put them together to have a whole picture of energy degradation through all units.

The procedure of calculating ETD is explained here by showing how it is done for the first unit, which is the pre-impregnation vessel. Figure 4 shows a schematic of this unit with energy-related data of input and output streams.

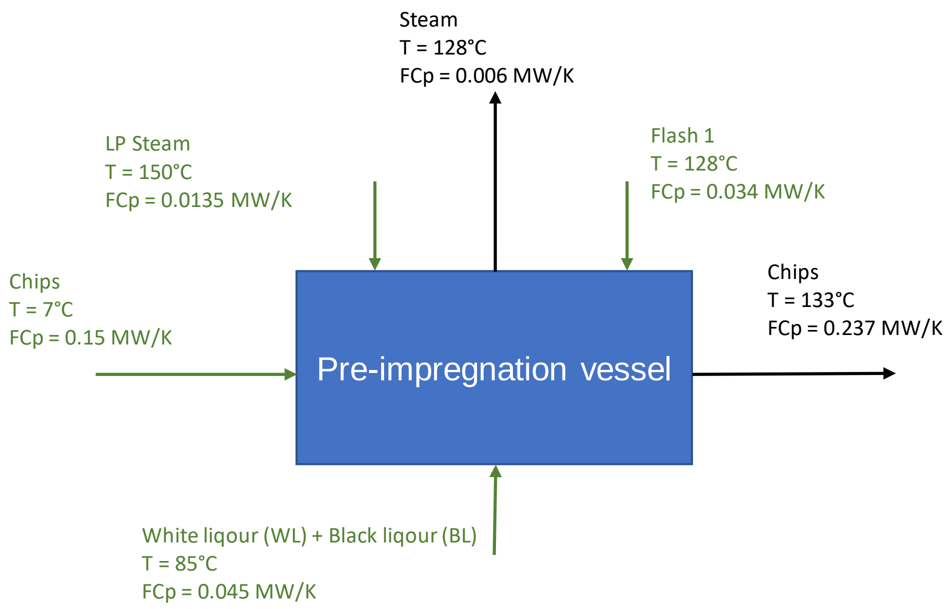

Figure 4- Pre-impregnation vessel input and output streams

Based on these data and the enthalpy formulation, the total inlet and outlet enthalpy curves of the pre-impregnation vessel are calculated and shown in figure 5.

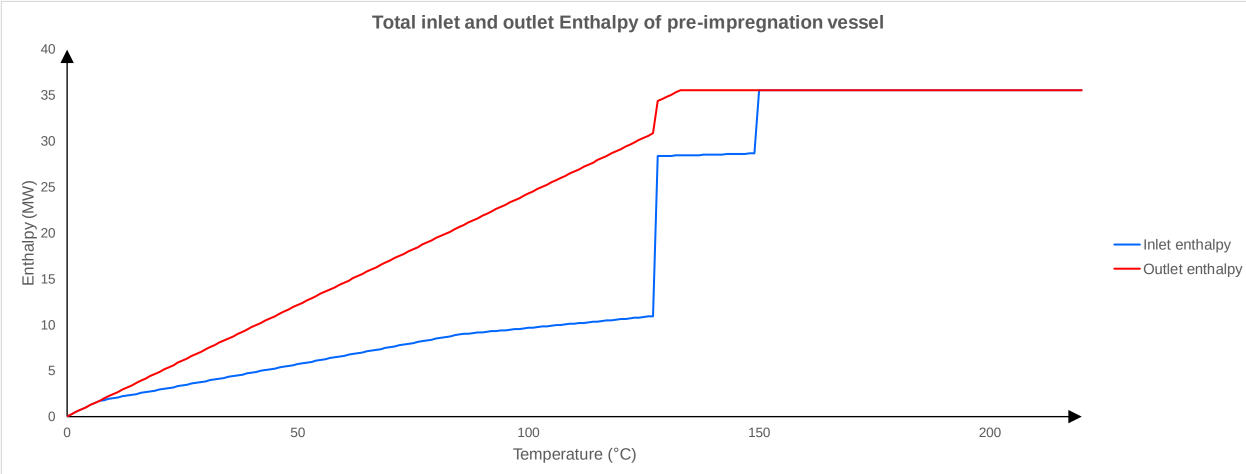

Figure 5- Total inlet and outlet enthalpy curves of the pre-impregnation vessel

The flow rate of transferred energy through this unit in the difference between the total outlet and inlet enthalpy rate. Figure 6 represents the energy cascaded as a function of temperature or ETD of the pre-impregnation vessel.

