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Parametric Costing Model Suitable for Economic Assessment of Heat Recovery Projects Implied by Site-Wide Energy Analysis Methods

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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Ce mémoire intitulé :

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présenté par **Hamid Reza SHAH HOSSEINI**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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

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RÉSUMÉ

Les industries peuvent être en mesure de réduire leurs coûts de production et de contribuer à la réalisation des objectifs de réduction des émissions en augmentant leur efficacité énergétique. L'objectif des études sur l'efficacité énergétique et l'intégration dans les usines de fabrication est d'examiner comment maximiser l'utilisation des fournisseurs d'énergie sur place tout en réduisant la dépendance à l'égard des sources d'énergie extérieures (par exemple, le pétrole, le gaz, le charbon, etc.).

Plusieurs approches systématiques, telles que les méthodes Pinch et Bridge, ont été proposées et développées pour détecter les opportunités associées à l'intégration croissante entre les flux de processus par le biais de la modernisation du réseau d'échangeurs de chaleur. Cependant, les efforts se sont principalement concentrés sur la définition et/ou le raffinement des outils de visualisation utilisés pour obtenir des objectifs d'économie d'énergie et trouver des projets de modernisation basés sur des critères thermodynamiques, avec peu d'attention accordée à l'évaluation économique des projets de modernisation des HEN. Cette thèse propose un modèle de coût paramétrique amélioré qui peut être utilisé pour améliorer l'évaluation économique préliminaire des projets de récupération de chaleur suggérés par les méthodes d'analyse énergétique à l'échelle du site. Pour atteindre cet objectif, les paramètres clés de conception et de coût qui ont un impact sur les coûts d'investissement totaux directs des projets et sur les économies de coûts d'exploitation totales associées sont identifiés par une analyse détaillée de divers projets recommandés par des méthodes d'analyse énergétique à l'échelle du site. À la suite de cette étape, un modèle d'évaluation économique global est proposé pour chaque type de modification du réseau d'échangeurs de chaleur, qui met en corrélation les coûts d'achat et d'installation des éléments d'équipement associés à l'intérieur et à l'extérieur des limites de la batterie du projet. De plus, pour montrer que la nouvelle méthode d'évaluation globale des coûts est un outil fiable qui fournit à l'analyste des données économiques plus précises pour l'aider dans le processus décisionnel ouvert de la modification du réseau d'échangeurs de chaleur, un exemple a été donné pour comparer l'évaluation économique globale des projets à la méthode traditionnelle d'évaluation des coûts abordée dans la documentation sur les méthodes d'analyse énergétique à l'échelle du site, qui ne tient compte que du coût de l'échangeur de chaleur.

S'il n'y a pas assez de données ou de temps pour effectuer une évaluation économique rigoureuse, des modèles de coûts basés sur des facteurs peuvent estimer le coût de l'équipement auxiliaire nécessaire à l'installation des éléments principaux en tant que pourcentage du coût d'achat de l'équipement (par exemple, HX, pompe). Cependant, deux problèmes majeurs sont associés aux modèles existants en conjonction avec diverses modifications de la topologie du réseau d'échangeurs de chaleur : (1) les facteurs de coût ne sont proposés que pour l'échangeur de chaleur, alors que les modifications de la topologie du réseau d'échangeurs de chaleur impliquent trois équipements principaux, l'échangeur de chaleur, la pompe/le compresseur et le système de tuyauterie requis pour connecter les différents modules de l'usine, et (2) les facteurs de coût de l'échangeur de chaleur ne sont pas fiables en raison de leur insensibilité aux alternatives de conception de l'équipement et à la topologie de l'usine. Ces lacunes motivent la proposition de modèles de coûts améliorés basés sur des facteurs pour chaque recommandation nommée : (i) ajout d'un nouvel échangeur de chaleur, (ii) modification d'un échangeur de chaleur existant, (iii) séparation-mélange de flux, et (iv) reséquencement d'un ou de plusieurs échangeurs de chaleur existants. En outre, les conditions d'exploitation qui influent sur la taille des équipements auxiliaires sont utilisées pour caractériser les facteurs de coût de l'échangeur de chaleur, de la pompe/du compresseur et du système de tuyauterie utilisé pour connecter deux modules de l'usine. Enfin, une comparaison est faite entre le modèle raffiné de coûts pondérés et l'approche conventionnelle existante de coûts pondérés. Ceci afin de montrer comment l'utilisation d'un bon modèle de calcul des coûts peut affecter le choix d'un décideur quant au projet économiquement réalisable parmi les projets suggérés par les méthodes d'analyse énergétique du site.

ABSTRACT

Industries may be able to lower production costs and aid in satisfying emission reduction targets by increasing their energy efficiency. Examining how to maximize the use of on-site energy suppliers while decreasing reliance on outside energy supplies (e.g., oil, gas, coal, etc.) is the goal of energy efficiency and integration studies in manufacturing plants.

Several systematic approaches, such as the Pinch and Bridge methods, have been proposed and developed to detect opportunities associated with the increasing integration between process streams through heat exchanger network (HEN) retrofitting; however, efforts have mostly focused on defining and/or refining visualization tools used to obtain energy saving targets and finding retrofit projects based on thermodynamic criteria, with little attention paid to the economic assessment of the HEN retrofit projects. This thesis proposes an improved parametric cost model that can be used to improve the preliminary economic assessment of heat recovery projects (HRPs) suggested by site-wide energy analytics methods (SWEAMs). To achieve this goal, key design and cost parameters that impact direct total investment costs (TICs) of HRPs and related total operating costs (TOCs) saving are identified through detailed analysis of diverse HRPs recommended by SWEAMs. As a result of this step, a Global Economic Assessment Model is proposed for each type of HEN modification that correlates the purchase and installation costs of HRP's ISBL and OSBL equipment items. Also, to show that the new global costing approach is a reliable tool that gives the analyst more accurate economic data to help with the open-ended decision-making process of the HEN retrofit, an example was given to compare the global economic assessment of the HRPs to the traditional costing method discussed in SWEAM-based literature, which only looked at the cost of the HX.

If there is not enough data or time to conduct a rigorous economic assessment, factored-based cost models can estimate the cost of auxiliary equipment needed to install main items as a percentage of equipment (e.g. HX, pump) purchase cost. However, there are two major issues associated with existing models in conjunction with various HEN topology modifications: (1) cost factors only proposed for HX, whereas HEN topology modifications imply three main equipment, HX, pump/compressor, and piping system required for connecting different modules of the plant, and (2) HX cost factors are unreliable due to their insensitivity to equipment design alternatives and plant topology. These gaps motivate to propose enhanced factored-based cost models for each

SWEAM's recommendations named: (i) Adding new HX, (ii) modifying existing HX, (iii) stream splitting-mixing, and (iv) resequencing of existing HX(s). Also, the operating conditions that affect auxiliary equipment's size are used to characterize the cost factors for the HX, pump/compressor and the piping system used to connect two plant modules. Lastly, a comparison is made between the refined factored-based cost model and the existing conventional factored-based costing approach. This is done to show how of using a good costing model may affect a decision maker's choice of an HRP that is economically feasible out of the projects suggested by SWEAMs.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACC	Advanced composite curve
CC	Composite curve
ETD	Energy transfer diagram
GCC	Grand composite curve
HELD	Heat exchanger load diagram
HEN	Heat exchanger network
HRAT	Heat recovery approaching temperature
HRP	Heat recovery project
HX	Heat exchanger
IMAT	Individual minimum approaching temperature
ISBL	Inside battery limit
OSBL	Outside battery limit
SWEAM	Site-wide energy analysis method
TIC	Total investment cost
TOC	Total operating cost
ACC	Advanced composite curve

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

1.1 Problem statement

In recent years, energy efficiency has emerged as a central issue for both the general public and the industry sector. At present, not only are rising energy prices a key factor, but the imperative to cut back on carbon dioxide emissions is also pushing industries to be more energy efficient[1] [2].

It is possible to start cutting down on the amount of energy that an industrial plant consumes at any time during the plant's lifespan. However, it is more cost-effective to prioritize energy efficiency from the start of the design process, so the most financially sensible choice is to incorporate energy efficiency enhancement strategies into the greenfield design of the plant from the start. Unfortunately, in most cases, the actual energy efficiency of the new plant is restricted by a lack of resources, knowledge, time, and money, as well as design requirements that are in conflict with one another [3]. Once a plant is operational, it can undergo continuous improvement in response to plant experience, shifting markets and regulations, and emerging technologies, all of which create openings to lower energy consumption [4]. Increasing energy efficiency in a plant that is already in operation can be broken down into three distinct groups: (i) improving plant’s operation, which refers to the utilization of effective strategies for managing energy consumption and plant control, (ii) retrofit of the plant, which refers to equipment items retrofit or replacement, heat exchanger network (HEN) retrofit, and site integration, and (iii) replacing the existing plant with new one, which the energy conservation incentive is not enough to make the cost of replacing a plant or process unit worthwhile [1, 5, 6] [7].

In conjunction with HEN retrofit, site-wide energy analytics methods (SWEAMs), have been shown to be highly effective in identifying heat recovery projects (HRP) in a wide range of industrial processes [8, 9]. However, despite their systematic nature, SWEAMs overlook design and cost considerations when identifying HEN retrofit projects, and in order to confidently select one retrofit project over another or assess the feasibility of a retrofit project, it is essential for HEN Retrofit projects to have a reliable design and cost estimate early in the design process. In this regard, the main motivation for this thesis is to define a rigorous cost estimation approach suitable for improved decision-making in the early design stage of a HEN retrofitting situation.

1.2 Objectives

The main objective of this thesis is as follows:

- To introduce a refined parametric costing model suitable for economic assessment of heat recovery projects implied by site-wide energy analysis methods.

The following supporting objectives have been linked to the main objective's success:

- Specific objective 1: To identify key design and cost parameters that impact the economic assessment of HRPs implied by SWEAMs.
- Specific objective 2: To introduce a factored-based cost model suitable for economic assessment of HRPs with minimum amount of input data and incorporation of good engineering judgement.

1.3 Thesis organization

There are five chapters in this thesis. In chapter 2, after looking at the literature about site-wide energy analytics methods (SWEAMs), we look at the literature to see how the design and cost evaluation of heat exchanger network retrofit projects based on insight-based techniques have changed and to find gaps in the body of knowledge. In this chapter, the project's hypotheses are also presented. Chapter 3 describes the methodology used to achieve the objectives. The first part of Chapter 4 is a summary of the articles and how they relate to each other. The second part of this chapter is about a synthesis of the results that are found while demonstrating the methodology. Finally, chapter 4 provides general conclusions.

The articles submitted to scientific journals as a result of this research project are presented in Appendices A and B.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Methods developed during the last several decades to minimize external energy consumption in industrial processes by boosting heat exchange between process streams may be classified into three broad categories: (i) insight-based methods, (ii) optimization-based methods, and (iii) hybrid methods[10] [11]. Insight-based methods, as the name suggests, use graphical tools like composite curves (CCs), grand composite curves (GCCs) [2], energy transfer diagram (ETD) [9] and etc. to find minimum energy targets with regards to stream individual minimum approaching temperature (IMAT). Then, with the objective of getting as close to the energy consumption targets as possible, each insight-based method employs a variety of data and methods to complete the essential stages for identifying topological modifications. In Section 2.2, we'll look at how insight-based approaches, Pinch and Bridge methods, have evolved in retrofit situations.

All insight-based methods, called site-wide energy analytics methods (SWEAMs), result in an inadequate definition of heat recovery projects (HRPs) [12]. This is due to the fact that these approaches rely only on the first and second thermodynamic rules to identify and characterise each HRP based on external energy saving potentials [2]. However, in order to find a feasible HRP, decision makers must specify the risk level of new heat exchanging between process streams as well as the economic consequences of each HRP, in addition to energy-saving key performance indicator (KPI) selection criteria. To solve these concerns, insight-based methodologies must be employed in conjunction with a framework called the site-wide energy analytics framework (SWEAF) [12]. In section 2.3, we'll look at the literature to see how the design and cost evaluation of HEN-based HRPs based on insight-based techniques has progressed.

The heat exchanger (HX) is one of the most costly items of field material suggested expressly or implicitly by many of the HRPs recommended by insight-based techniques [13]. HRP profitability assessment at the beginning of the design stage may be significantly impacted by an accurate estimate of the HX's purchase cost [14]. Consequently, in section 2.4, the HX cost estimation approaches are reviewed when there is insufficient data to estimate the HX's detailed cost. In addition, this section reviews the factored-based cost models used to estimate the auxiliary equipment items required for the erection, installation, and interconnection of the new HX with other modules of the existing plant in order to make it operational.

Prior to reviewing the literature mentioned above, it is necessary to explain why this chapter does not include a review of the development and application of optimization-based and hybrid techniques in HEN retrofit situations.

During the last three decades, several HEN retrofit techniques based on optimization-based models proposed by Ciric et al. [15] and Grossman et al. [16] have been investigated and presented [4]. While the majority of mathematical techniques are rigorous, it is still difficult to obtain a decent optimum solution for huge problems due to the prevalence of non-convexities. Additionally, the approaches require an adequate initialization in order to get a realistic solution, and their solutions entail mostly heat exchanger adjustments and relocations, which may be impractical and economically unfeasible [17].

Hybrid methods were developed to use the strengths of insight-based method (Pinch approach) and optimization-based methods to define an automated and interactive approach [18]. This approach does not seek a global optimum but enables the identification of feasible strategies for lowering energy usage. Nonetheless, hybrid techniques fail to uncover significant changes even in straightforward settings. To limit the number of instances in which the technique is ineffective, new heuristic principles have been devised [19].

2.2 Site-wide energy analysis methods (SWEAMs)

2.2.1 Pinch-based methods

Tjoe and Linnhoff [20] were the first to investigate the feasibility of using the Pinch approach for HEN retrofitting. Their technique is separated into two main stages: (i) the targeting stage, and (ii) the design stage. In accordance with the subsequent steps, the targeting stage established targets for HEN external energy savings and required capital costs: (1) for all hot and cold process streams, supply and target temperatures as well as heat capacity flows must be gathered, (2) by choosing the streams' Individual Minimum Approaching Temperatures (IMATs), CCs, GCC, or Problem Table Algorithm used to evaluate the minimum hot and cold utility demands, (3) with regard to Heat Recovery Approaching Temperature (HRAT), the assumption that in an ideal HEN design the HXs are placed vertically (Figure 2.1) on CCs provides the opportunity to estimate the minimum overall HXs' area using Equation 2.1.

$$A_{target} = A_1 + A_2 + \ldots + A_n = \sum_{i}^{intervals} \frac{1}{\Delta T_{LM}} \left[\sum_{j}^{stream} \frac{q_j}{h_j} \right]_i$$ Equation 2.1

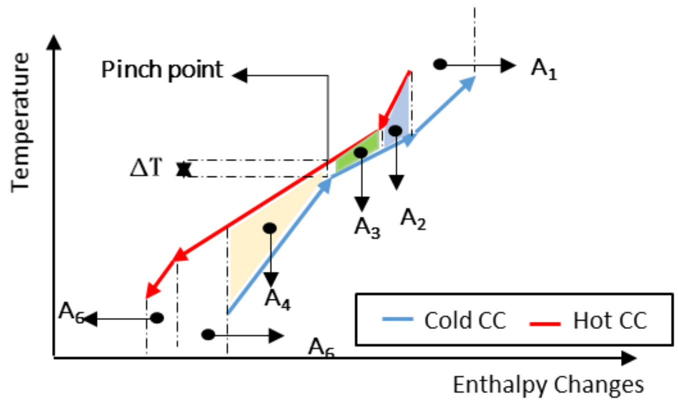


Figure 2.1.Vertical heat exchanging between hot and cold CCs.

Where q_j and h_j represent heat exchanging flow and overall film and fouling coefficient associated with temperature interval i and stream j. (4) Using various IMATs, repeat steps (2) and (3) to plot the ideal Energy saving – Investment curve. The design stage is accomplished by applying three basic pinch technology principles: no cross-pinch temperature heat exchange between energy supplier and demand process streams, and no external cooling and heating of hot and cold process streams above and below the pinch point. This approach served as the foundation for several following investigations on HEN retrofitting using pinch technology.

Polly et al. [21] stated that experience has shown that Tjoe and Linnhoff's strategy of using the stream heat transfer coefficient to find the required new HX area and thus capital cost target required to meet energy saving targets can lead to incorrect design initialization, which can mislead decision makers to do or not do design part of the HEN retrofitting. It was stated that the heat transfer coefficients are currently estimated using the performance of existing HXs for thermal exchange between two streams. This is acceptable if there is only one HX on the stream. However, if there are multiple HXs on the stream, each with a different heat transfer coefficient, there is no systematic way to drive a single value that is representative of the stream specifications. This reality is complicated by the fact that the heat transfer coefficient assumed in the targeting stage may not be consistent with that finally achieved in the HX detail design. This is due to the fact that HXs are designed based on the allowable pressure drop rather than the assumed heat transfer coefficient, or to achieve a specific coefficient. Based on this fact, they created a HX area calculation based on stream pressure drops that offers consistency between the investment cost target and the needed cost value that would be computed after designing improved HEN.

Carlsson et al. [22] proposed a new computer-based retrofit targeting model suitable for improving the investment cost estimation of HEN retrofit modifications, which was previously based solely on the HX area assuming vertical heat exchange between hot and cold composite curves. The new targeting model has the capability find near optimum HEN retrofit project prior to design stage through taking into account cost implications associated with the HX type and related material of construction, the cost of the piping system required to connect new HX into other modules of the plant when thermal integrity is required between two parts of the plant that are far apart, as well as the cost of the pump/compressor required to eliminate new pressure drops associated with friction losses in new piping system and new HX.

Reisen et al. [23] presented a novel approach, termed path analysis, that picks and analyses fractions independent of the remaining network using heuristics or an algorithm in order to minimize significant effort in HEN retrofit design introduced in reference [20] when employing Pinch technology. The key elements of the network that should be adopted in a refit scenario can be found by comparing all fractions based on qualitative KPI's like controllability, flexibility, and complexity, etc., as well as quantitative KPIs like energy saving targets and required investment cost. While it is true that using the path analysis approach decreased the complexity of retrofit design, several issues might be regarded shortcomings of this method: (i) Increasing the number of process streams and exchanger units increases the number of potential subnetworks in Path Analysis. In this case, producing Investment-Saving curves for each subnet would take a long time, (ii) Ranking subnetworks based on complexity, practicality and controllability as well as risk issues highly depending on users experience, therefore bad decisions might have devastating implications.