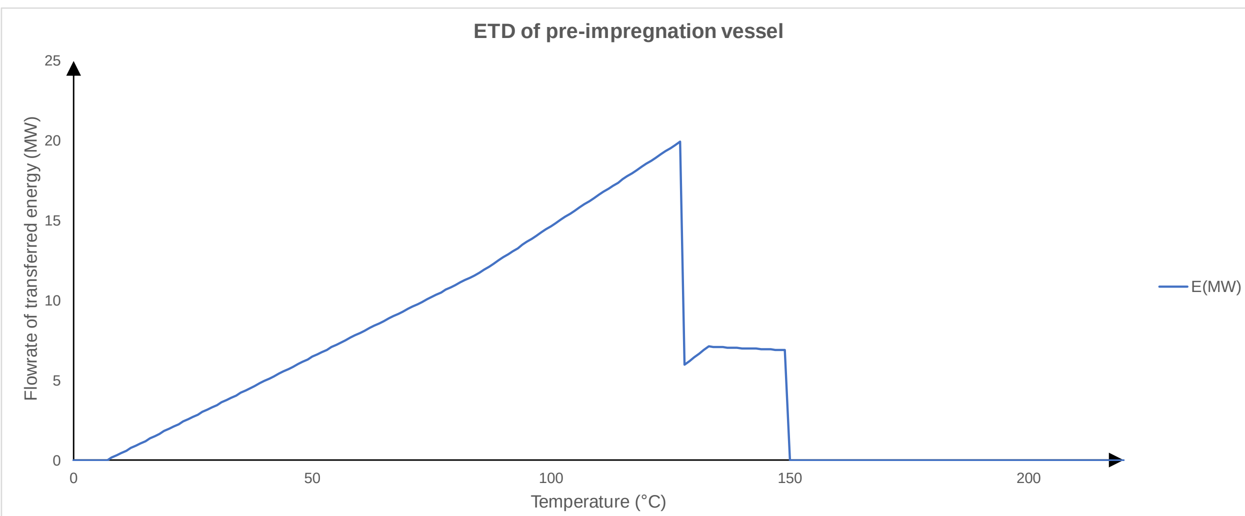

Figure 6- ETD of the pre-impregnation vessel

This procedure has been done for all units, and the final ETD is shown in figure 7. This ETD represents the way that energy cascades through different units. As it is mentioned before, this diagram helps to identify process operation modifications.

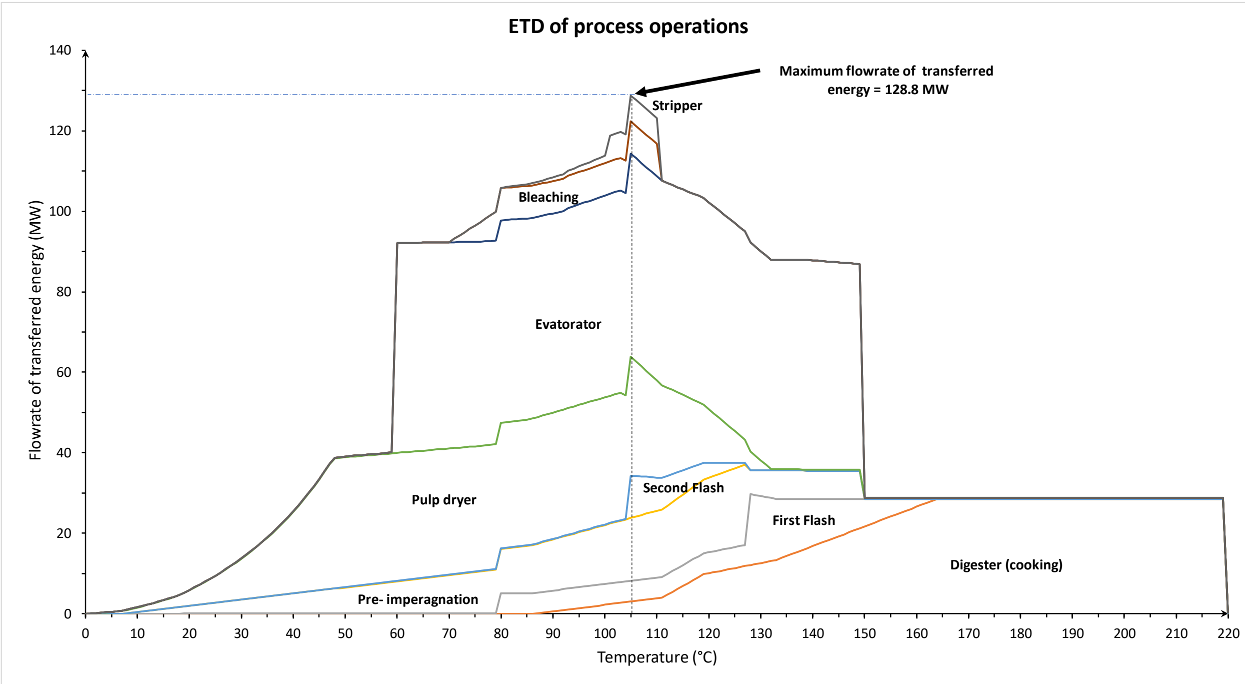

Figure 7- The ETD of all process operations

The maximum of the process operation curve happens at 105 °C. At this temperature, the total flowrate of energy or total energy transferred is equal to 128.8 MW. As it is represented in table 4-15, the evaporator and the pulp dryer have the highest impact on total transferred energy.

Table 18- The sorted list of process operations

Sorted list of procss operations based on their energy degradation at the peak temperature	
Evaporator	50.5 MW
Pulp dryer	29.5 MW
Pre-impregnation	15.6 MW
Second Flash	10.5 MW
Bleaching	8 MW
Stripping	6.5 MW
First Flash	5.2 MW
Cooking	3 MW

A calculation engine can automatically generate the ETD and information in table 15. Based on this information, the focus of the open-ended decision-making process in this step is to find a solution to modify the evaporator and pulp dryer. The ETD of the evaporator is shown in figure 8. In this case, LP steam is used as an input in the first effect of the evaporator, and the steam from the first effect is sent to the next effect. The steam from the sixth effect is employed by the surface condenser to generate warm water at 50 °C.

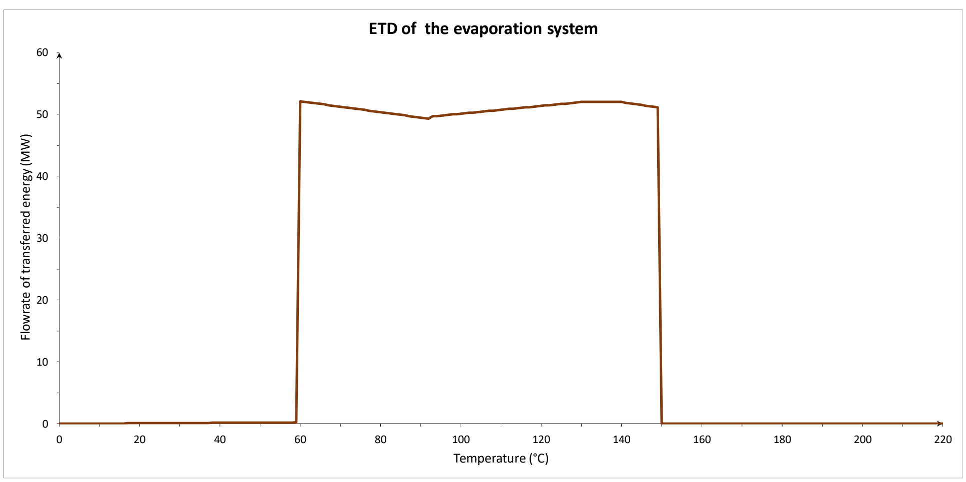

Figure 8- The ETD of the evaporator

To reduce the hot utility usage of the evaporator, the number of effects can be increased. It leads to an increase in investment cost, and a techno-economic analysis is needed to assess the profitability of this project. Another solution is the method developed in Chalmers University to use excess heat from a process at high temperature at using it in the fourth or fifth effect of evaporation train and reducing the LP steam demand. Using new technology such as electric evaporator can significantly decrease the hot utility demand and could be an interesting option to consider. Figure 9 represents the individual ETD of the pulp dryer.