Nordman and Berntsson [24] presented a new graphical tool called Advanced Composite Curves (ACCs). This graphical tool may be used to determine the precise temperature domain within which current process-process HXs, as well as hot and cold utilities, are operating. Prior to HEN retrofit design, it would be feasible to examine the economic and technical implications of HEN topological adjustments. ACCs include four curves above the temperature Pinch point known as the Hot Utility Curve (HUC), the Extreme Heating Load Curve (EHLC), the Theoretical Heating Load Curve (THLC), and the Actual Heat Load Curve (AHLC), and four curves below the temperature Pinch point known as the Cold Utility Curve (CUC), the Extreme Cooling Load Curve (ECLC), the Theoretical Cooling Load Curve (ACLC). The following qualitative opportunities for HEN retrofitting can be extracted based on the location of AHLC in relation to EHLC and THLC:

- AHLC lies close to EHLC: This instance illustrates how heaters are situated outside of the process pinch temperature range in a high temperature region. This is the best example of design based on a greenfield approach because it demonstrates how heat exchangers can be placed vertically in the composite curve to use the maximum amount of HXs in a system. According to a retrofit perspective, this is (Figure 2.2) the worst scenario possible because an unloading heater requires a large area process-process heat exchange unite. This is due to a reduced driving force between hot and cold streams in high temperature regions.
- AHLC lies close to THLC: Heaters placed in a low temperature domain near the process pinch point temperature represent this situation. This is the worst case of grass-roots design because it shows that we have crisscrossing matches in the system, which means that we have more area of HXs installed than is theoretically required. This is the best case for retrofitting (Figure 2.3) because by unloading the heater, we can place the process-process heat exchange unit in the most cost-effective area. This is due to proper deriving force.

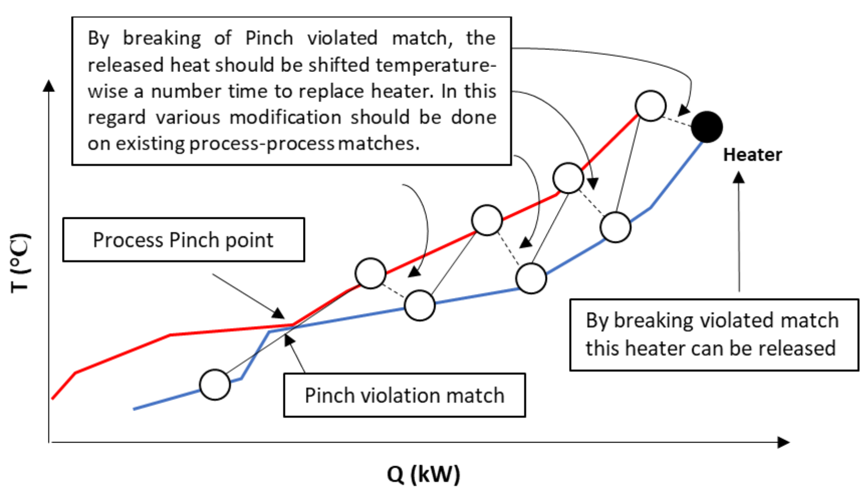


Figure 2.2. CCs related to the situation where AHLC is close to EHLC.

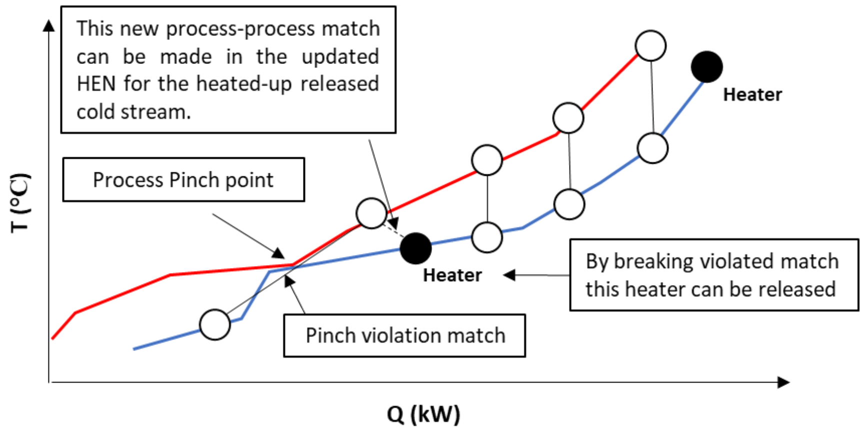


Figure 2.3. CCs related to the situation where AHLC is close to THLC.

- ACLC placed above the AHLC in some regions: This situation indicates that the cooler(s) are operating in the higher temperature domain of the heater(s), allowing the heater and cooler to be unloaded and process-process heat exchange to be used instead.

Additionally, this graphical tool enables the user to determine the ideal temperature setting for integrating new process units into an existing company. The combined heat and power system, the heat pump unit, and the bio-refinery unit are all examples of processes that may be integrated with existing plants relative to the additional energy saved by retrofitting existing HEN [25].

- AHLC lies close to THLC: Integrating a gas or steam turbine is a cost-effective option. This is due to the fact that effluents can be used instead of fresh steam in heaters located in the low temperature domain.
- AHLC lies close to THLC and ACLC lies close to TCLC: Integrating a Heat Pump (HP) is a cost-effective choice. This is possible because HP's condenser can be placed in the low temperature domain above the pinch point instead of a heater and HP's evaporator can be placed below the pinch point instead of a cooler in the high temperature domain.

When this graphical tool is chosen for HEN retrofit analysis, the following deficiencies can still be found, despite the fact that ACCs fill many gaps in the body of prior knowledge: (i) ACC does not indicate how different streams' heat transfer coefficients differ, (ii) ACC cannot address available pressure drop for different retrofitting options, (iii) ACC cannot address forbidden matches, and (iv) ACC cannot address the distance between streams and the consequences of piping.

Li and Chang [26] proposed a novel systematic pinch-based approach suitable for improving the design phase of HEN retrofitting, which was previously based on heuristics. The proposed retrofit procedure can be implemented in accordance with the steps outlined below:

- Step 1: Regarding new stream IMATs, utilizing GCC, CCs, or a problem table method to determine the minimal external heating and cooling requirements, as well as the hot and cold Pinch temperatures.
- Step 2: Identifying and removing cross Pinch matches from the existing HEN grid diagram. Then divide its thermal duty into two portions on the process streams: above and below the process pinch temperature.
- Step 3: The split thermal loads of each stream that are not matched and are on the same side (i.e., below or above the pinch) should be combined depending on pinch-based parameters taken into consideration for the best designing HEN in a greenfield situation [2].
- Step 4: To simplify the modified HEN, break the heat load loops above and below the pinch temperature, and recalculate the heat responsibilities, supply, and target temperatures of the relevant matches in loops [2].

Lai et al. [27] claimed that the CCs which is employed to set energy targets and Pinch temperature do not represent the temperature intervals of the individual streams, thus a grid diagram is used adjacent CCs for the diagnosis of Pinch violation matches and the design of improved HEN. Grid diagrams are not drawn to any specific temperature or enthalpy scale, therefore HRP diagnoses must be used in conjunction with iterative computations to assess the enthalpy balance, temperature viability, and area implications of each individual HX match. To address the aforementioned shortcomings, Lai et al. provide a novel single graphical tool that allows for the simultaneous diagnosis of inefficiencies and retrofit design of an existing HEN by visualising temperature-enthalpy associated with individual streams rather than composite streams. In the diagnosis phase, it is necessary to plot the STEP linked with the existing HEN and to identify the pinch temperature using CCs or a problem table algorithm. This phase provides information regarding the prospective and targeted streams that may be impacted by the retrofit design. The studies mentioned provided the foundation for employing pinch technology for HEN retrofit targeting and design. However, they have not been able to fill the holes that have arisen as a result of critical analysis:

- Developments in graphical tools haven't been able to introduce a single map of heat degradation between hot utility and cold utility caused by HEN and process units suitable for decision-makers looking for energy-saving projects [4].
- Pinch-based approaches use heuristics in the HEN retrofit design stage and fail to identify systematically the type of HRP required to reduce HEN external heating and cooling demands. Inserting new HXs, changing and/or relocating existing HXs, and finally stream splitting comprise HEN HRPs.
- After installing HRPs, pinch-based techniques fail to find new supply and target temperatures of existing HXs and balance the rest of the HEN thermodynamically.
- Pinch-based techniques lack the capacity to automatically create HEN HRP ranges that are consistent with utility energy savings ranges.

In this context, Bonhivers and Stuart [9] developed the Bridge approach to overcome all of the shortcomings indicated above caused by employing Pinch-based methods for HEN retrofit.

2.2.2 Bridge method

Bonhiver et al. [9] introduced an energy transfer diagram (ETD) as a novel graphical tool for site-wide energy analysis. The ETD illustrates heat degradation between hot utility and environment caused by process operations and current HEN. This tool gives decision-makers a worldwide perspective of heat savings opportunities, allowing them to determine the path of HEN-HRPs named Bridges and the minimal HEN external heating and cooling requirements related to stream IMATs. According to Figure 2.4, the shape of the ETD would be rectangular if the energy that is transferred from the hot utility is not converted into another form of the energy by the process units. This would indicate that energy is conserved at each temperature level, and the global process curve's maximum would equal the minimum utility usage achieved by HEN retrofitting. In addition, changing existing process operation unit(s) and/or replacing existing ones with new technologies resulted in a reduction of the minimum hot utility demands caused by HEN retrofitting, which corresponds to a decrease in the maximum point of the process operation curve.

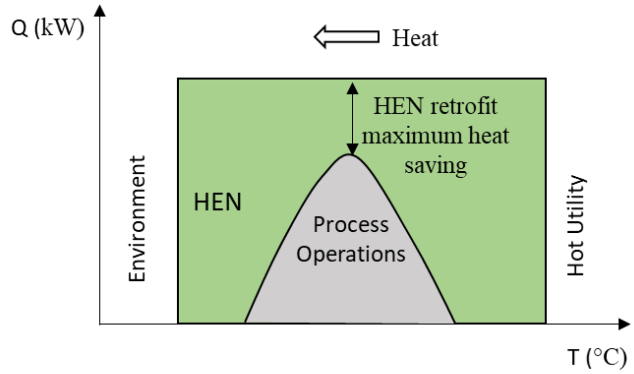


Figure 2.4 Energy transfer diagram (ETD) and greatest probable energy savings with HEN retrofitting

ETD is only capable of indicating where energy savings are possible on the HEN; it is not capable of enumerating and quantifying primary and compound bridges. In another research, Bonhivers et al. [28] proposed a numerical tool called a network table to quickly enumerate and evaluate bridges which are connections between energy suppliers of cooler(s) and energy receptors of the heaters.

None of the ETDs or network tables could identify a viable configuration as a consequence of HEN adjustments, which include decreasing or increasing the thermal duty of existing HXs, stream splitting, and moving existing process-process and/or process-utility HX units. To address these gaps, Bonhivers et al. [29] introduced a new graphical tool called the Heat Exchanger Load Diagram (HELD), which can recognize changed HEN that correlates to HRPs enumerated and assessed through network table. Additionally, this study clarified the relationships between pinch-based tools such as CCs and GCs, ETD and HELD, and proposed and applied a method for HEN retrofit that combines insights from pinch analysis and Bridge's tools. The proposed synthesis fills a gap in pinch analysis, and its concepts can aid in the development of software for HEN retrofit.

According to Bonhivers et al. [30] study, retrofitting HEN is a sequential process that comprises of three major stages: (i) identification of possible bridges. This step requires the use of both the ETD and the network table to identify and quantify all thermodynamically possible bridges. Besides each Bridge's energy savings potential, engineering study is necessary to determine the amount of risk associated with new connections proposed by Bridges. (ii) designing modified HEN. This stage identifies modified HENs associated with the bridges specified in step 1 by using existing HEN representations and HELD. (iii) modification to reduce economic consequences. This step requires additional study of the modified HEN obtained in stage 2 in order to lower the needed investment cost. The following are the primary kinds of improvements that may be made to lower the investment cost: (1) redistribution of load between process-hot utility and/or process-cold utility HXs; (2) decrease in the number of exchangers. At this step, a few examples were offered to help develop a global picture of the many circumstances that decision-makers may confront when attempting to cut investment costs.

One of the shortcomings in the ETD presented by Bonhivers et al. is that it lacks the capacity to quantify the bridges that may be visually depicted on this diagram. This gap was filled by a research published by Walmsley et al. [31]. In addition, the ETD's representation was modified in this research to highlight which parts of the diagram correspond to energy supply/demand streams. Another section of this work developed a surplus-deficit table for large HEN retrofit challenges where discovering and measuring adjustments with reduced ETD is difficult.

Finally, Bonhivers et al. [29] provided the most recent version of the Bridge method for HEN retrofitting, outlining benefits and drawbacks of the pinch and network pinch approaches, as well as how the Bridge technique may aid in their improvement. It was shown that using the Bridge technique may aid in the improvement of heuristics for generating additional heater-cooler pathways suited for network pinch approaches.

According to Lal et al. [32], HENs that have a variety of hot and cold process streams as well as hot and cold utility demands have a variety of various retrofit design alternatives available to them. As a result of this, in order to identify a manageable amount of design options, they proposed automated Bridge analysis. This analysis has the capability to reduce retrofit Bridge options by taking into account constraints related to thermodynamics, investment cost, payback periods, piping, and plant layout. Using these limitations provides the opportunity for the decision maker (or makers) to address difficult HEN retrofit problems quickly. The utilisation of the suggested strategy at the Kraft pulp mill, which presently consists of 54 HXs and 73 hot and cold process streams, resulted in a reduction in the number of prime and compound Bridges from 10^{20} to 15.

Walmsley et al. [33] present a new automated retrofit methodology that employs a heat surplus-deficit table in conjunction with the Bridge approach developed by Bonhivers et al. [28] to find, quantify, and compare HEN adjustments that connect cooler supplier(s) and heater receptor(s). Excel can be used to implement the proposed strategy, which would result in the creation of a cost-effective tool that can solve complex HEN retrofit issues in a matter of seconds. The efficiency of the method was evaluated by taking into account a large refinery HEN that consists of 24 coolers, 18 process-process HXs, and 4 heaters in order to locate a retrofit opportunity that involves the installation of three new HXs and results in a profit of 752 000 USD per year with a payback period of 1.6 years that is reasonable.

2.2.3 Design and cost assessment of HEN-based HRPs implied by SWEAMs

As noted in the chapter's introduction, this section will review the design and cost assessment of HEN-based HRPs suggested by Pinch and Bridge methods.

Tjoe and Linnhoff [20] used the suggested pinch technique for HEN retrofitting connected with the Aromatic plant, which has four hot streams and five cold streams, five process-process heat exchanging units, three coolers, and two heaters. In terms of new stream IMAT, it was discovered that in order to reach energy savings targets, one new HX must be introduced while the thermal duty of two current HXs and two process-hot/cold utility HXs must be lowered. It was believed that, for units that must be run on reduced thermal duty, it is feasible to discharge part of the area of existing HXs and that the economic effect of HEN retrofitting only comes from purchasing new HX, as calculated from Equation 1.

$$C_{HX} = 8600 + 670A^{0.83}, \quad for\ 10 < A < 300\ m^2 \qquad \text{Equation 2.2}$$

In this analysis, it was also believed that TOCs savings induced by the installation of HRPs are proportional to the quantity of fuel used to generate the hot utility stream, and savings related with lowering cold utility needs were neglected.

To identify economically feasible HEN-HRPs, Ahmad et al. [34] recommended that the current simple cost model for assessing capital costs be expanded to include the influence of non-uniform construction materials and HX types, as well as operational pressure on the purchase price of new HX. Through illustrative case studies, it was shown that a rigorous cost model can accurately estimate the profitability of retrofit projects in a way that a basic model cannot.

The accuracy of defining energy and cost targets before to designing a modified HEN is highly reliant on the cost model used in calculations. Hall et al. [35] provide a cost model using vendor's data from 1983 that enables designers to account for changes in HX type, building material, and operating pressure using a series of HX purchase cost models shown in Table 2.1. Furthermore, it was stated that the suggested cost models can account for the cost implications connected with auxiliary equipment items necessary for installing the new HX unit and making it operational. Furthermore, it was thought that the existing pump/compressor could overcome the additional pressure loss generated by the installation of the new unit. In an illustrative case study, it was shown that the suggested adjustment to current cost models significantly improves the accuracy of cost targets when applied to networks with non-uniform exchanger characteristics.

Table 2.1. Installed HX cost laws for different construction materials and operating pressure.

HX type	Construction material (shell/tube)	Cost model (1983)	Operating pressure CS-shell/CS-tube (bar)	Cost model (1983) CS-shell/CS-tube
Shell and tube	CS/CS	$C_{HX}(USD) = 30800 + 750A^{0.81}$	10/10	$C_{HX}(USD) = 30800 + 750A^{0.81}$
	SS/SS	$C_{HX}(USD) = 30800 + 1644A^{0.81}$	10/35	$C_{HX}(USD) = 30800 + 890A^{0.81}$
	CS/SS or SS/CS	$C_{HX}(USD) = 30800 + 1339A^{0.81}$	35/35	$C_{HX}(USD) = 30800 + 1089A^{0.81}$
	TI/TI	$C_{HX}(USD) = 30800 + 4407A^{0.81}$	10/60	$C_{HX}(USD) = 30800 + 983A^{0.81}$
	CS/TI or TI/CS	$C_{HX}(USD) = 30800 + 3349A^{0.81}$	60/60	$C_{HX}(USD) = 30800 + 1438A^{0.81}$
	SS/TI or TI/SS	$C_{HX}(USD) = 30800 + 3749A^{0.81}$	35/60	$C_{HX}(USD) = 30800 + 1201A^{0.81}$
Plate and frame	SS	$C_{HX}(USD) = 1950A^{0.78}$	-	-
Spiral plate	SS	$C_{HX}(USD) = 19687A^{0.9}$	-	-

Carlsson et al. [22] utilized their costing technique that includes HX, piping and pump purchase cost as well as maintenance cost to estimate the economic viability of Pulp & Paper mill HEN retrofit projects indicated by pinch technology to demonstrate how a new costing model might shift the order of projects that have a shorter payback time when compared to the results of a simple costing model. The cost of each HEN modification project is divided into two parts: (1) HX area-dependent part, (2) Fixed cost which is dependent on piping and other auxiliary cost. In another study, HEN retrofit of Aromatic plant is used as an exemplary case study by Reisen et al. [23], to assess their retrofit technique named Path analysis. In this investigation it was believed that purchasing a new HX just implies cost, and the following parametric cost equations were applied:

$$HX\ purchase\ cost\ (Dfl): 24 \times 10^3 + 1.9 \times 10^3\,(shell\ area\ (m^2))^{0.83} \qquad \text{Equation 2.3}$$

$$Hot\ utility\ cost\ (Dfl/year): 0.177W\,(kW)$$

$$Cold\ utility\ cost\ (Dfl/year): 0.02W\,(kW)$$

Asante et al. [36] used a crude oil HEN with 7 hot streams, 1 cold stream, 8 process-process heat exchanging units, 3 coolers, and one heater to demonstrate the strengths and disadvantages of network pinch approach appropriate for HEN retrofit over other pinch-based methods. To meet energy savings targets, following HRPs were discovered: (i) two HXs must be relocated, (ii) one

HX must be operated under new operating conditions implying higher thermal duty, (iii) one stream splitting and two new process-process HXs must be inserted into new HEN, and finally (iv) existing heaters and coolers must be operated under lower thermal duties as a result of increasing heat recovery between process streams. However, it was believed that only adding a new process-process HX unit imply a cost that can be calculated using Equation 2.4 suitable for estimating purchase cost of shell and tube HXs when CS is considered as a construction material of the shell and tube sides.

$$C_{HX} = e^{\{8.551 - 0.30863[\ln(A)] + 0.06811[\ln(A)]^2\}} \qquad \text{Equation 2.4}$$

From an overall perspective, all HEN units conduct the identical calculations related to the energy and mass balance, however certain calculations are depending on the individual kind of operation, according to Nielsen et al. [37] experiences. For HX units, for example, the energy and mass balances are often independent of the heat exchanger type and corresponding construction material, whereas the design equations and pricing equations typically vary greatly depending on the exchanger model. HEN-HRPs costing has been constrained in the past by a number of simplifications. They developed a new framework to address this issue.

According to Nordman et al., [24] study, the expense of HRPs that implies raising the duty of existing HXs has so far been overlooked since it was considered that current HXs are flexible enough to be adopted depending on new operating conditions. However, in this research, they demonstrated via illustrative case studies that new areas must be added to existing units or new HX must be put in series with existing units in order to meet new increased thermal load. Equation 2.5 was used in their calculation when estimating the purchase cost of a new unit, while Equation 2.6 was used when estimating the cost of expanding the area of existing units.

$$C_{HX}(USD) = 50000 + 500A \qquad \text{Equation 2.5}$$

$$C_{HX}(USD) = 25000 + 500A \qquad \text{Equation 2.6}$$

Bengtsson et al. evaluated the feasibility and economics of utilizing excess heat detected by ACCs and quantified by Matrix software for HEN retrofitting of the Swedish Skoghall mill, which is integrated with both chemo – thermo mechanical pulp effluent and kraft mill. In addition to the HX area, the HX type and construction material, fouling tendency of streams, correct heat transfer coefficients, and distance between streams are taken into consideration by the Matrix software before determining which HRP is the most cost-effective option. The Equation 2.7 provides the cost information that is utilised in the assessment of projects. This study did not take into account the financial repercussions that would result from relocating HXs or the pipework that would be necessary for stream splitting and mixing.

$HX\ cost\ (USD)$: $40000 + 400A(m^2)$ Equation 2.7

EnhancedHXcost (USD): $10000 + 400\text{A}(\text{m}^2)$

Piping(USD): 350L(m)

Oilprice: 19.1E(MWh)

Electricity Price: 21E(MWh)

Axelsson et al. [38] investigated the economic gains that could be made by intensifying the thermal integration of a modern magazine paper mill and making use of the steam surplus in one of four different ways. These ways include (1) Finding a user for purchasing the mill excess steam; (2) delivering it to the plant district heating system; (3) using a condensing steam turbine to generate electricity; and (4) blowing it out to the atmosphere to reduce plant cooling demands. The equation displays the cost data that was utilized in the process of assessing the economic effects of the HEN thermal intensifications that were made by a reduction in the streams' IMATs. The economic evaluation of this study did not take into account the budgets that would be necessary for increasing – decreasing the area of the existing process - process and process - utility HXs. It also did not take into account the stream splitting-mixing that would be implied after inserting new HXs in order to balance the modified HEN thermodynamically.

$HX\ cost\ (USD)$: $10000 + 324A^{0.91}(m^2)$ Equation 2.8

Piping cost (USD): 670L(m)

A year later, Axelsson et al. [39] explored the technical and economic repercussions of enhancing lignin extraction and/or power generation using steam surplus created by increasing heat integration in Scandinavian pulp mills by reducing IMATs and removing pinch violations. They claimed that existing HXs are flexible enough to be used in situations where it is required to have higher and/or lower duty demands, and that the cost data used for estimating HEN retrofit projects were extracted from real experiences gained by Chalmers Energy Group due to doing many real projects and working with a pulp and paper consultant named AF Celpap.

Nordman et al. [40] chose another HEN from a pulp and paper mill to look at the economic consequences of retrofit projects to show how important it is to think about the HEN topology when HRPs are costed. It was shown that Cost modelling based on the purchase price of new HX isn't reliable. They found projects that need less new HX area but because of long distances between streams, the sum of the HX cost and the investment cost for purchasing and installing the piping system and pump to eliminate new pressure drops is much higher than for projects that need more area but require shorter piping system. This is what they said after looking at the results. They concluded from these findings that, when adjustments to the pinch technology used to identify retrofit projects were beneficial, detailed HRPs costing models were applied to account for the HEN's topology.

Axelsson et al. [38] investigated the HEN of a modern magazine paper mill from the standpoint of energy savings prospects and associated economic effects. For the first time, they account for the effect of HRPs on power savings resulting from external cooling demand reductions met by cooling towers. It was discovered that depending on the cost of power, these electricity reductions may exceed the operational cost savings associated with reduced hot utility consumption. Additionally, in another research, Axelsson et al. analyzed two models of Scandinavian bleached market pulp mills for heat integration potential that result in steam excess that may be utilized to increase power output through steam turbines and/or remove additional lignin from wood chips. Economic calculations were made in this research using equipment cost data given by the consultant, but no indication was made of the level of detail considered. The process of identifying HRPs by applying pinch-based approaches to a variety of case studies has been continued by the following researchers: Nordman et al. [41] evaluated the efficacy of ACCs on a kraft pulp mill; and Olsson et al. [42] evaluated the effectiveness of employing ACCs to generate more steam for the purpose of extracting more lignin and/or producing more power, Becker et al. [43] used pinch technology to assess the HEN of a mechanical pulp mill in order to identify opportunities for heat pump integration; Hackl et al. [44] used total site analysis to provide new HEN between five existing chemical companies in order to reduce external heating and cooling demands; and Fornell et al. [45] used ACCs to assess energy savings potentials in a Swedish pulp mill in order to identify additional steam suitable for integration with an ethanol production plant, which has a high energy demand. However, when their economic analysis was compared to other costing models previously published to establish the economic feasibility of HRPs, there were no gains. In conjunction with the Bridge method, the attempts were only made to develop and modify graphical and numerical tools that were suitable for identifying energy integration measurements that caused a reduction in plant energy demands. No emphasis was placed on improving the design and costing phases of the projects [12].

2.3 Primary design and costing of HX

Among different cost estimation tools and methods, ASPEN Process Economic Analyzer (APEA) is the most reliable cost estimator because the models that are utilized are produced by a team of cost engineers from data obtained from Engineering, Procurement, and Construction (EPC) businesses (also known as contractors) and equipment manufacturers, and then tested in real-world scenarios [46]. APEA, on the other hand, requires additional information for cost estimation than accessible data at the early design stages of HRPs implied by SWEAMs. Thus, alternative expedient costing approaches that estimate the cost of HX based on calculable design variables during the preliminary design stage must be used. These methods include the following: (i) cost-to-capacity or power law estimation using reference cost data from other studies and industrial reports; (ii) expeditious parametric cost correlations; and (iii) graphs depicting the cost of HX as a function of design variables (e.g., Area of heat exchanging) [46, 47]. Table *2.2* contains the review of the released HX parametric cost models which is the focus of this part, which was allotted for that purpose in light of the overall context of this research. This table provides a characterization of each model based on the following criteria: (1) the type of mathematical formulation; (2) the year of publication and, as a consequence, the related Chemical Engineering Plant Cost Index (CEPCI); and (3) the potential of each model to be adapted based on changes in HX type, construction material, and operating pressure In this table, A represents the heat transfer area, while fm and fp are correction factors that account for variations in construction material and operating pressure.

Table 2.2 Overview of the widely used HX parametric cost estimates models.

<table>
<tr><th>Author of HX parametric cost model</th><th>Reference year</th><th>Formulation</th><th>specifications</th></tr>
<tr><td>Corripio [48]</td><td>1995 (CEPCI=381.1)</td><td>$f_p[e^{\{k_1+k_2\times[ln(A)]+k_3\times[ln(A)]^2\}}]$</td><td rowspan="5">- Despite the HX cost models' accuracy, all five models can be used to estimate the cost of shell and tube HXs, which can be classified according to their rear end type as fixed head, floating head, or U-tube.
- Corripio model and Smith model do not provide cost data when it is necessary to cost shell and tube HXs classed as Kettle reboiler, Bayonet, and thermosiphon reboilers.
- Smith model is only viable for pricing when the estimated size of shell and tube HXs is larger than $1100\ m^2$.
- Despite the Corripio and Smith models, the remaining costing models can be used to estimate the purchase costs of the new HX classed as a Plate HX.
- For calculating the cost of an air cooler HX, the Corripio and Towler models cannot be employed. Also, if the impact of changes in operating pressure and air cooler tube construction material on base cost is important to decision makers, the Turton cost model should be used.
- In the case of special HXs such as double pipe, multiple pipes, scraped wall, spiral tube, and spiral plate, the literature review indicated that the nearly Turton cost model is the preferred choice because it not only covers the appropriate range of heat transfer area but also allows for adjustment for a wide range of HX construction materials and operating pressures.</td></tr>
<tr><td>Smith [13]</td><td>2000 (CEPCI = 394.1)</td><td>$f_m f_p[a\left(\frac{A}{b}\right)^n]$</td></tr>
<tr><td>Turton [49]</td><td>2001 (CEPCI = 394.3)</td><td>$f_m f_p[10^{\{M_1+M_2\times log(A)+M_3\times[log(A)]^2\}}]$</td></tr>
<tr><td>Towler [50]</td><td>2010 (CEPCI = 532.9)</td><td>$f_m f_p[a+bA^n]$</td></tr>
<tr><td>Seider [46]</td><td>2013 (CEPCI = 567)</td><td>$f_m f_p[e^{\{N_1+N_2[ln\,(A)]+N_3[ln(A)]^2\}}]$</td></tr>
</table>

The size, type, and material of construction HX are three factors that must be determined for the primary costing of HXs, according to a critical study of the HX parametric cost equations. Table *2.3* illustrates how to pick unfired HX for use as process-process and process-utility heat exchangers based on major parameters such as operating temperature and pressure, fluid characteristics, size range, and cost [51].

Table 2.3 Primary guideline suitable for selecting HX type

Criteria	Type of Heat Exchanger				
	Shell and Tube	Plate	Double Pipe	Scraped surface	Spiral plate
Max. pressure (bar)	550	30	40	40	20
Temperature range (℃)	-200 to 700	-200 to 980	-200 to 700	Max. 315	Max. 400
Area range/unit (m^2)	5 - 1000	Up to 10000	0.25 – 200	2 - 20	0.5 - 350
Corrosion risk	Poor	Good	Good	Fair	Good
Fouling risk	Very poor	Very good	Fair	Very good	Good
Duty change after installation	Very poor	Good	Very poor	Very poor	Very poor
Viscose flow	Very poor	Good	Poor	Fair	Good
Heat sensitive fluids	Very poor	Good	Poor	Very good	Good
Solids flowing	Very poor	Poor	Fair	Very good	Good
Gases	Good	Very poor	Good	Very poor	Fair
Phase change	Good	Very poor	Good	Very good	Good
Maintenance ease	Poor	Very good	Fair	Poor	Good

Table 2.3 shows that shell-and-tube HXs are the most versatile exchangers for a wide range of operating pressures and temperatures. Additionally, because of the possibility of fouling, compact heat exchangers are typically favoured for non-fouling applications. If the user is convinced by other design criteria to use the shell and tube HX, the fluid with the highest fouling potential should be placed on the tube side for ease of cleaning. For fouling services, scraped surface and plate heat exchangers are preferable. Even at comparable low velocities, the flow pattern in these HXs creates a turbulence [51].

Consider the suitability of various HXs for duty changes following installation. The guidance offered in Table *2.3* demonstrates that unit expansion for higher thermal needs is often possible using plate HXs. surface scraped HXs is indicated for heating and cooling heat-sensitive items. This is because the scraper blades continuously remove and renew the film, preventing products from remaining on the heat transfer surface for a long time. When slurries, suspensions, or pulps are present, Table *2.3* proposes that spiral plate HXs be used. This is because the single curving channel and the presence of spacer studs in this type of HX provide a rigid flow path that ensures turbulent flow regimes even at low velocities [51].

With so many aspects to consider when selecting a material of construction for field material items, the user must decide which criteria are most important. Thermal efficiency, affordability, availability, corrosion resistance, cleanability, and durability are all factors to consider. The user must next consider the advantages and disadvantages of the solutions that best fit their priorities, as there is usually more than one good option. For example, the best heat transfer material for shell and tube HX may not be sanitary enough for a certain application, or the most corrosion-resistant alternative may be out of reach financially. As a result, there is no single table that can consider all the factors that can provide primary guidance and the final selection of construction material may necessitate consulting manufacturer's bulletins and consulting with individuals who are specialists in the field of application. A more in-depth look at the selection of materials of construction for the necessary field material items is provided in Reference [52].

It is critical to note that the existing thermal design calculations used to specify the mechanical design parameters that defined the geometry of the selected HXs are applicable to the most frequently used tubular HX types. This is because such units have historically been readily available and have been the subject of extensive research over a long period of time [51]. Non-tubular HXs, on the other hand, such as plate and plate-fin, and spiral exchangers, are highly specialised and available only from a small number of fabricators who have their own carefully chosen models and associated heat transfer and pressure loss data that have not been published.

In this regard, in this study, the HX thermal design task is to determine the size based on streams' heat transfer coefficients using the basic relationships of Equation 2.9, Equation 2.10, and Equation 2.11 [46].

$$A = \frac{FC_{p,h/c}\Delta T_{h/c}}{U\Delta T_{LMTD}}$$ Equation 2.9

$$\Delta T_{LMTD} = \frac{\Delta T_h - \Delta T_c}{\ln(\frac{\Delta T_h}{\Delta T_c})}$$ Equation 2.10

$$\frac{1}{U} = \frac{1}{h_h} + R_h + \frac{1}{h_c} + R_c$$ Equation 2.11

$A(m^2)$ is HX size, $FC_{p,h/c}(\frac{kW}{°C})$ streams' heat capacity flow, $\Delta T_{h/c}$ (°C) is temperature difference between input – output flow in hot streams and/or cold streams, $U(W/m^2 °C)$ is overall heat transfer coefficients, ΔT_{LMTD} (°C) is logarithmic approaching temperature, $R_h - R_c$ $(W/m^2 °C)^{-1}$ are streams fouling tendency coefficients, $h_h - h_c$ $(W/m^2 °C)$ are streams heat transfer coefficients.

In a retrofit situation, it was recommended that the new HX be sized (**Error! Reference source not found.**) according to the allowable pressure drop rather than the streams' heat transfer coefficient in order to minimize the pressure drop in the system [53].

Module HX cost models

Auxiliary equipment is needed to make the HX purchase functional [50]. These auxiliary equipment components, named as HX inside battery limit (ISBL), include the following: (i) piping system for hot and cold HX-sides, paint and insulation; (ii) foundation; and (iii) control and instrumentation. Preliminary costing for HX ISBL equipment items often uses factored-based cost methods due to a lack of time and information. The following table summarises the data for the factors used in Equation 2.12 as provided by Gutheri [54], Smith et al. [13], and Towler et al. [50].

$$C_{MC-HX} = C_{HX}\sum(f_{piping} + f_{foundation} + f_{Instrumentation} + f_{paint} + f_{insulation})$$ Equation 2.12

Where C_{MC-HX} is module cost of new HX, C_{HX} f.o.b is purchase HX cost. Additionally, Turton et al. [49] determined the HX module cost in Equation 2.13 by using the HX's f.o.b purchase cost (C_{HX}).

$$C_{BMC-HX} = C_{HX}(B_1 + B_2)$$ Equation 2.13

Where C_{MC-HX} is HX bare-module cost. Table 11 contains the B_1 and B_2 module factors which are the average of values from following references: Guthrie [54] and Ulrich [55].

Table 2.4 Module HX cost factors.

Bare-Module Cost Factors	Gutheri Model (1969)	Smith Model (2000)	Towler Model (2010)
Piping f_{PIP}	$0.456C_{HX,refined}$	$0.7C_{HX,refined}$	$0.8C_{HX,refined}$
Instruments and control $f_{Ins\&C}$	$0.102C_{HX,refined}$	$0.2C_{HX,refined}$	$0.3C_{HX,refined}$
Insulation material $f_{insulation}$	$0.049C_{HX,refined}$	-	-
Paint f_{paint}	$0.005C_{HX,refined}$	-	$0.1C_{HX,refined}$
Foundation f_{FDN}	$0.081C_{HX,refined}$	$0.4C_{HX,refined}$	$0.3C_{HX,refined}$
Electrical wiring f_{ELE}	$0.002C_{HX,refined}$	$0.1C_{HX,refined}$	$0.2C_{HX,refined}$

Table 2.5 Turton et al. bare-module factors [49].

Heat Exchangers	Turton et al. HX bare-module factors	
	B_1	B_2
Double pipe, Multiple pipe, Scraped wall, and spiral tube	1.74	1.55
Shell and tube HX: Fixed tube sheet, floating head, U-tube, bayonet, kettle reboiler, and Teflon tube	1.63	1.66
Air cooler, Spiral plate, and flat plate	0.96	1.21

2.4 Gaps in the body of knowledge

The following gaps emerge from the literature review carried out above:

- There is no clear link between SWEAM's recommendations and actual design solutions that specify how HRPs might be represented in modified HEN grid diagrams. For instance, when SWEAMs recommend increasing heat integration between two streams of an existing HEN and there is an existing HX between them, it is more cost-effective to raise the thermal duty of the existing HX. This crucial improvement may be recorded via many realistic design methods in modified HEN, with variable cost implications. In this sense, it is necessary to establish a clear connection between SWEAM's suggestions and the actual design solutions they imply.