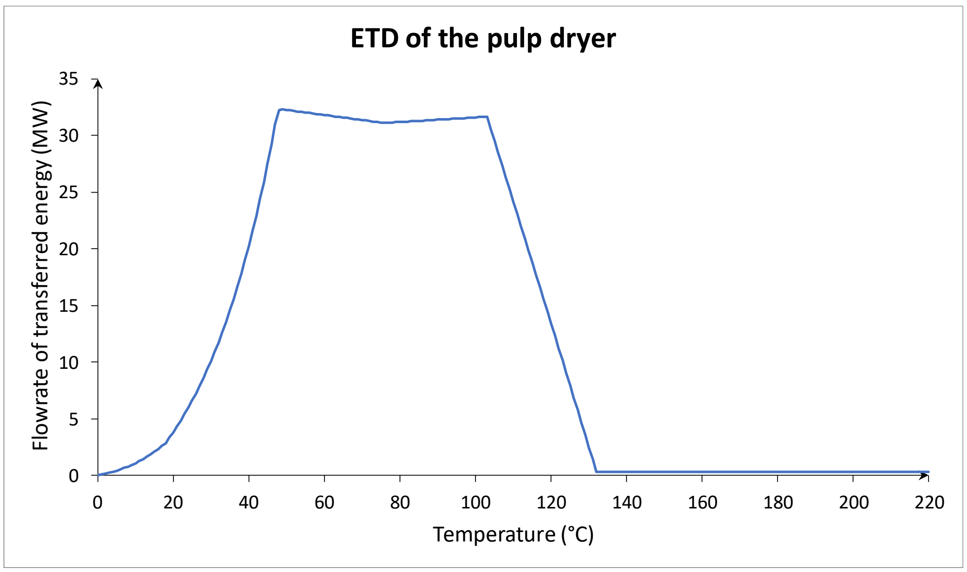

Figure 9- ETD of the pulp dryer

The inlet air to the pulp dryer is preheated with the warm outlet air and an LP steam. An option to reduce energy consumption is to increase the surfing area in the dryer and reduce the hot air flowrate. Another option is to use new technologies such as infrared radiation to reduce steam demand. In general, the plant process engineer, and the plant energy superintendent are working together to assess the process operations, confirm the operational viability and do the simulation for viable modification.

In the third step of the framework, the feasibility of connecting process sources and sinks are evaluated. Figure 10 shows the connection table that is utilized to identify infeasible connections and the level of risk associated with the rest. Since this case is a hypothetical model of a mill, the risk level of connections does not reflect the reality of the process.

			BuilE:Pding heating (LP)	Wood yard	WW50	Make up boiler water	WW 75	WW 85	White liquor - imp. (MP)	Wood chips	Air heating (LP)	Circulation air (LP)	Stripper (LP)	BL evap (LP)	Rest (LP)	Hi-Heat (MP)	White liquor - digester (MP)	Digester circ. (MP)	Oxygen stage (MP)	Bleach plant (MP)	Rest (MP)
			P. Si 1	P. Si 2	P. Si 3	P. Si 4	P. Si 5	P. Si 6	P. Si 7	P. Si 8	P. Si 9	P. Si 10	P. Si 11	P. Si 12	P. Si 13	P. Si 14	P. Si 15	P. Si 16	P. Si 17	P. Si 18	P. Si 19
			H1	H2	E1	E2 - H3	E3-E4-E6-H4	E5-E7-H5	H6	E8 - H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18
General cooling	P. So. 1	C1																			
Chemical preparation	P. So. 2	C2			1		1	1	1								1				
Excess condensate	P. So. 3	C3		1	2	2	2	2	1								1				
Pulp dryer effluent	P. So. 4	C4			2	1	2	2													
Surfac condenser	P. So. 5	C5 - E1			2	2	2	2	2								2				
D1-stage effluent	P. So. 6	C6			2		2	2	1								1				
D1-stage filtrate	P. So. 7	C7			2		2	2	1								1				
D0-stage effluent	P. So. 8	C8 - E3			2		2	2	1								1				
D0-stage filtrate	P. So. 9	E2			2		2	2	1								1				
EOP-stage effluent	P. So. 10	C9 - E4			2	1	2	2	1								1				
Stripper second condenser	P. So. 11	C10		1	2	2	2	2	1								1				
Digester bottom	P. So. 12	C11			3	1	3	3	3								3				
Stripper condenser	P. So. 13	C12		1	2	2	2	2	1								1				
Steam smelt dissolver	P. So. 14	C13		1	1	3	1	1	1	1							1				
Black liquor cooling	P. So. 15	E5			3	1	3	3	3				1	2	1	3	3	3	1		
Condensate	P. So. 16	E6			3	1	3	3	3				1	2	1	3	3	3	1		
BL flash steam 2	P. So. 17	E7		2	3	1	3	3	3	3			1	2	1	3	3	3	1		
BL flash steam 1	P. So. 18	E8		2	3	1	3	3	3	3			1	2	1	3	3	3	1		

Figure 10- The connection table

The next step is to enumerate the Bridge modifications. Bridge Method has a systematic approach to identify the energy saving capacity of each modification. The minimum temperature contribution of each stream is an important parameter to calculate the heat flowrate for each match.