- SWEAMs, aided by good engineering judgment, recommend the HEN modifications from the following list in order to meet the energy-saving target: (i) Adding new HX unit(s), (ii) modifying existing HX(s), (iii) Resequencing of existing HX(s), (iv) stream(s) splitting-mixing. The literature lacks design and cost details for the last three mentioned HEN modifications.
- Each HRP has two main areas, inside battery limit (ISBL) and outside battery limit (OSBL). ISBL equipment refers to the auxiliary items required to install new equipment and make it operational (e.g. piping, instrumentation and etc.). However, OSBL equipment is what is needed to connect new equipment to other plant modules and regulate the operating conditions that are disrupted after installing the SWEAMs recommendation. Literature that focuses on the design and cost of HRPs indicated by SWEAMs omits the design and cost of needed changes that have been discussed.
- Literature lacks the specific list of key design and cost components that have an impact on the direct investment cost of the HRPs and operating cost reductions generated by better thermal integration across process streams of the current HEN.
- The reviewed literature do not indicate the accuracy of the HX parametric cost models designed to predict the purchase price of the new-sized HX, which is characterized by its construction type and material.
- Factor-based cost models have been developed to estimate the cost of the auxiliary equipment necessary for installing new HX and making it functional. Nevertheless, despite the plant's structure, these models employ the same variables for calculating the module cost of the HX in three distinct situations: (i) Liquid-liquid heat exchanging (small streams' mass flowrate), (ii) Liquid-liquid heat exchanging (high streams' mass flowrate), (iii) Gas-gas heat exchanging (small streams' mass flowrate), (iv) Gas-gas heat exchanging (high streams' mass flowrate). This example demonstrates that factored-based cost models do not offer decision-makers with appropriate guidance.
- It is true that global costing of HRPs suggested by SWEAMs may improve the quality of decision makers looking to determine the feasibility of thermal integration enhancement projects. However, sufficient data and time are required for the costing of projects' ISBL and OSBL equipment items, which are not accessible during the preliminary design stage. On the other hand, expedient costing approaches, addressed in literatures, lack sufficient

precision. The examined literature does not include the parametric cost model appropriate for pricing HRPs suggested by SWEAMs at the preliminary design stage, which includes the costing of ISBL and OSBL of HRPs.

2.2 Hypothesis

The main hypothesis of this research project is the following:

- Enhanced parametric costing technique with the incorporation of good engineering judgement enables decision makers to more precisely evaluate the economic feasibility of Heat Recovery Projects suggested by Site-Wide Energy Analytic Methods with minimum data and time requirements.

This is a unique hypothesis, since the examination of relevant literature revealed that no one has discovered an enhanced parametric method corresponding to HRPs indicated by SWEAMs. In addition, this is an important hypothesis because, during the early design phase, when there are insufficient input data, a reliable enhanced parametric cost equation helps to generate sufficient confidence to choose between heat-exchanging projects or determine the economic viability of a project. Two risks are associated with this hypothesis: (1) it is unclear how to identify the essential parameters in the enhanced parametric approach, and (2) it is uncertain whether a better parametric approach produced from this technique would result in improved early-stage design decision-making. Lastly, it is a testable hypothesis because it is feasible to compare the enhanced parametric method to previously published detail costing and parametric costing models.

Following are the two sub-hypotheses that have been created from the main hypothesis:

- Specific hypothesis 1: Through the detailed analysis of diverse HRPs recommended by SWEAMs, key parameters can be identified that impact the global costing of heat recovery projects.
- Specific hypothesis 2: Enhanced parametric approach suitable for costing with minimum amount of input data and incorporation of good engineering judgment can be identified.

CHAPTER 3 OVERALL METHODOLOGICAL APPROACH

An improved parametric cost model that is suitable for increasing the reliability of economic analysis of the HRPs implied by SWEAMs has been developed in this study in order to address the identified gaps in the body of knowledge. This chapter begins with an explanation of the methodology that was followed to develop that new costing strategy.

3.1 Methodology overview

The current HEN-based HRPs costing approach fail to systematically account for the ISBL and OSBL equipment cost of four different HRPs implied by SWEAMs. This thesis studies the key design and cost components that influence total investment cost of the HRP and operating cost savings produced by decreasing the streams IMATs, and then uses them to develop an enhanced costing model appropriate for using at early-stage decision making when time and data availability are limited. Figure *3.1* depicts the primary steps used to achieve this target along with the articles that resulted from showing each step. As shown in the diagram, this project was completed by following two main phases:

- Detailed study of HEN-based HRPs suggested by SWEAMs, highlighting key parameters that affect TICs of HRPs implied by SWEAMs and TOCs savings.
- Introducing a novel factored-based cost model, demonstrating how to involve cost components of HEN-based HRPs that include the purchase cost of the project's ISBL and OSBL equipment items in a single parametric equation suited for costing with a minimum amount of data and good engineering judgment.

Each of these two key steps, which are shown as blue boxes in Figure *3.1*, is further subdivided into multiple sub-steps, which are depicted as white boxes, and are described in more detail in the sections that follow.

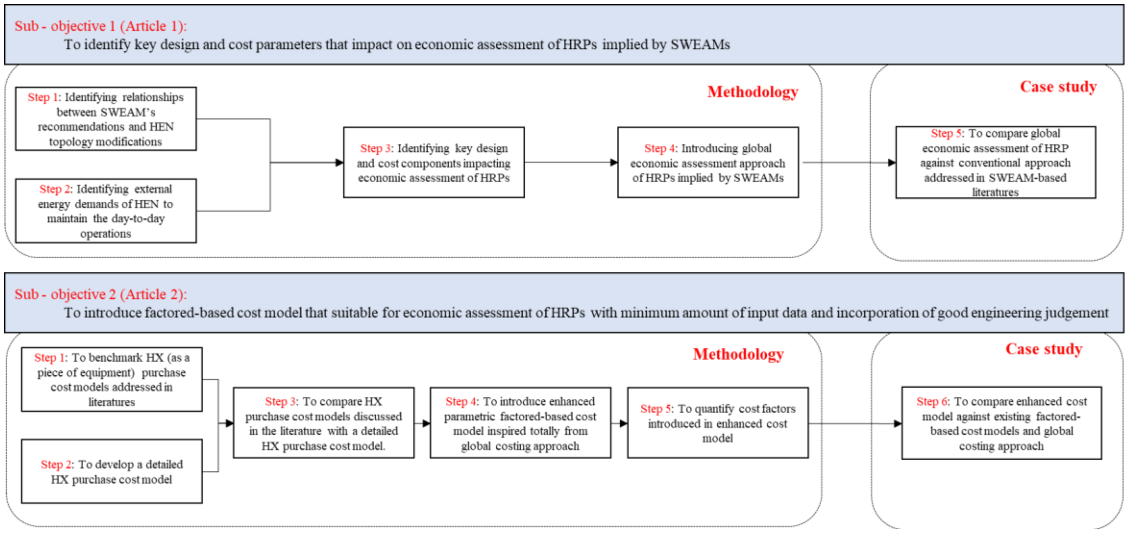


Figure 3.1 Overview of the methodology

3.1.1 Identifying key design and cost components that impact HRP's economic assessment

This part is intended to address the first sub-objective of this thesis, which is to determine the key parameters that influence the TICs of HRPs suggested by SWEAMs and TOCs savings generated by modifying existing HEN by lowering streams' IMATs.

The methodology required to meet this sub-objective contains the following steps:

- Identifying the relationships between SWEAMs recommendations and HEN topology modifications, leads to (i) identifying the ways in which recommendations can be manifested in modified HEN, and (ii) identifying the equipment required to adjust the HEN topology in accordance with the modifications. Also, determining the external energy requirements for HEN to continue daily operations.
- Defining global economic assessment of HRPs implied by SWEAMs that include the key design and cost components associated with HRPs' ISBL and OSBL.
- Conducting economic analysis for the case study in which the Bridge technique was used to identify a number of possibilities for energy-saving, and contrasting global economic assessment approach versus existing conventional models addressed in SWEAMs' literature, where only the cost of the HX is considered.

3.1.2 Defining novel HRP's factor-based cost model

This section is intended to address the second sub-objective of this thesis, which is to introduce an enhanced factored-based cost model for four different SWEAMs' recommendations that incorporate the influence of ISBL installation auxiliary equipment and OSBL equipment cost and on project profitability. According to Figure 3.1, the following procedures are necessary to achieve the stated objectives:

- In the situation that there is more than one cost model estimation candidate, benchmarking the accuracy of each cost model for plate and shell and tube HXs (which are the most commonly used HXs in industries) against detailed HX cost model [51] results to see how the accuracy of models changes as the heat transfer area of a HX is increased.
- Identifying that what preferred characteristics make a parametric cost model suitable for costing of HRPs implied by SWEAMs at early design stage.
- Defining a new factored-based cost model that is completely inspired by golabl costing of HRPs through characterizing of key parameters suitable for HRPs when the time and data are minimum.
- Comparing enhanced cost model against existing factored-based cost models and global costing approach obtained by accomplishing the first sub-objective.

3.2 Case study introduction

To compare the rigours economic assessment of the HRPs implied by SWEAMs to the conventional economic assessment introduced in the SWEAMs-based literature, and compare refined factored-based cost model to the conventional factored-based cost models, the case study was considered which was depicted by process flowsheet (*Figure 3.2*). This plant can be divided into four distinct zones, as shown by the red boxes in the diagram, with the following characteristics for each: (1) There is no difference in elevation between any of the streams that are part of a given unit and the other four units., (2) The distance between two streams that are part of the same unit is 50 m, while the distance between two streams that are part of different units is 200 m, (3) A hot utility stream is The MP steam produced by the steam turbine that expands the HP steam generated by the biomass (40% wet) combustion in the boiler. Also, the cold utility stream is supplied by cooling water from a cooling tower.

The HEN for this process flowchart is shown in *Figure 3.3*; it consists of two light organic mixture energy supplier streams (R1 and R2), two heavy organic mixture energy receptor streams (F1 and F2), and two process-process HXs (E1 and E2). Also, existing HEN has a hot utility demand of 1400 kW (as shown by H1) and a cold utility demand of 1320 kW (shown by C1).

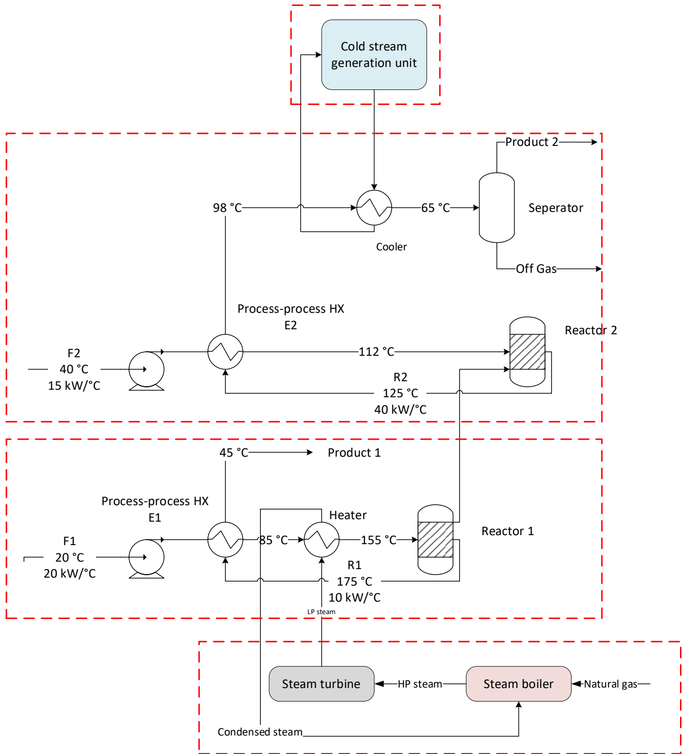


Figure 3.2. Case study – Process flowsheet

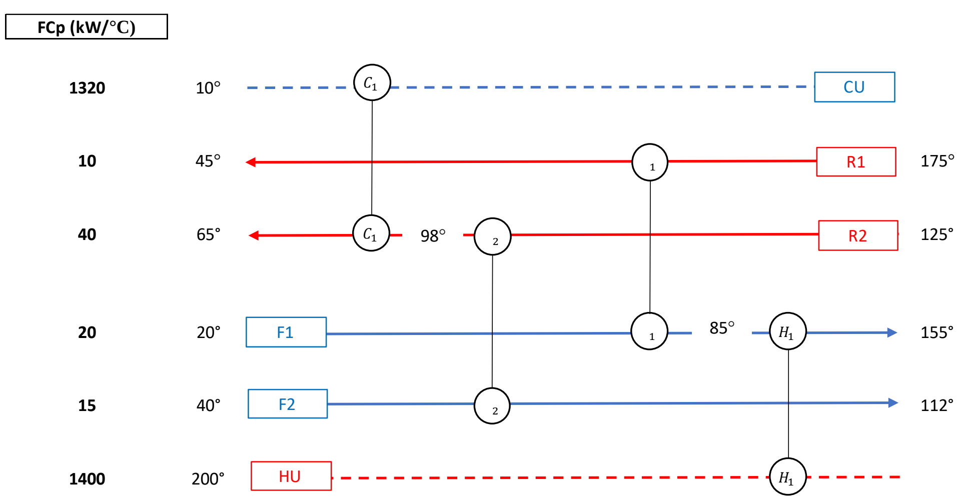


Figure 3.3. Case study – existing HEN grid diagram

CHAPTER 4 SYNTHESIS OF RESULTS

4.1 Presentation of publications

Following the articles submitted to scientific journals and included in Appendices A to B of this dissertation:

- Article 1: Shah Hosseini, HR., Moussavi, AR., Stuart, P. (2022). Key parameters impacting the profitability assessment of heat recovery projects at the early design stage. *Submitted to Chemical Engineering and Processing-Process Intensification.*
- Article 2: Shah Hosseini, HR., Moussavi, AR., Stuart, P. (2022). Factor-based cost model for the economic assessment of heat recovery projects at the early design stage. *Submitted to Applied Thermal Engineering Journal.*

The first article starts by reviewing the literature that addressed the design and cost assessment of the HRPs implied by SWEAMs. A review of the relevant literature reveals that HEN retrofit and greenfield project costs are connected with a number of design complexity and cost aspects that are not addressed in economic analysis. In greenfield and retrofit settings, however, all SWEAMs result in an incomplete HEN specification. In order to fill in the gaps, the purpose of the first study was to identify the major criteria affecting the profitability evaluation (TICs and TOCs) of HRPs as specified by SWEAMs. The results of the first article served as the basis for the second.

The second article begins by going over HX purchase cost models and HX module cost models. A critical review of the models revealed that existing HX purchase cost models do not factor in the cost implications of equipment items required for installing and connecting new HX into other modules of the plant, into the profitability assessment of the HRPs referred to as inserting new HX. Furthermore, because they use the same project-type factors, module cost models are not sensitive to plant topology. To fill the gaps and improve the accuracy of the HRPs' profitability assessment, the second article's goal was to define an enhanced factored-based cost model suitable for the primary design stage, where there is insufficient time and data to do the detailed design and costing of HRPs.

The sections that follow provide a summary of the findings in these articles.

4.2 Synthesis

4.2.1 Connections between SWEAMs recommendations and HEN topology modifications

To meet the requirements of this section, the SWEAM recommendations were first clarified. The connections between SWEAM recommendations and practical design solutions, that elucidate how HRPs can manifest in the plant, were then discovered. Finally, the required topology modifications for fulfilling the requirements of the previous part in a real plant were identified, which is critical for defining rigorous design and costing of HRPs.

Figure 4.1 illustrates the three main steps that were completed in order to find SWEAM's recommendations. First, through the Energy Consumption Analysis step, the energy consumption of the system was translated into process requirements, in order to understand where, why and how much energy is consumed. The first outcome of this step is: (i) characterized hot and cold process streams, utility streams and heat exchanger units which is belonging to the HEN are identified, and (ii) Existing HEN Grid Diagram of the system can be plotted.

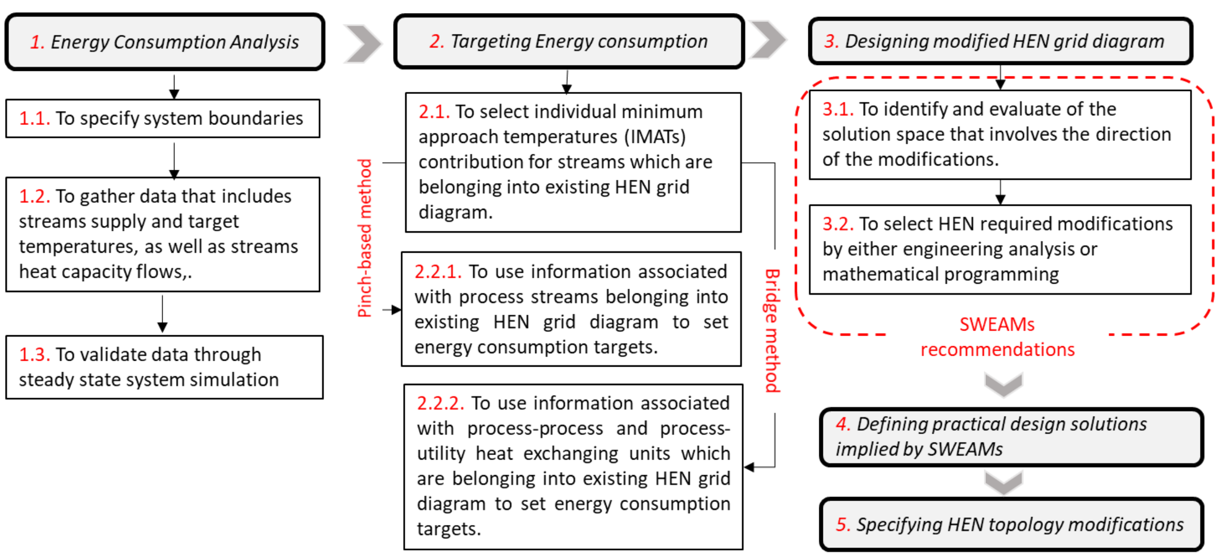


Figure 4.1 The general process by which SWEAMs generate recommendations for heat integration in conjunction with HEN.

Second, through the Targeting Energy Consumption step, it is possible to determine how much external heating and cooling is required if the HEN associated with the existing Grid Diagram is correctly designed. Each SWEAM uses a unique set of resources and data to establish energy consumption targets. The results of an economic analysis based on data collected during the targeting phase are insufficiently precise for decision-making during the early design phase of heat recovery projects. This is due to the fact that information about selecting and evaluating topology modifications required to meet energy consumption targets is absent from the informatio n assumed when energy consumption targets are established. In this regard, it is required to design modified HEN grid diagram. Through this step, with the objective of getting as close as possible to the energy consumption targets, each SWEAM use different information and methodologies to fulfill necessary steps to identify solution space. Then, HEN modifications, **known as a SWEAMs recommendation**, can be identified from the following list using either engineering analysis or mathematical programming, with the restriction that existing HXs be used as much as possible by modifying or relocating them: *(1) Inserting new process-process heat exchanging unit(s), (2) Increasing duty of existing process-process heat exchanging unit(s), (3)Decreasing duty of existing process-process heat exchanging unit(s), (4) Decreasing duties of process-utility heat exchanging units, (5) Resequencing of Heat exchanging units, and (6) Process stream(s) splitting-mixing*.

4.2.1.1 Practical design solutions implied by SWEAMs recommendations

SWEAMs recommendations clarify which of the existing HXs should be left where they are, which should be relocated or modified, which stream should be split, and where should the new HXs be located. However, they do not have any information regarding how the HEN modifications that were mentioned can manifest themselves in plants. In this regard, a relationship between SWEAM's recommendations and practical design solutions was identified, and the mapping of that relationship can be found in **Error! Reference source not found.**.

Inserting new process-process HX

Direct HX and indirect HX, which make use of a heat transfer intermediate fluid, are both viable options for accomplishing the goal of inserting new process-process HX, which is implied by modified HEN. A process will typically be broken up into several logically distinct portions or zones. A couple of examples include the "reaction region" and the "separation area" of the process. It might be necessary to keep these sections separate in order to facilitate things like starting up, shutting down, increasing operational flexibility, or improving safety. In these kinds of

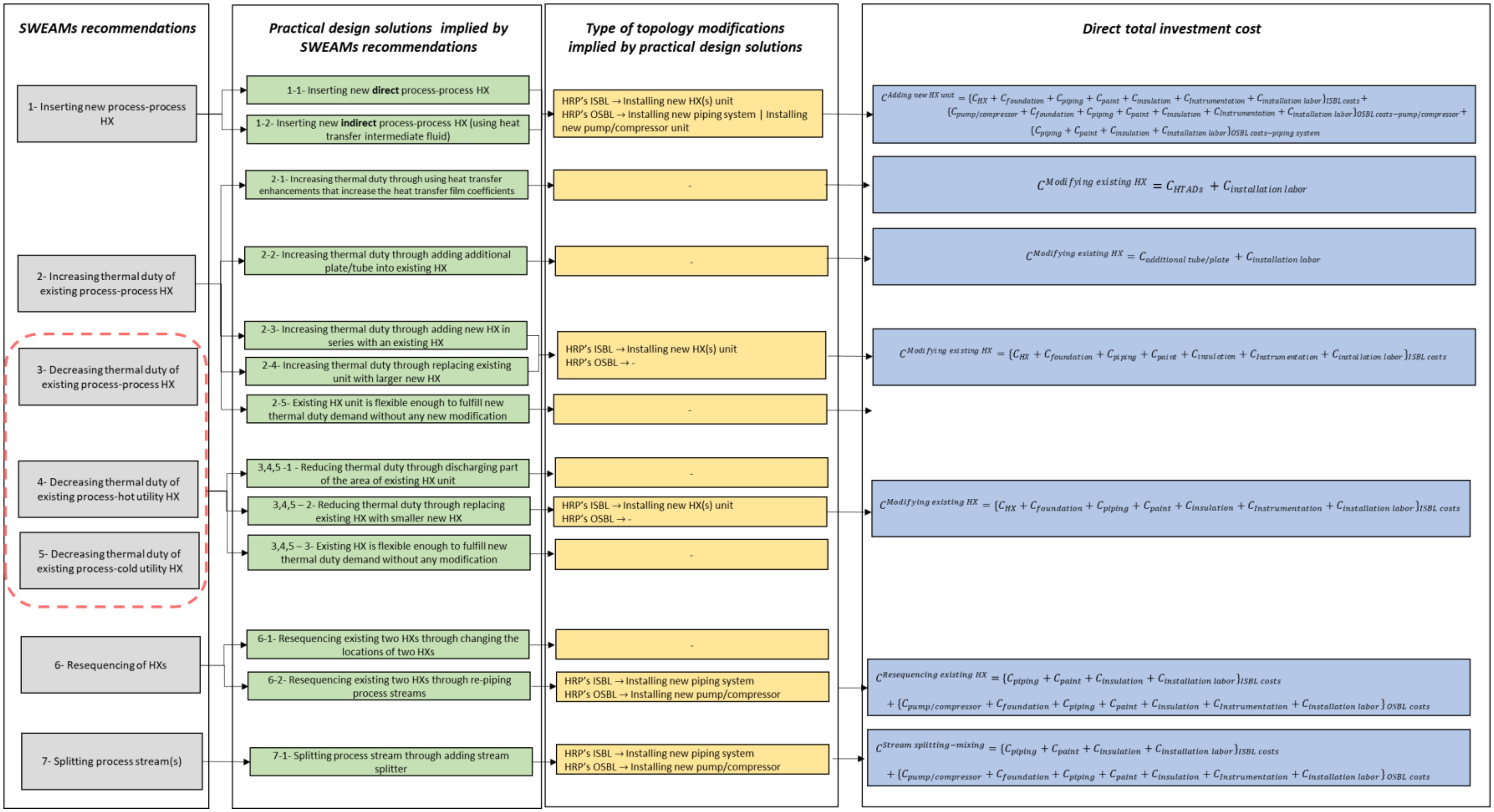


Figure 4.2. relationships between SWEAMs recommendations, practical design solutions, HEN topology modifications, and related TICs formulation.

autonomous zones, also known as areas of integrity, the amount of heat that can be transported there is severely restricted. Since two locations cannot be dependent on one another for heating and cooling via direct heat recovery, indirect heat exchange by means of an intermediate fluid is clearly utilized in order to guarantee operational independence.

Increasing thermal duty of existing process-process HX

There are five different pathways that can be pursued in order to reach the objective of increasing the thermal duty of the process-process heat exchanging units that are already in operation, as suggested by the modified HEN grid diagram. The most common retrofitting methods included (i) expanding the area of the existing unit; (ii) adding a new HX unit in series with the existing unit; and (iii) discharging the existing unit and replacing it with a new HX unit that has a larger heat transfer area. On the other hand, implementing changes to the network topology typically results in significant retrofit costs. (iv) Using intensified heat transfer mechanisms is another approach that can be taken to resolve these issues. For instance, multiple approaches can be taken to enhance the heat transmission in shell-and-tube HXs. Twisted-tape inserts, coiled-wire inserts, and mesh inserts can all be utilized for tube-side upgrades. In order to make modifications to the shell's side, segmental and helical baffles can be used [56]. The last and most important point to make is that sometimes affected HX have sufficient flexibility to perform under new operating conditions in order to deliver a higher rate of heat exchange between two process streams (no additional equipment is required).

Decreasing thermal duty of existing HX(s)

In every HEN retrofit scenario, the thermal duty of HXs, in conjunction with units that are used as both a heater and a cooler, must unquestionably be reduced to the minimum possible level. It may also be necessary, depending on the type of case study being conducted, to decrease the thermal duty of one or more process-process HXs in order to achieve a modified HEN that is thermodynamically balanced after the addition of a new unit and/or the increase in the duty of an existing unit. In order to accomplish this reduction, there are three different strategies that can be implemented: (i) cutting back on the existing area by removing part of the area covered by existing units ; (ii) getting rid of existing units and replacing them with new ones that have a smaller heat transfer area; and (iii) making use of the existing units' adaptability to perform under new operating conditions (no area discharging is required).

Resequencing of HXs

It is possible to resequence two HXs units by making use of two separate design options, which are as follows: (i) moving the units to separate places; and (ii) re-piping of the process streams. Both of these options are described in more detail below. In the first possibility, the unit is moved to a new location within the network; however, it continues to exist between the same streams as it did in the initial match. Re-piping, on the other hand, enables the unit to be moved to a new position that involves streams that are different from those in the original location. As a result, the unit is no longer limited to functioning between the same streams as it was before. Re-piping is a more general solution than moving the location of the unit; however, it may not be possible for a variety of reasons, such as the use of construction materials that are inappropriate for other streams.

Splitting-mixing process streams

The use of a split or exchanger bypass, followed by non-isothermal mixing, is something that SWEAMs frequently advise their customers to do in order to adjust the flow of the process stream's stream heat capacity. For instance, when utilizing the "Pinch" method, if the heat capacity inequalities for all streams cannot be satisfied at the "Pinch" point, then "stream splitting" may be a necessity. The choice to split up is not without its drawbacks, which makes it a challenging option. For instance, the addition of piping and the introduction of a new control variable for the process both occur whenever a split is made. In these kinds of circumstances, the user needs to give careful consideration to whether or not stream splitting is necessary, and they also need to investigate other options.

4.2.1.2 HEN topology modifications

Error! Reference source not found. demonstrates that the type of topology modifications that are implied by SWEAM's recommendations depends on the practical design solution(s) that decision-makers choose in order to fulfill requirements. In order to select an economical design, it is necessary to select one that calls for the current HEN topology to undergo the fewest number of modifications possible. This is a design philosophy that must be adhered to. However, the feasibility of many practical design alternatives associated with a single SWEAMs recommendation also needs to be evaluated based on known qualitative practical constraints. These constraints are categorized into three main levels of operational performance and are named controllability, flexibility, and special operations such as startup, shutdown, emergency, and maintenance. In this regard, engineering judgment was essential in determining topology modifications in conjunction with the recommendations of SWEAM.

4.2.2 Defining the global economic assessment approach of HRP implied by SWEAMs

4.2.2.1 Direct TICs of SWEAMs' recommendations

Equation 4.1 can be regarded as the relationship between the cost of four main SWEAMs' recommendations that depending on the size of the energy-saving project, the nature of the case study, and good engineering judgment, some or all of them contribute to the estimation of cost of the HRP.

$$TICs_{HRP} = \sum_{i=1}^{n} C^{i}_{Adding\,new\,HX\,unit} + \sum_{j=1}^{m} C^{j}_{modifying\,existing\,HX} + \sum_{k=1}^{s} C^{k}_{Resequencing\,exsiting\,HX} + \sum_{d=1}^{p} C^{d}_{stream\,spliting-mixing} \qquad \text{Equation 4.1}$$

In conjunction with each HRP, in this equation, *i* represents the number of newly required HX(s), *j* represents the number of existing HX(s) requiring modification, *k* represents the number of stream re-piping required for HX(s) relocation, and *d* represents the number of stream splitting-mixing projects. According to **Error! Reference source not found.**, the cost of inserting the new HX unit, $C^{i}_{inserting\,new\,HX}$, whether direct or indirect, is the sum of the HX purchase cost (C_{HX}), new HX ISBL piping cost (C_{piping}), Civil cost (C_{civil}), Control instrumentations cost ($C_{instruments}$), insulation and paint costs ($C_{insulation}$, C_{paint}), as well as the labor cost for erection and installation of all equipment items defined for the ISBL of the project. Additionally, the cost of the module piping system ($C_{module\,piping}$) needed to connect the new unit with other plant components and the cost of the new module pump ($C_{module\,pump}$) needed to eliminate any new pressure drops must be considered for projects that are outside of the battery limit (OSBL). Assuming that the existing piping system is usable, the costs of the OSBL piping system, pump and related installation labor are excluded from the project's costs, $C^{j}_{modifying\,existing\,HX}$, when it is necessary to discharge an existing HX and replace it with a new one of a larger size and/or smaller size. Notably, this HX replacement does not add a new pressure drop and consequently a new pump to the system, as the new area is calculated based on the allowable pressure drop and not the heat transfer coefficients of the streams [53]. The only costs associated with the SWEAMs' recommendations referred to as stream splitting – mixing and stream re-piping are module piping costs and pump module costs necessary to eliminate new pressure drops caused by the installation of new equipment. Generally existing costing tools are dependent on three main variables that must be defined and/or calculated by decision-makers and/or design and economical software: (i) equipment type, (ii) equipment construction material, and (iii) equipment size. In this study, defining these three parameters was referred to as the design of the equipment required to implement SWEAM's recommendations, which were defined in the preceding section.

4.2.2.2 TOCs saving implied by SWEAMs' recommendation

Equation 4.2 represents the four main cost components that have a contribution on the HRP's TOCs savings as a result of decreasing HEN's streams IMATs and increasing thermal integration between process streams. (i) C_{HU}^{i} and C_{CU}^{j} represent the cost savings resulting from hot utility i and cold utility j reductions, respectively, which are supplied by steam and cooling water; (ii) C_{Elec}^{k} is the cost of the new electricity demands that must be supplied due to increasing power demands of machinery equipment to eliminate new pressure drops caused by new HX's OSBL piping, stream re-piping, and new piping system associated with stream splitting-mixing ; and (iii) $C_{M}^{l}$is the new maintenance cost resulting from installing new HX l.

$$TOCs_{saving} = \sum_{i=1}^{n} C_{HU}^{i} + \sum_{j=1}^{m} C_{CU}^{j} - \sum_{k=1}^{d} C_{Elec}^{k} - \sum_{l=1}^{f} C_{M}^{l} \qquad \text{Equation 4.2}$$

The proper evaluation of the economics of proposed SWEAM's HRP requires accurate knowledge of the cost of the hot utility stream, C_{HU}, supplied by steam; it is possible that a large number of worthwhile projects will be overlooked or rejected due to inaccurate cost calculations, while undesirable projects may be given the green light for implementation. The total cost of the raising steam are made up of different parts, such as the cost of fuel, the cost of raw water, the cost of treating boiler feed water, which includes clarification, softening, demineralization, power for pumping the boiler feed water, the cost of power for air fans, and so on. However, historical evidence indicates that the cost of fuel is typically the most crucial factor, accounting for as much as 90% of the total cost of steam [13]. The cost of steam was investigated in this study under two distinct scenarios: (1) when the required steam flowrate was lower than 6 kg/s, and (2) when steam flows were greater than 6 kg/s, which is an instance in which it is typically more cost-effective to generate by-product electricity by expanding the steam through a backpressure steam turbine. In the first case, the price of steam is just the same as the price of the fuel that must be burned in the boiler to produce the desired amount of steam, whereas in the second, the price of power must be subtracted from the price of the fuels that must be burned to produce steam at the boiler's point of steam generation.

4.2.3 Examining the impact of the candidate key cost components on the global economic assessment of the HRP implied by SWEAM

This section investigated the effect of each candidate cost components listed in the previous section on the TICs of four different HEN modifications' implied by SWEAMs and good engineering judgement when size, type, and material of the construction of the projects' ISBL and OSBL equipment, as well as the plant's topology, are altered. Few hypothetical case studies were considered for this task.

Stream re-piping and/or stream splitting-mixing

Figure *4.3* depicts the framework of the 96 hypothetical case studies chosen for qualitative evaluation to illustrate the effect of changing the characteristics of the items that impact on TICs of HEN modification named "stream re-piping and/or stream splitting-mixing".

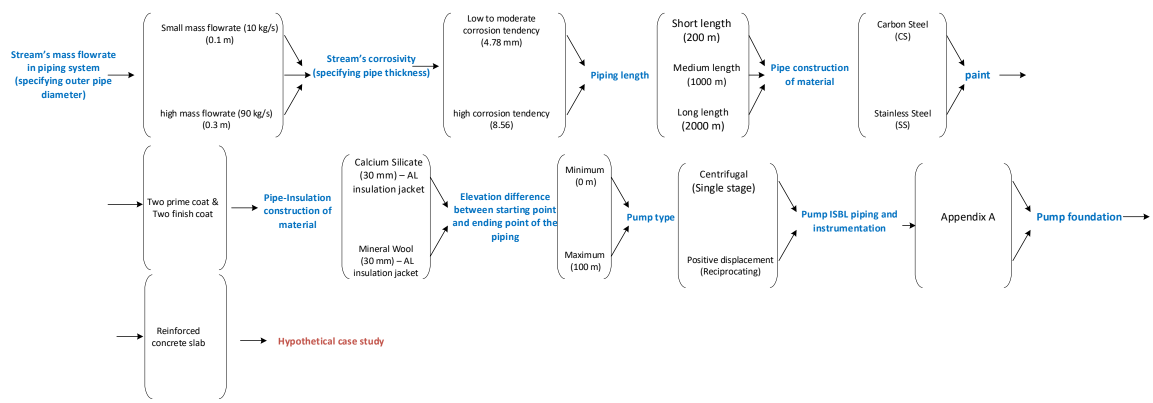
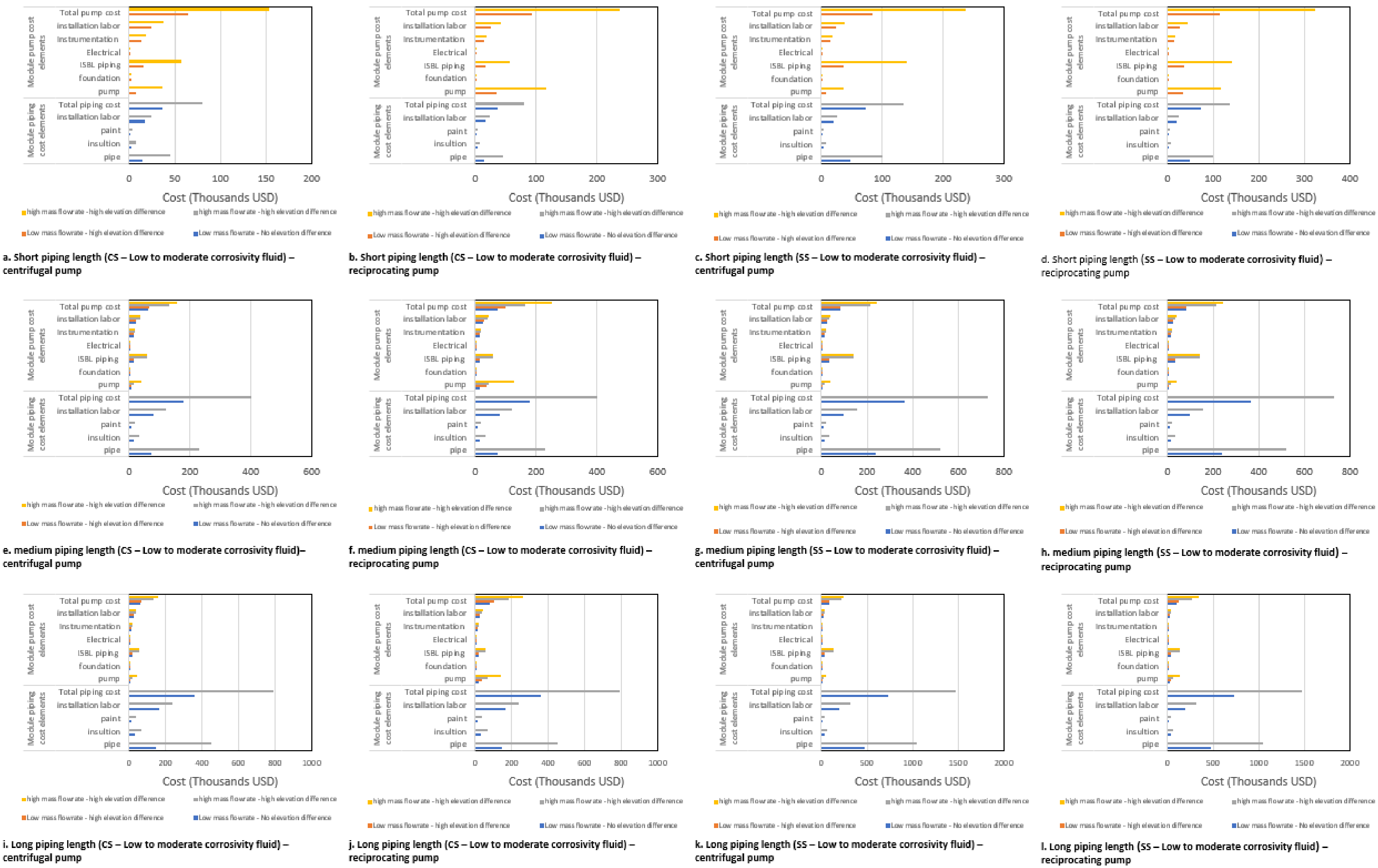