	CU	E1	E2	E3	E4	E5	E6	E7	E8	H1	H2	H3	H4	H5	H6	H7	H8	H9	H14
HU	Saving									1.1	1.6	3.5	1.0	1.7	0.8	8	3.7	28	12
E8									**12.9**	1.1	1.6	3.5	1.1	1.6	0.8	8.0	3.4	12.9	5.6
E7								**12.4**	12.4	1.1	1.6	3.5	1.1	1.6	0.7	4.9	0.6	3.9	2.8
E6							**0.7**	0.7	0.7	0.7	0.7	0.7	0.6	0.4	0.3	0.5	0.0	0.0	0.3
E5						**4.9**	0.7	4.9	4.9	1.1	1.6	3.5	1.1	1.6	0.5	3.9	0.0	0.0	2.0
E4					**5.0**	4.4	0.7	5.0	5.0	1.1	1.6	3.5	1.1	0.0	0.0	0.2	0.0	0.0	0.0
E3				**2.3**	2.7	2.7	0.7	2.7	2.7	1.1	1.6	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E2			**2.1**	2.1	2.1	2.1	0.7	2.1	2.1	1.1	1.6	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E1		**32.5**	2.1	0.8	1.4	1.0	0.3	2.5	9.0	1.1	1.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C13	3.2	3.2	2.1	2.7	3.2	3.2	0.7	3.2	3.2	1.1	1.6	3.2	1.1	1.6	0.4	3.2	0.0	0.0	1.4
C12	4.4	4.4	2.1	2.7	4.4	4.4	0.7	4.4	4.4	1.1	1.6	3.5	1.1	1.6	0.4	3.3	0.0	0.0	1.4
C11	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.0	0.8	0.0	0.0	0.0
C10	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.5	0.0	0.0	0.0
C9	4.5	4.5	2.1	0.6	1.0	0.8	0.2	1.0	4.5	1.1	1.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C8	4.6	4.6	2.1	0.7	1.2	0.9	0.2	1.2	4.6	1.1	1.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C7	1.8	1.8	1.8	1.6	1.8	1.8	0.5	1.8	1.8	1.1	1.6	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6	11.9	11.9	2.1	1.2	2.1	1.5	0.4	3.9	9.6	1.1	1.6	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C5	19.5	20.8	2.1	0.7	1.2	0.9	0.2	2.3	8.9	1.1	1.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C4	1.8	1.8	1.8	0.3	0.3	0.3	0.2	0.3	1.8	1.1	1.6	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C3	1.0	1.0	1.0	0.2	0.2	0.2	0.2	0.2	1.0	1.0	1.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C2	1.2	1.2	1.2	0.0	0.0	0.0	0.0	0.0	1.2	1.1	1.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C1	9.0	9.0	1.6	0.0	0.0	0.0	0.0	0.0	4.8	1.1	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 11- The network table

The total number of Bridge modifications depends on the number of heaters, coolers and internal heat exchangers. Selecting the practical solutions among the list of all Bridge modifications should be done by a user. The energy saving capacity and the level of risk for each modification is assessed by the plant process engineer to choose the most practical options for further analysis. Tables 16 to 18 represent the list of practical Bridge modifications with one, two, and three matches that are selected in this step.

Table 19- List of practical Bridge modifications with one match

Bridges with one match	Heat saving capacity	Qualitative weighting factor
C12H3	3.5	2
C13H3	3.2	1
C12H5	1.6	2
C13H5	1.6	3
C12H2	1.6	3
C13H2	1.6	3
C5H3	1.6	2
C12H14	1.4	3
C13H14	1.4	3
C4H3	1.2	3
C12H4	1.1	2
C13H4	1.1	3
C3H2	1.0	3

Table 20- List of practical Bridge modifications with two matches

Bridges with Two matches	Heat saving capacity	Qualitative weighting factor
C12E7,E7H7	4.4	2 - 1
C6E7,E7H7	3.9	2 - 1
C6E7,E7H3	3.4	2 - 3
C12E4,E4H3	3.4	2 - 3
C12E5,E5H3	3.4	1 - 2
C12E7,E7H3	3.4	2 - 1
C13E4,E4H3	3.2	3 - 3
C13E5,E5H3	3.2	3 - 3
C13E5,E5H7	3.2	1 - 1
C13E7,E7H3	3.2	3 - 3
C13E7,E7H7	3.2	3 - 1
C6E7,E7H14	2.8	2 - 1
C12E7,E7H14	2.8	2 - 1
C13E7,E7H14	2.8	3 - 1
C5E7,E7H3	2.3	2 - 3
C5E7,E7H7	2.3	2 - 1
C5E7,E7H14	2.3	2 - 1
C6E4,E4H3	2.1	2 - 3
C12E5,E5H14	2.0	2 - 1
C13E5,E5H14	2.0	3 - 1