Figure 4.3 Hypothetical case studies' super-structure in conjunction with HRP named "stream re-piping and/or stream splitting-mixing"

When comparing results of quantitative analysis illustrated in Figure 4.4 and Figure 4.5, it becomes clear that, with the exception of short piping lengths, the module new piping cost is much greater than the module new pump cost needed to eliminate new pressure drop. Therefore, more care needs to be taken when estimating the size and cost of this section of the project.



a. Short piping length (CS – Low to moderate corrosivity fluid) – centrifugal pump

b. Short piping length (CS – Low to moderate corrosivity fluid) – reciprocating pump

c. Short piping length (SS – Low to moderate corrosivity fluid) – centrifugal pump

d. Short piping length (SS – Low to moderate corrosivity fluid) – reciprocating pump

e. medium piping length (CS – Low to moderate corrosivity fluid)– centrifugal pump

f. medium piping length (CS – Low to moderate corrosivity fluid) – reciprocating pump

g. medium piping length (SS – Low to moderate corrosivity fluid) – centrifugal pump

h. medium piping length (SS – Low to moderate corrosivity fluid) – reciprocating pump

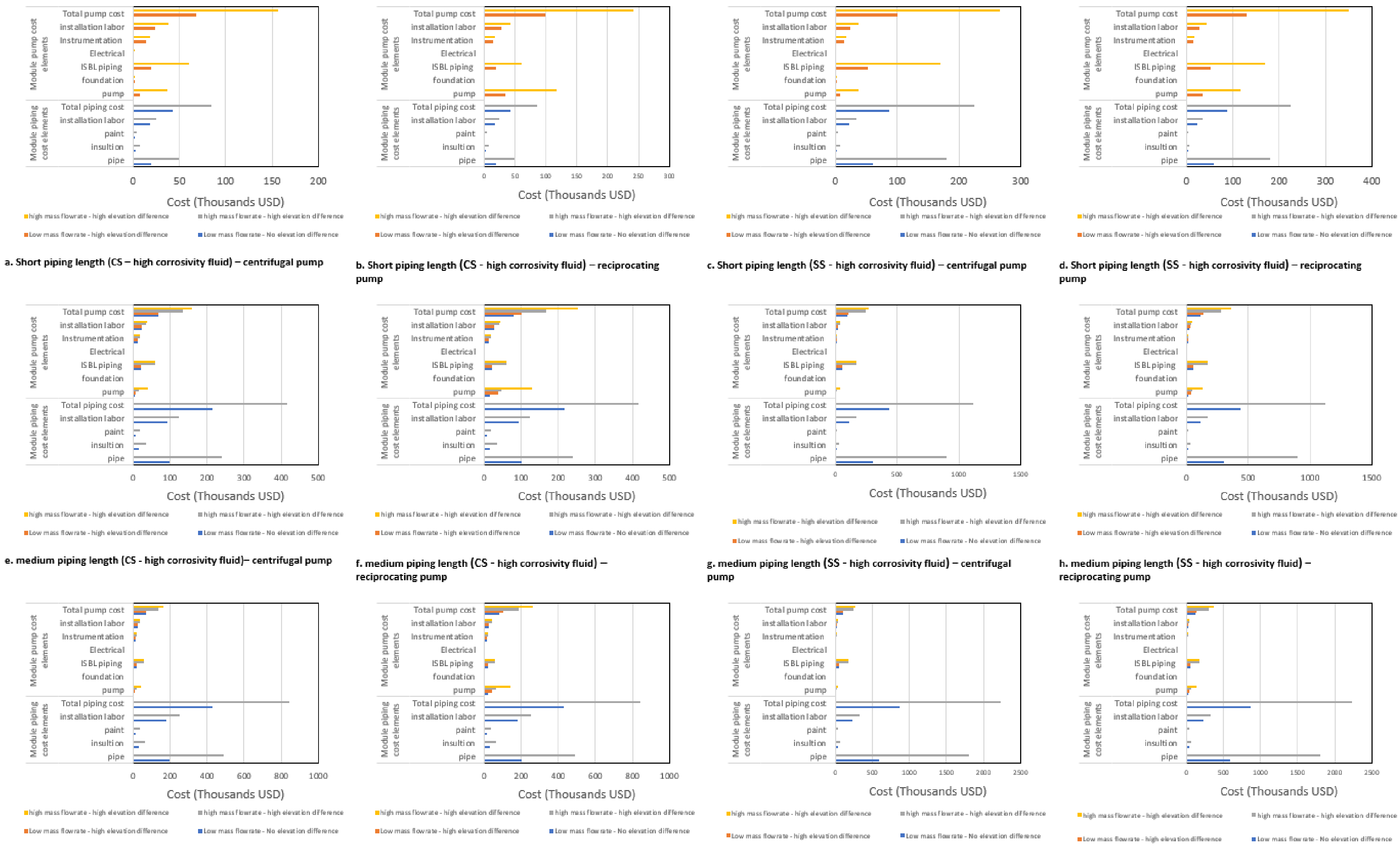
i. Long piping length (CS – Low to moderate corrosivity fluid) – centrifugal pump

j. Long piping length (CS – Low to moderate corrosivity fluid) – reciprocating pump

k. Long piping length (SS – Low to moderate corrosivity fluid) – centrifugal pump

l. Long piping length (SS – Low to moderate corrosivity fluid) – reciprocating pump

Figure 4.4. TICs of HEN modification named “stream splitting-mixing and/or stream repiping” (low to moderate stream’s corrosivity tendency).



a. Short piping length (CS – high corrosivity fluid) – centrifugal pump

b. Short piping length (CS - high corrosivity fluid) – reciprocating pump

c. Short piping length (SS - high corrosivity fluid) – centrifugal pump

d. Short piping length (SS - high corrosivity fluid) – reciprocating pump

e. medium piping length (CS - high corrosivity fluid)– centrifugal pump

f. medium piping length (CS - high corrosivity fluid) – reciprocating pump

g. medium piping length (SS - high corrosivity fluid) – centrifugal pump

h. medium piping length (SS - high corrosivity fluid) – reciprocating pump

i. Long piping length (CS - high corrosivity fluid) – centrifugal pump

j. Long piping length (CS - high corrosivity fluid) – reciprocating pump

k. Long piping length (SS - high corrosivity fluid) – centrifugal pump

l. Long piping length (SS - high corrosivity fluid) – reciprocating pump

Figure 4.5. TICs of HEN modification named “stream splitting-mixing and/or stream repiping” (high stream’s corrosivity tendency).

Also Among the blue-highlighted candidate key components in Figure 2, the electrical cost and foundation cost do not need to be accounted for when estimating the cost of a module pump, and the paint cost does not need to be accounted for when estimating the cost of module piping, if there is insufficient information to do so.

Replacing existing HX with new smaller/bigger HX and/or installing new HX in series with existing HX

Choosing hypothetical case studies for qualitative evaluation relies on a framework, as shown in Figure 4.6. The evaluation's blue-highlighted candidate key parameters are meant to illustrate how adjusting those parameters can affect the project's overall direct cost.

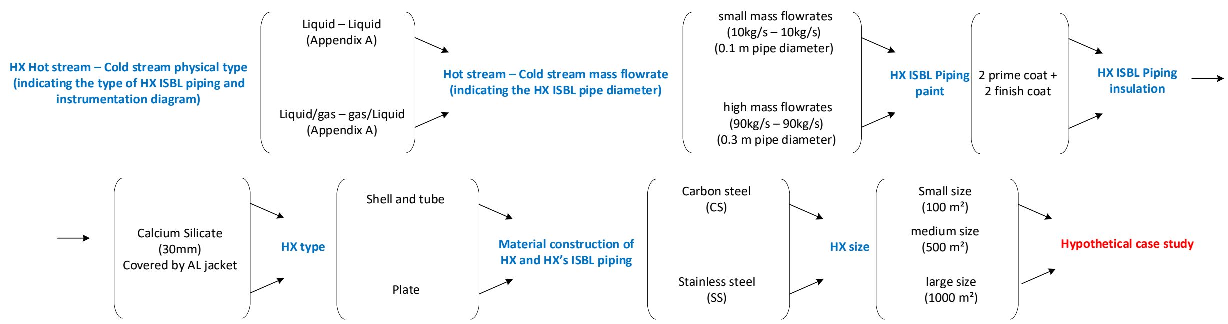


Figure 4.6. Hypothetical case studies' super-structure in conjunction with HRP named "Replacing existing HX with new smaller/bigger HX and/or installing new HX in series with existing HX"

According to critical analysis of the quantitative assessment illustrated in *Figure 4.7*, a relationship that correlates the impact of cost components on the direct TICs of the retrofit project named "modifying existing HX by replacing it with smaller/larger new HX" can exclude paint and civil costs because they are so small in comparison to other cost components. Also, regardless of the HX type and size, taking into account the fouling tendency of the process streams causes an increase in the amount of required HX area, which in turn causes an increase in the cost of HX which is reflected in global costing approach. Moreover, Due to the fact that the cost of the HX varies significantly based on the HX type and construction material, regardless of the size of the HX, it is necessary to use good engineering judgment to specify them according to the operating conditions and thermophysical properties of the stream. Finally, The cost of ISBL piping and control instrumentation differs depending on the P&ID that was selected to make the new HX operational, the material of construction used for the piping, and the diameter of the piping, which varies depending on the mass flowrate of the streams but stays the same regardless of the size or type of the HX.

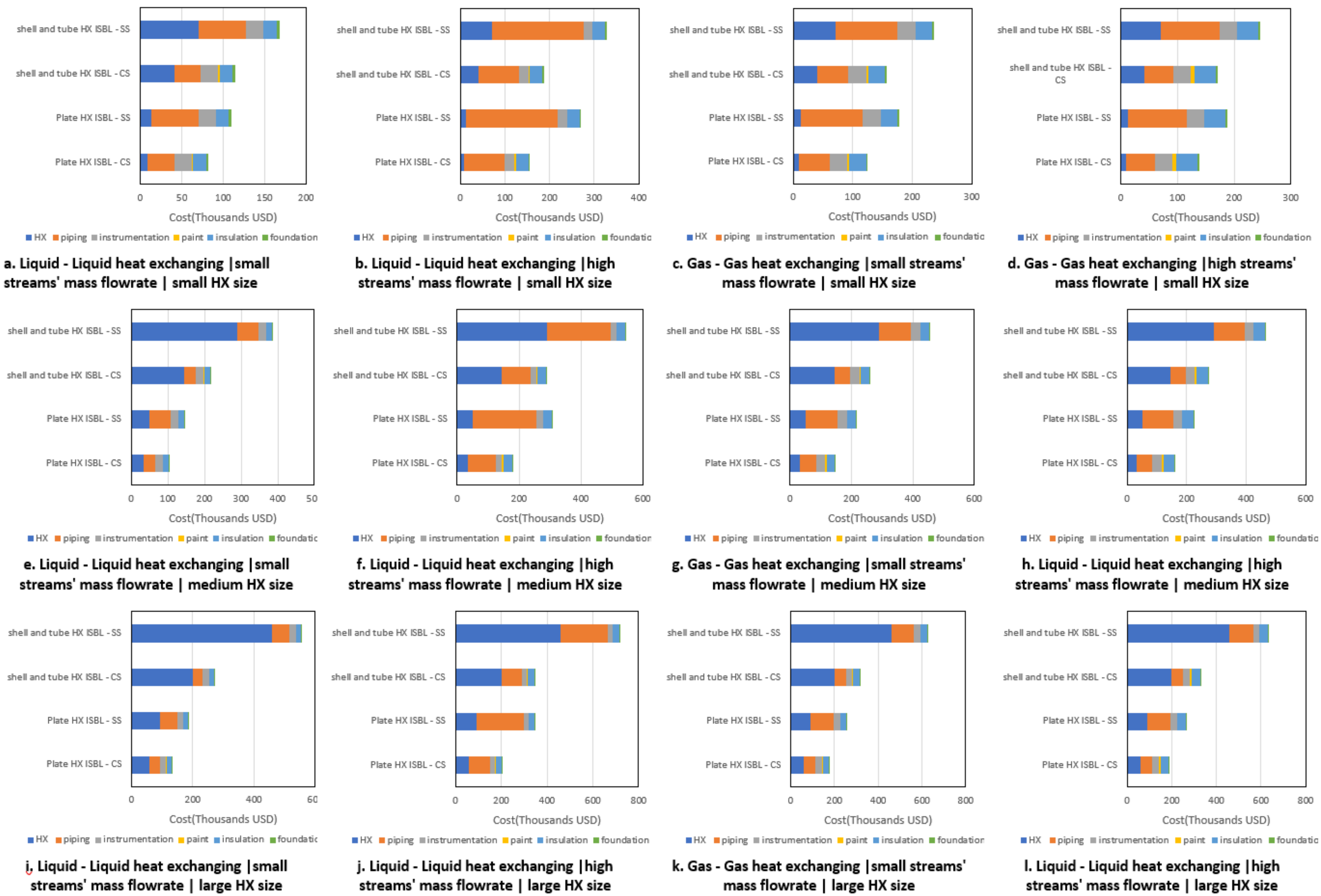


Figure 4.7. TICs of HEN modification named "increasing/decreasing thermal duty of existing HX(s)" when replacing existing HX with new one is chosen

Adding new HX unit

associated with SWEAM's recommendation titled "Adding new HX unit, Figure 4.9 is the result of an economic evaluation conducted for a variety of scenarios that were super-structured in Figure *4.8*.

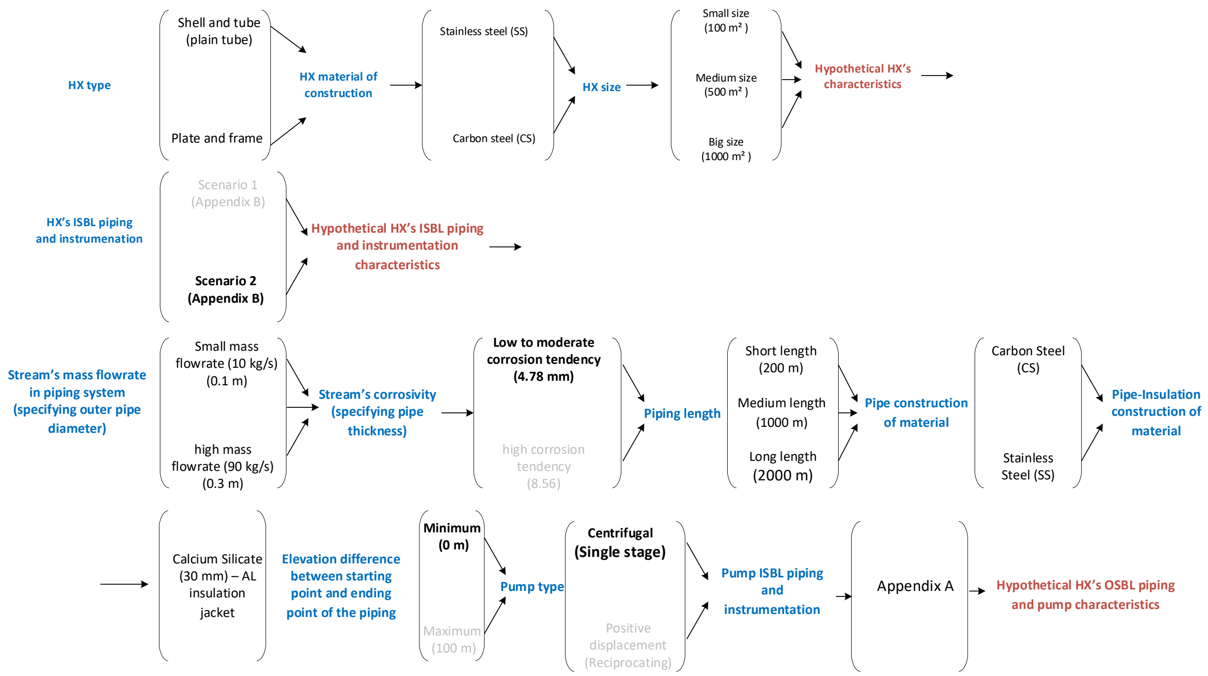
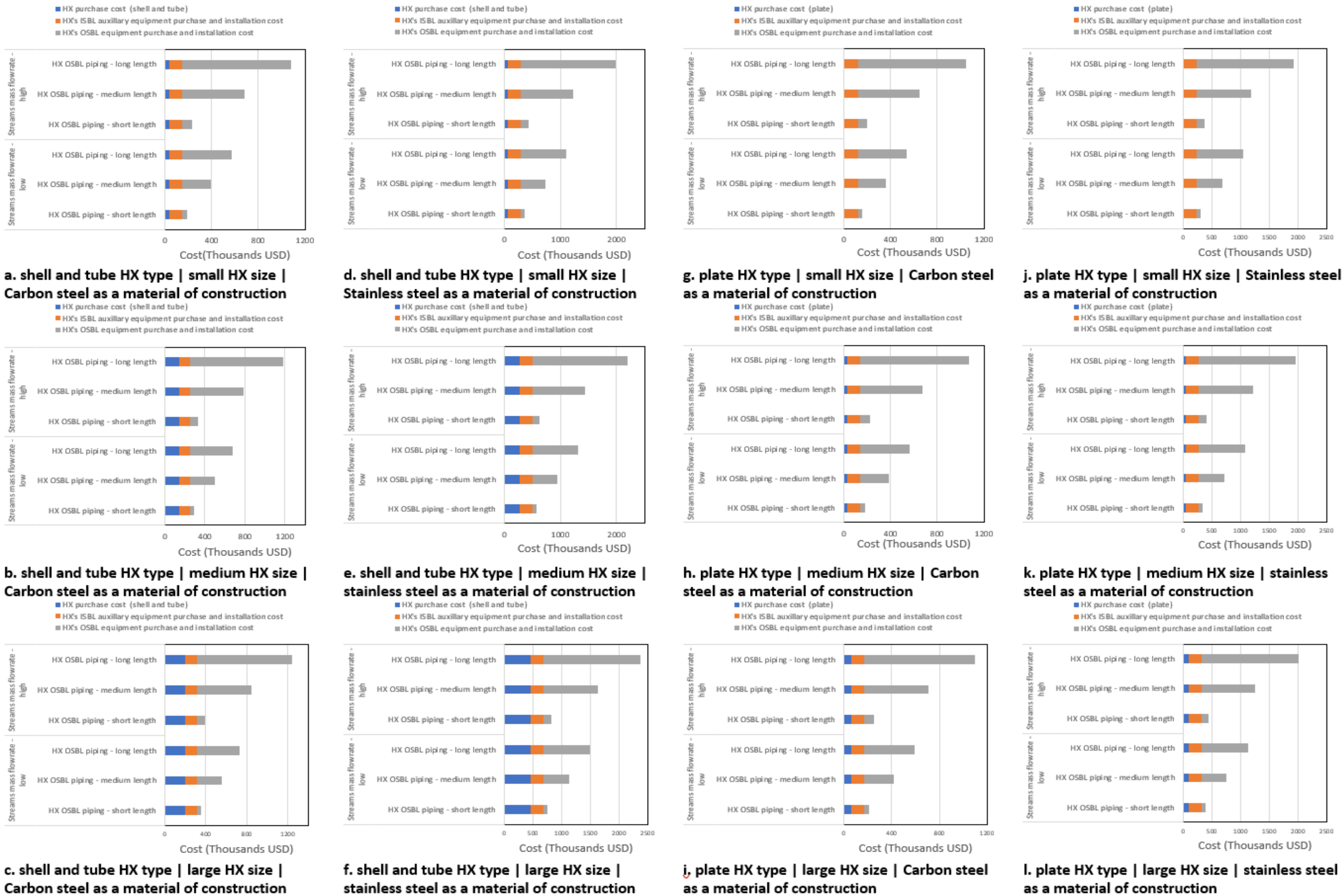


Figure 4.8. Hypothetical case studies' super structure in conjunction with HRP named "inserting new HX".

The critical analysis of the results revealed that, the proportion of HX cost to total direct cost is highest (at 60% for shell and tube type and 24% for plate type) when the HX (SS) needed for the new heat recovery between process streams is big and OSBL piping system (SS - small diameter) is short. When the length of HX OSBL piping is increased to medium and long sizes, the contribution of HX purchase costs to total direct costs is reduced by 40% and 30%, respectively, for shell and tube HX, as well as by 12% and 8%, respectively, for plate HX. Also, the data presented in this figure demonstrates that changing the HX construction material from SS to CS results in a reduction in the HX cost contribution to the total direct cost of the project. As a whole, Figure 8 demonstrates how it is possible to grossly underestimate the cost of the SWEAM project known as "inserting new HX" by simply taking into account the cost of the HX as the only cost component, as is done in published articles.



a. shell and tube HX type | small HX size | Carbon steel as a material of construction

d. shell and tube HX type | small HX size | Stainless steel as a material of construction

g. plate HX type | small HX size | Carbon steel as a material of construction

j. plate HX type | small HX size | Stainless steel as a material of construction

b. shell and tube HX type | medium HX size | Carbon steel as a material of construction

e. shell and tube HX type | medium HX size | stainless steel as a material of construction

h. plate HX type | medium HX size | Carbon steel as a material of construction

k. plate HX type | medium HX size | stainless steel as a material of construction

c. shell and tube HX type | large HX size | Carbon steel as a material of construction

f. shell and tube HX type | large HX size | stainless steel as a material of construction

i. plate HX type | large HX size | Carbon steel as a material of construction

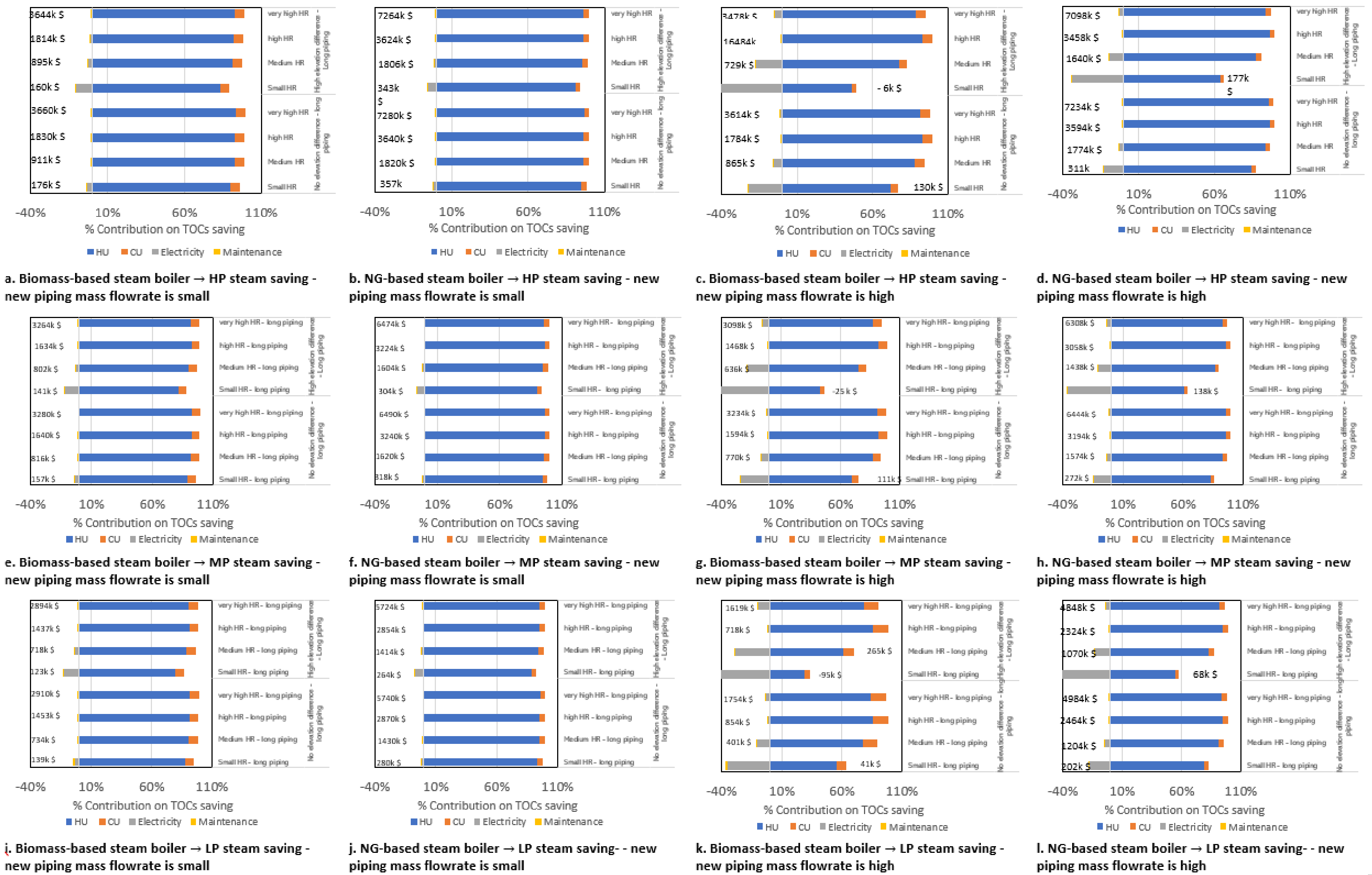
l. plate HX type | large HX size | stainless steel as a material of construction

Figure 4.9. Global direct investmet cost of the HRP named “adding new HX”.

TOCs saving implied by SWEAM's recommendation

This section examined the effect of each cost component correlated in Equation 11 on the detail TOCs savings in order to rank them from most relevant to least relevant, when the quantity of the hot and cold utility demands' savings, steam generation pathway, steam pressure requirement (LP-4bar, MP-17bar, and HP-40bar), type of burning fuel in steam boiler (NG, and biomass 40% moisture), total length of the new piping system, and elevation differences (0m and 100m) implied by enhanced HEN grid diagram and good engineering judgment, are changed. As a nomination for low, medium, high, and very high external energy saving capacity, 1MW, 5MW, 10MW, and 20MW were proposed. Also, two different pathways were considered for steam used in HEN, (i) steam boiler, and (ii) steam boiler → steam turbine. In addition, 200m and 2000m were considered as nominations for short, and very large lengths of new piping system. The quantitative analysis illustrated in Figure 4.10 and Figure 4.11 was critically examined as follows:

- The cost component associated with the annual maintenance cost of the new HX implied by SWEAMs can be eliminated from the Detail TOCs saving formulation.
- When a steam boiler is operated based on the combustion of Diesel and NG, the detail TOCs savings implied by a modified HEN grid diagram and good engineering judgment can be estimated based only on the HU (steam) cost savings, C^{i}_{HU}, which depends on the amount of steam saved, the steam pressure, and the steam generation pathway (boiler, boiler - steam turbine).
- When a steam boiler is operated using a cheap fuel (e.g., Biomass 40% wet), the quantitative analysis results can be classified into the following categories:
    - If the case study's conditions, as determined by SWEAM's recommendation and good engineering judgment, are compatible with the following requirements, then a detailed TOCs saving in relation to the HRP can be estimated solely on the basis of the HU (steam) cost saving: **(i) the amount of external energy savings is greater than 2MW, (ii) the pressure of the saved steam can be classified as MP or HP, and (iii) the steam generated in the steam boiler is utilized directly by HEN**.



a. Biomass-based steam boiler → HP steam saving - new piping mass flowrate is small

b. NG-based steam boiler → HP steam saving - new piping mass flowrate is small

c. Biomass-based steam boiler → HP steam saving - new piping mass flowrate is high

d. NG-based steam boiler → HP steam saving - new piping mass flowrate is high

e. Biomass-based steam boiler → MP steam saving - new piping mass flowrate is small

f. NG-based steam boiler → MP steam saving - new piping mass flowrate is small

g. Biomass-based steam boiler → MP steam saving - new piping mass flowrate is high

h. NG-based steam boiler → MP steam saving - new piping mass flowrate is high

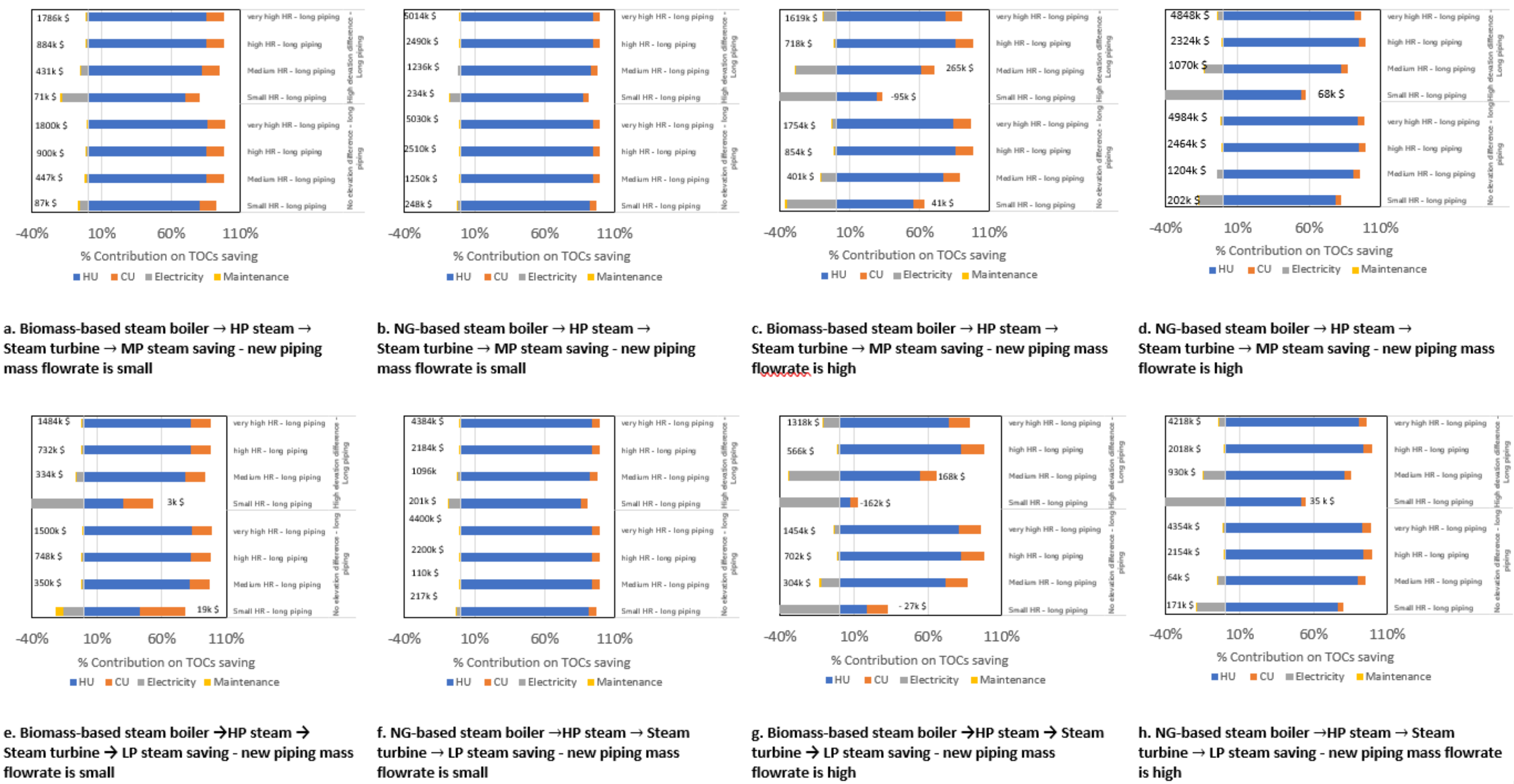
i. Biomass-based steam boiler → LP steam saving - new piping mass flowrate is small

j. NG-based steam boiler → LP steam saving- - new piping mass flowrate is small

k. Biomass-based steam boiler → LP steam saving - new piping mass flowrate is high

l. NG-based steam boiler → LP steam saving- - new piping mass flowrate is high

Figure 4.10. Global operating cost saving when steam generated in steam boiler used directly in HEN.



a. Biomass-based steam boiler → HP steam → Steam turbine → MP steam saving - new piping mass flowrate is small

b. NG-based steam boiler → HP steam → Steam turbine → MP steam saving - new piping mass flowrate is small

c. Biomass-based steam boiler → HP steam → Steam turbine → MP steam saving - new piping mass flowrate is high

d. NG-based steam boiler → HP steam → Steam turbine → MP steam saving - new piping mass flowrate is high

e. Biomass-based steam boiler → HP steam → Steam turbine → LP steam saving - new piping mass flowrate is small

f. NG-based steam boiler → HP steam → Steam turbine → LP steam saving - new piping mass flowrate is small

g. Biomass-based steam boiler → HP steam → Steam turbine → LP steam saving - new piping mass flowrate is high

h. NG-based steam boiler → HP steam → Steam turbine → LP steam saving - new piping mass flowrate is high

Figure 4.11. Global operating cost saving when steam generated in steam boiler expanded in steam turbine before using in HEN

- If previous conditions remained unchanged and only the steam generation pathway changed from boiler→HEN to boiler→steam turbine→HEN, the detailed TOCs savings would sum of cost components associated with the HU, C_{HU}^{i}, and CU, C_{CU}^{i}, savings.
- If steam savings implied by SWEAMs and good engineering judgment are compatible with scenario Biomass-based steam boiler →HP steam → Steam turbine → LP steam saving, then the detail TOCs savings equal the sum of cost components associated with the HU, C_{HU}^{i}, and CU, C_{CU}^{i}, minus cost component associated with the new power requirement, C_{Elec}^{k}, implied by the new piping system. This situation is also applicable if the amount of energy saved is small (1 MW), the length of the new piping system is very long (>4 km), and the saved steam is compatible with one of the following conditions: Biomass-based steam boiler → HP, MP, or LP steam →HEN, and Biomass-based steam boiler → HP steam → Steam turbine → MP steam →HEN.

4.3. Introducing enhanced factored-based parametric cost model for assessing SWEAMs' recommendations

This section was assigned to introduce an improved factored-based cost model appropriate for early in the design process, when there is insufficient information to carry out the global costing approach necessary for the rigorous economic assessment of HRPs implied by SWEAMs. The only data that is required to find out SWEAMs recommendations are the supply and target temperatures, mass flowrate, and heat capacity of the process streams that need to be heated up and cooled down when the Pinch technology is chosen, and the same information for hot and cold process streams of each existing HX when the Bridge technology is chosen. This data, along with good engineering judgment, can be used in the initial design stage of HEN-based HRPs to simply estimate the size, material of construction and type of HRP's ISBL and OSBL equipment.

HX is one of the most expensive pieces of equipment among the various field material items implied explicitly or implicitly by SWEAM's HRP [11, 46, 57]. Due to a lack of information about HEN matches when conducting SWEAMs, heat recovery recommendations do not include enough information to calculate the mechanical design parameters of the new HX(s) [58]. In this regard, it is difficult to go below the preliminary cost estimates for HX(s) when a user wants to estimate economic indicators to choose between alternative retrofit projects or determine the viability of a retrofit project. Next sub-section was designated to benchmark HX cost models named Corripio model (1995) [48], Smith model (2000) [13], Turton model (2001) [49], Towler model (2010) [50], and Seider model (2013) [46] against detail HX cost model introduced in reference [51] in order to provide a general guideline for decision makers looking to select an appropriate HX f.o.b costing model for primary HX cost calculation through parametric cost correlations.

Benchmarking HX parametric cost models against detail HX cost model

This section was started with elucidating strengths and limitations of five cost models by responding to four main questions that might emerge during the preliminary design stage of HX; (i) associate with a certain kind of HX (e.g. shell and tube, plate, double pipe and etc.), what range of heat transfer area (A) may each HX parametric cost equation be utilized for?, (ii) What kind of HX construction materials may each HX parametric cost equation be utilized for?, (iii) What kind of shell and tube HX models may each HX parametric cost equation be utilized for?, and finally (iv) which of the f.o.b HX parametric cost models may be changed in response to changes in operating pressure?.

With regard to shell and tube HX, critical analysis of cost models revealed that the Smith model is capable of estimating the f.o.b purchase cost for a broad range of HX sizes. On the other hand, the Corripio model is only applicable when the new HX's heat transfer area is between 1 m^2 and $100m^2$. Turton, Towler, and Seider models are only capable of covering the cost of HX to the extent that their predicted heat transfer area is dropped in the small or medium size range.

Additionally, based on the list of materials used to manufacture the shell and tube sides of the HX, the Corripio model is only appropriate in situations when decision makers choose CS-shell/CS-tube. Smith model is not suited when Cu, Ni, Ti, Mo, or brass is used to form the shell and/or tube sides. On the other hand, the Turton model is capable of accounting for the influence of a broad variety of building materials indicated in literature review, except where operating conditions and the nature of the process fluids dictate that Mo, AL, or brass be used to create the tube side of the HX. Also, critical analysis of the results showed that Towler HX's cost model does not include a cost adjustment factor for changes in the shell and tube sides' construction materials. If the materials for the shell and tube sides are selected as CS-shell/Cr-Mo-tube, Cr-Mo-shell/Cr-Mo-tube, or CS-shell/Brass, Seider model for estimating the purchase cost of the shell and tube HX was recommended.