Table 21- List of practical Bridge modifications with three matches

Bridges with Three matches	Heat saving capacity	Qualitative weighting factor
C12E5,E5E7,E7H7	4.4	2 - 1 - 1
C12E7,E7E8,E8H7	4.4	2 - 1 - 1
C12E7,E7E8,E8H14	4.4	2 - 1 - 1
C6E7,E7E8,E8H7	3.9	2 - 1 - 1
C6E7,E7E8,E8H14	3.9	2 - 1 - 1
C12E4,E4E7,E7H3	3.4	2 - 2 - 3
C12E7,E7E8,E8H3	3.4	2 - 1 - 3
C13E4,E4E7,E7H7	3.2	3 - 2 - 1
C13E5,E5E7,E7H3	3.2	3 - 1 - 3
C13E5,E5E7,E7H7	3.2	3 - 1 - 1
C13E7,E7E8,E8H7	3.2	3 - 1 - 1
C13E7,E7E8,E8H14	3.2	2 - 1 - 1
C12E4,E4E7,E7H14	2.8	2 - 1 - 1
C12E5,E5E7,E7H14	2.8	2 - 1 - 1

The last step of the framework aims to calculate the payback period and IRR for each modification. The energy saving cost is calculated using equation I:

$$Energy\ saving\ cost\ (USD) = 312000 \times (energy\ saving\ capacity\ (MW))$$

All Bridge modifications, in this case, need a new connection and, therefore a new heat exchanger. To estimate the cost of adding an exchanger area, equation II is applied:

$$Cost\ of\ new\ heat\ exchnager\ (USD) = 984093 + 1127 \times \left(A(m^2)\right)^{0.98}$$

Based on the literature, the total investment cost is the total investment cost for HEN retrofit can be estimated by using equation III:

$$Total\ investment\ cost\ (USD) = 1.3 \times \sum_i^n Cost\ of\ new\ heat\ exchnager$$

Figures 12 to 14 represent a payback period and the internal rate of return for modifications with one, two and three matches. A gray line shows the energy saving capacity corresponding to each Bridge.

The modifications are sorted based on energy saving capacity the first one has the highest saving. The modification, C12H3, has the lowest payback period and highest IRR, and that makes it an exciting retrofit project. The second modification, C13 H3, has the same payback period and very good IRR. We should keep in mind that these modifications are not all independent. For example, if we modify the network based on C12H3 Bridge, we cannot do another modification like C13H3, because the receptor of the H3 exchanger is already modified.

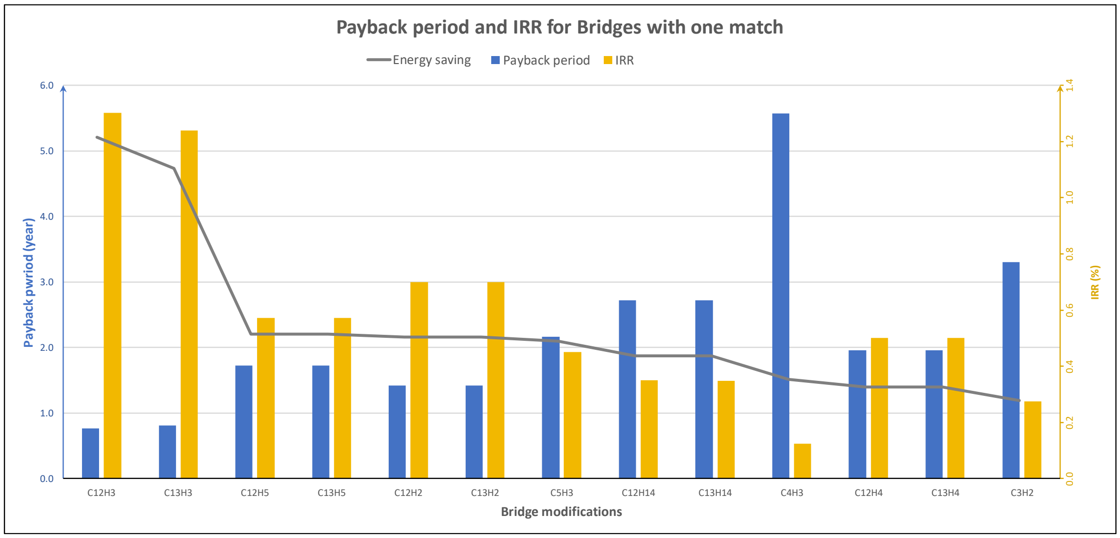

Figure 12- Payback period and IRR for Bridges with one match

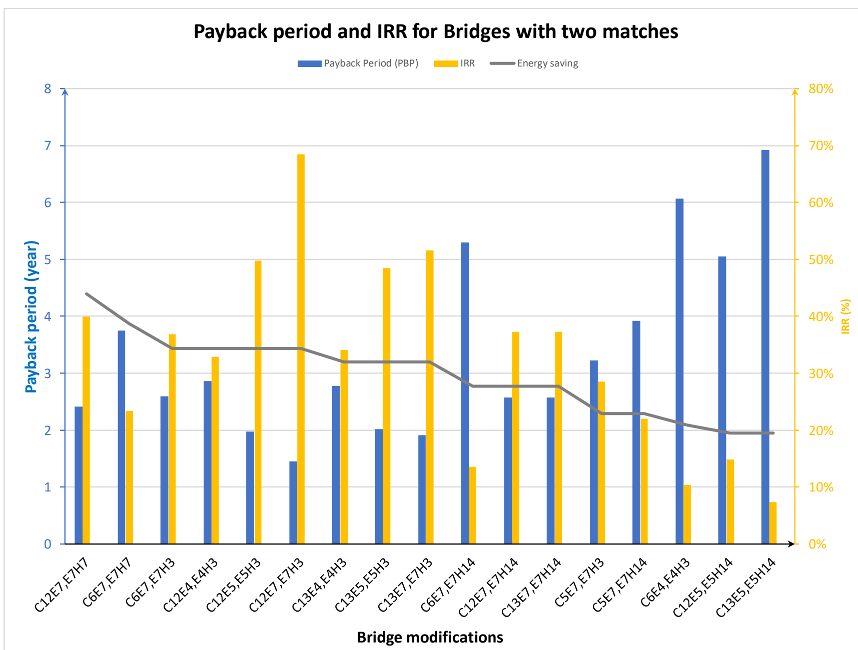

Figure 13- Payback period and IRR for Bridges with two matches

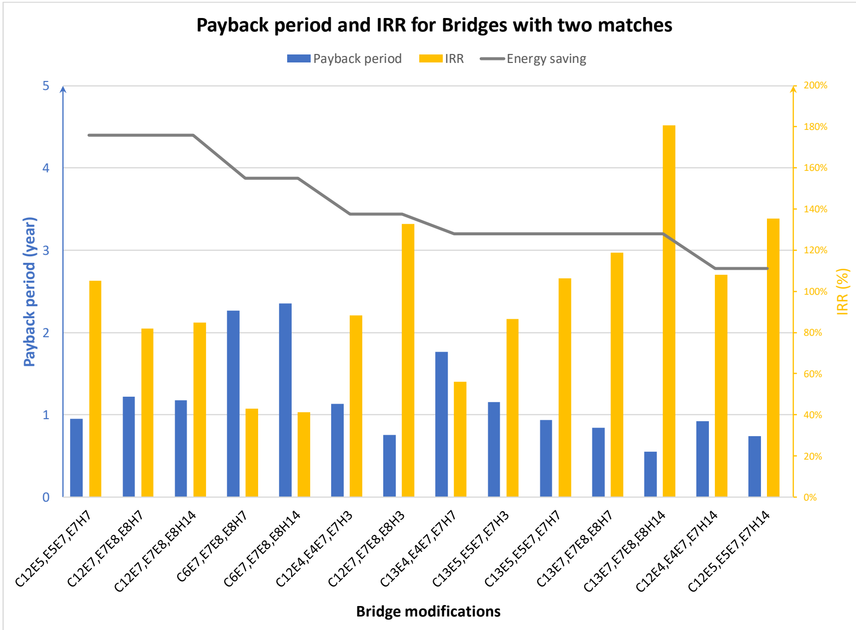

Figure 14- Payback period and IRR for Bridges with three matches

The independent Bridge modifications can be done at the same time and can be considered in the same group as one retrofit projects. The information of three retrofit projects is shown in figure 15. In the first group, C12H3 and C13H5 modifications have a heat-saving capacity of 5.1MW. The payback period (PBP) of this group is 1.1 years which is slightly higher than the individual PBP of individual Bridges (0.8 year). The internal rate of return over a period of 10 years is almost 90%.

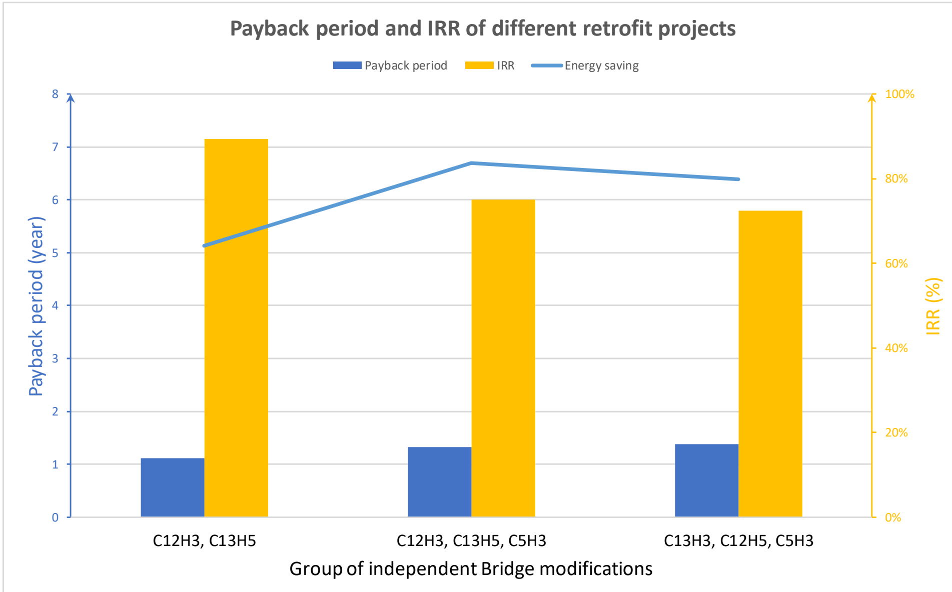

Figure 15- Payback period and IRR of different retrofit projects

These charts and figures can be created through an automated computer algorithm and presented on the dashboard. An expert user such as a process engineer with an energy specialist

5. Conclusion

The sequential design decision making Bridge framework is applied for energy analytics of a large-scale problem. The transferred energy through process operations of this case has been identified by using the ETD. The process operations with the highest impacts on the overall hot utility demand of the plant are recognized and a list of prioritized operations has been prepared. This can be a practical approach to find appropriate opportunities through an open-ended decision-making procedure. The connection table is used to identify feasible connections and the risk level associated with each one. Some streams were eliminated due to the connection constraints, which led to reduce in searching space to enumerate practical Bridges. At the last step of the framework, the payback period and Internal rate of Return (IRR) for the list of practical Bridges with one, two and three matches are calculated and presented in charts. Independent Bridges can be executed at the same time which increases the total heat saving capacity of the retrofit projects.

References:

1. (IEA), I.E.A. CO2 Emissions Statistics. 2017.

2. IEA. https://www.iea.org/reports/tracking-industry-2019. 2019.

3. Bonhivers, J.-C., et al., Energy transfer diagram for improving integration of industrial systems. Applied Thermal Engineering, 2014. 63(1): p. 468-479.

4. Bonhivers, J.-C., Nouvelle méthode d'intégration énergétique pour la rétro-installation des procédés industriels et la transformation des usines papetières. 2013, École Polytechnique de Montréal.

5. Bonhivers, J.-C., B. Srinivasan, and P.R. Stuart, New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 1–Concepts. Applied Thermal Engineering, 2014.

6. Bonhivers, J.-C., et al., New analysis method to reduce the industrial energy requirements by heat-exchanger network retrofit: Part 2 – Stepwise and graphical approach. Applied Thermal Engineering, 2017. 119: p. 670-686.

7. Bonhivers, J.-C., et al., Linking pinch analysis and bridge analysis to save energy by heat-exchanger network retrofit. Applied Thermal Engineering, 2016.

8. Bonhivers, J.-C., et al., Analysis of Heat Cascade Through Process Components to Reduce the Energy Consumption in Industrial Systems. Process Integration and Optimization for Sustainability, 2018.

9. FRAM, Bleached market kraft pulp mill, Reference and type mill (FRAM 09). 2005: Stockholm.

10. Axelsson, E., et al., Heat integration opportunities in average Scandinavian kraft pulp mills: Pinch analyses of model mills. 2006. 21(4): p. 466-475.

11. Olsson, M.R., E. Axelsson, and T. Berntsson, Exporting lignin or power from heat-integrated kraft pulp mills: A techno-economic comparison using model mills. Nordic pulp & paper research journal, 2006. 21(4): p. 476-484.

12. Bonhivers, J.-C., et al., Comparison between pinch analysis and bridge analysis to retrofit the heat exchanger network of a kraft pulp mill. Applied Thermal Engineering, 2014. 70(1): p. 369-379.