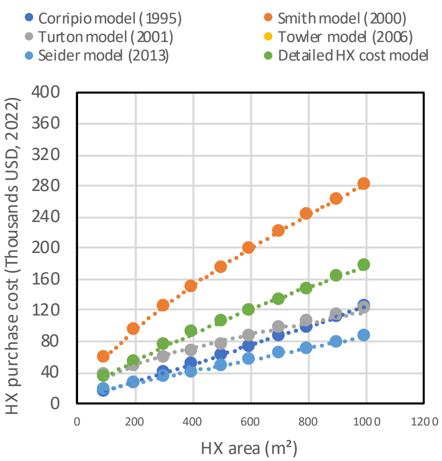
Shell and tube HXs are classified according to the kind of front head, shell side, and rear end. Contrary to the Smith model, critical analysis showed that the Corripio, Turton, and Seider cost models are sensitive to changes in the back end of the HX whether the floating head, fixed tube, or U-tube is used. Additionally, they may be customised according on the kettle shell used. Also, only Turton and Towler models may be used to cost Bayonet HX and Thermosiphon reboilers, respectively. Finally, critical analysis illustrateed that, although the Towler model is only appropriate in situations when the operating condition is compatible with the ambient pressure, the Smith and Turton cost models may be used to a broad variety of operating pressures. This table also shows that the Seider model is ineffective when operating pressure is chosen in the Medium (300psig<P<900psig) and High (900psig<P) pressure levels.

If it is chosen to employ plate HX to improve heat recovery in HEN, decision-makers should be aware that the Corripio and Smith HX cost models cannot be adjusted to work with plate HX costs. Additionally, the remaining costing models are incapable of estimating the cost of the plate HX when its heat transfer area is limited to a large size range $(1001m^2 < A)$. Critical analysis indicated that the Seider cost model cannot be employed if operational circumstances require the use of a construction material other than CS. Except when the user must choose Cu, Ti, or Mo, the Towler cost model can take into consideration the whole list of construction materials given in literature review. Also, literature review illustrated that when decision makers use the Turton model in conjunction with other criteria, they can be certain that this model is appropriate whether the material construction is CS, SS, Cu, Ni alloy, or Ti. Finally, none of the costing models are appropriate for a situation in which the decision maker wants to improve the accuracy of the plate HX purchase cost estimation by selecting a model of the plate HX from four well-known models: (i) gasket plate HX, (ii) welded plate HX, (iii) semi-welded plate HX, and (iv) brazed plate HX. Furthermore, it was demonstrated that if a user wishes to work with the Towler model, it is not feasible to account for variations in operating pressure on the HX purchase price. When the pressure is between 100 and 300 psig, the Turton and Seider model allows the user to alter the basic cost by multiplying with the pressure correction factor.

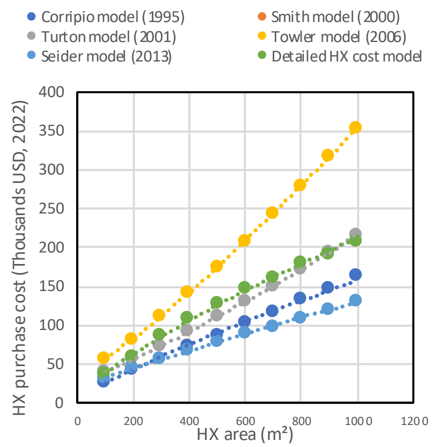
When assessing the purchase cost of a double pipe HX, the Corripio and Smith cost models are inapplicable, however the Seider cost model can be utilised for a larger range of heat transfer area than the Turton and Towler models. However, when the heat transfer area of the heat exchanging between process streams is less than 10 m^2, the Turton model allows you to consider the impact of using Ni, Ti, or Cu as the construction material of the shell and/or tube sides on the base cost of the double pipe HX generated using CS-shell/CS-tube. If it is necessary to estimate the cost of multiple pipe and scrapped wall HXs, only the Turton model gives this option. Finally, it was elucidated that the Turton and Seider models are both suitable for determining the purchase cost of the spiral plate HX. The former is appropriate when the construction material is CS, Cu, Ni alloy, and Ti and the heat transfer area is less than 100 m^2, while the latter is appropriate when the construction material is larger than 100 m^2 but less than 185 m^2 and the construction material is SS. Finally, when it comes to budgeting Spiral tubes, the Turton model is the best option when compared to other models. Because it can be utilised for a larger variety of heat transfer areas between process streams than the Seider model and can be changed when alternative construction materials and operating pressures other than CS and ambient pressure are employed.

Plate and shell and tube HXs (fixed head, floating head, and U-tube) constructed from carbon-steel and stainless steel are the most commonly used HXs in industries. On the other hand, according to an in-depth analysis and evaluation of the aforementioned body of literature, it has been determined that there are specific circumstances under which different HX cost models are able to price the same mentioned HX type, heat transfer area, and construction material. In this regard, it was required to benchmark the accuracy of each cost model for plate and shell and tube HXs against HX detail costing approach [59] to see how the accuracy of calculations changes as the heat transfer area of a HX is increased.

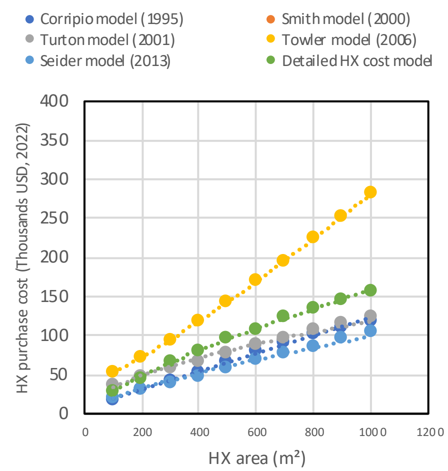
First, critical analysis of the Figure *4.12* showed that some cost models under- or overestimate the HX cost when compared to detail cost results, and this can be attributed to factors such as the quality of the data and the type of fitting curve correlation. When a shell and tube HX type made from CS is chosen, as shown in Figure *4.12*, the results from the Turton cost model are most consistent with those from the detail HX cost model. This holds true whether the HX's rear end is designed as a fixed head, floating head, or U tube. However, if the material used in the HX's tubes were upgraded to SS, the HX's rear end type would determine the most accurate cost model: (i) Smith model for fixed head, and (ii) Towler model for Floating head and U-tube. Figure 2 also shows that the Towler cost model estimates are most in line with the detailed cost model's results when the HX type is changed to a Plate type constructed from SS or CS.



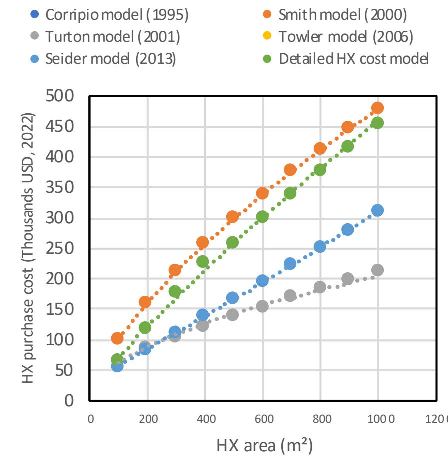
a. Shell and tube HX (Fixed head) – carbon steel



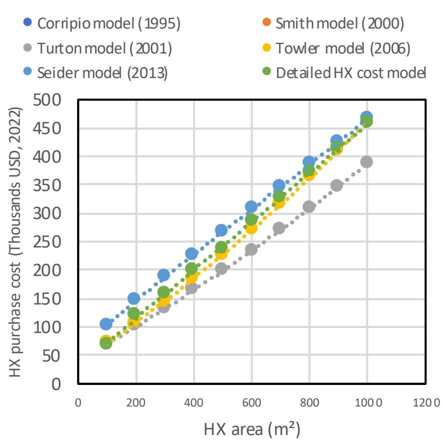
b. Shell and tube (Floating head) – carbon steel



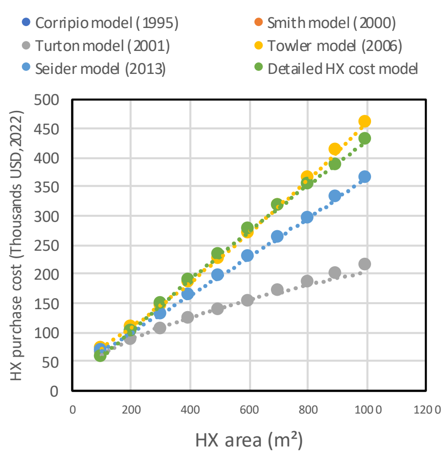
c . Shell and tube (U tube) – carbon steel



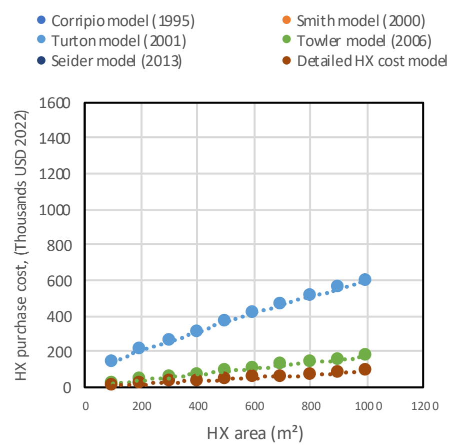
d. Shell and tube HX (Fixed head) – stainless steal



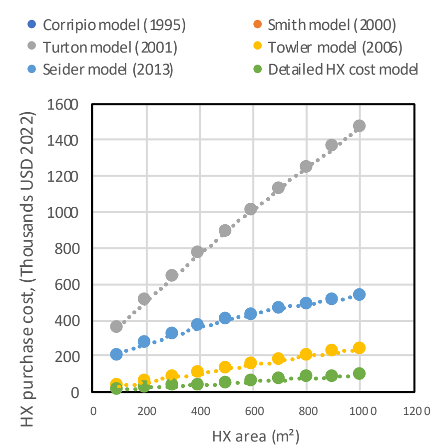
e. Shell and tube (Floating head) – stainless steel



f. Shell and tube (U tube) – stainless steel



g. Plate HX – carbon steal



h. Plate HX – Stainless steel

Figure 4.12. Benchmarking existing plate and shell-tube HXs parametric cost models against detail costing results

Enhanced factored-based cost model

Based on the assumption that each HEN retrofit project has two major areas, the inside battery limit (ISBL) and the outside battery limit (OBL) (OSBL), Figure *4.2* presents the global costing of each HEN modification type. The purpose of this research is to use these equations as a starting point for creating a refined factored-based cost model (Equation 24 through Equation 26) that can be used for HRP costing with limited data and the application of sound engineering judgment.

- Adding new HX unit (either for direct or indirect heat exchanging)

Equation 4.3

$$C^{Adding\,new\,HX\,unit} = \{C_{HX} + C_{HX}[f_{foundation} + f_{piping} + f_{paint} + f_{insulation} + f_{Instrumentation}]\}_{ISBL\,cost-HX\,unit} + \{C_{pump/compressor} + C_{pump/compressor}[f_{foundation} + f_{piping} + f_{paint} + f_{insulation} + f_{Instrumentation}]\}_{OSBL\,cost-pump/compressor\,unit} + \{C_{pipe} + C_{pipe}[f_{paint} + f_{insulation}]_{OSBL\,cost-piping\,system}$$

- Modifying existing HX – discharging existing HX unit and replace it smaller/bigger HX unit. After the discharge of the old HX unit, the old HX OSBL piping system and pump/compressor are expected to be usable by the new HX unit.

Equation 4.4

$$C^{Modifying\,existing\,HX} = \{C_{HX} + C_{HX}[f_{foundation} + f_{piping} + f_{paint} + f_{insulation} + f_{Instrumentation}]\}_{ISBL\,cost-new\,\,HX}$$

- Resequencing of existing HX(s) and/or stream(s) splitting – mixing

Equation 4.5

$$C^{Resequencing\,existing\,HX}and/or\,C^{stream\,splitting-mixing} = \{C_{piping} + C_{piping}[f_{paint} + f_{insulation}]\}_{ISBL\,cost-\,new\,\,piping\,system} + \{C_{pump/compressor} + C_{pump/compressor}[f_{foundation} + f_{piping} + f_{paint} + f_{insulation} + f_{Instrumentation}]\}_{\,OSBL\,cost-pump/compressor\,unit}$$

A description of the symbols that are used in these equations can be found as follows:

- $\boldsymbol{C_{HX}}$ displays the new HX purchase cost estimated based on parametric models which benchmarked against detail HX cost model in previous section. Dependent upon the nature of the hot and cold streams and the operating conditions, it is possible to specify HX type and material of construction using engineering judgment. Also, data used to identify HRPs, in addition to the allowable pressure drop of the system, are those pieces of information that can be used for estimating the size of the HX in this step of the design process.
- $\boldsymbol{f_{piping}}\left(\frac{\boldsymbol{HX\ ISBL\ piping\ cost, USD}}{\boldsymbol{HX\ cost, USD}}\right)$, $\boldsymbol{f_{instrumentation}}\left(\frac{\boldsymbol{HX\ ISBL\ instrumentation, USD}}{\boldsymbol{HX\ cost, USD}}\right)$, $\boldsymbol{f_{paint}}\left(\frac{\boldsymbol{HX\ ISBL\ paint\ cost, USD}}{\boldsymbol{HX\ cost, USD}}\right)$, $\boldsymbol{f_{insulation}}\left(\frac{\boldsymbol{ISBL\ insulation\ cost, USD}}{\boldsymbol{HX\ cost, USD}}\right)$ illustrate the costs of the auxiliary equipment items, as a percentage of the cost of the new HX, that need to be purchased in order to make new HX operational. *Figure 4.14* and Figure 4.15 depicted the quantitative value of these factors, which were calculated for a variety of situations super-structured in Figure *4.13*.

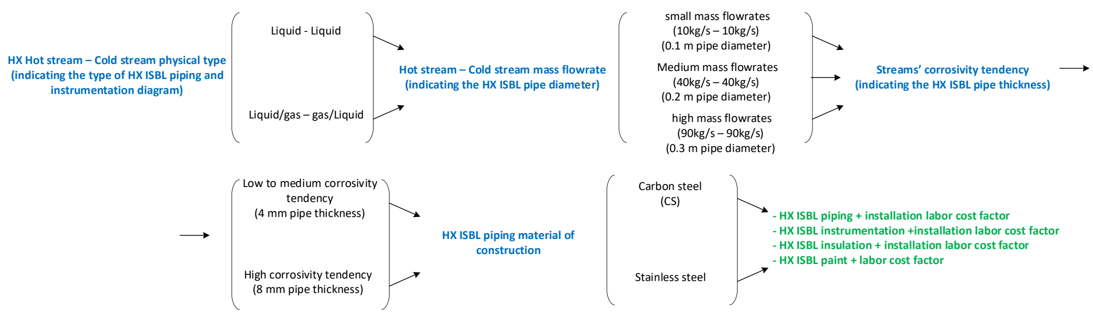
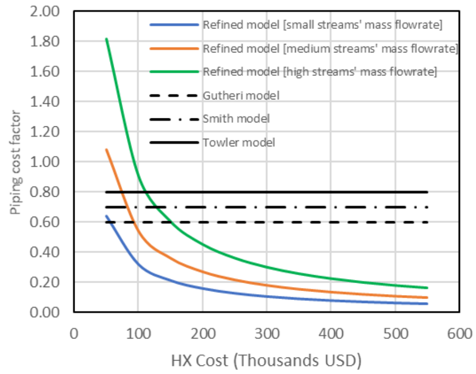
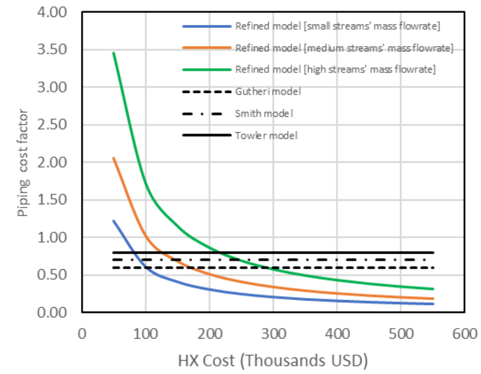


Figure 4.13. Superstructure of the characteristics used for refining new HX ISBL auxiliary cost factors.

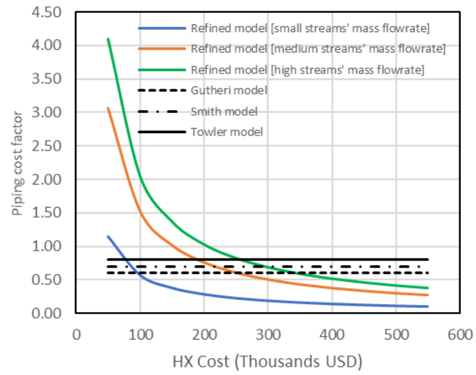
According to Figure *4.13*, the quantities of HX ISBL cost factors are influenced by the following parameters: (1) Phase of the HX's hot and cold streams, which specifies the type of process and control diagram chosen for new HX; (2) Mass flowrates of hot and cold process streams, which specifies the diameter of the HX ISBL piping system; and (3) hot and cold process streams' corrosivity tendency, which specifies the thickness of the HX ISBL piping and material of construction. Quantities of insulation and paint cost factors were refined based on two additional assumptions: (i) the amount of insulation required for HX ISBL is computed based on silicate calcium (30 mm thick) as an insulation type which covered by an AL jacket, and (ii) the amount of paint required for HX ISBL is computed based on two prime coats plus two finish coats.



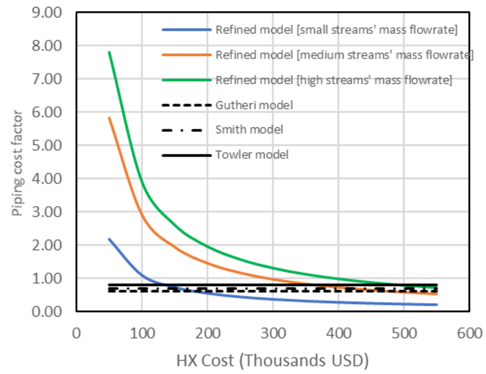
a. Piping (Carbon steel) cost factor for streams with low to medium corrosivity tendency



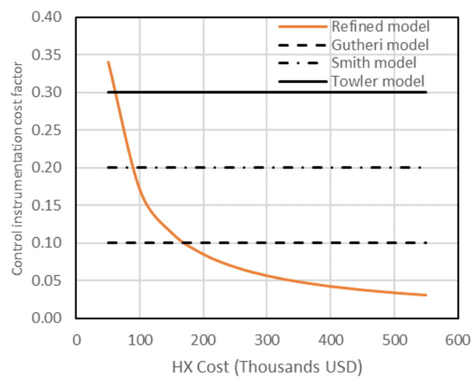
b. Piping (Carbon steel) cost factor for streams with high corrosivity tendency



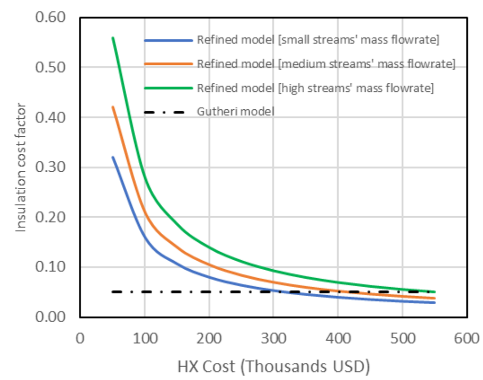
c. Piping (stainless steel) cost factor for streams with low to medium corrosivity tendency



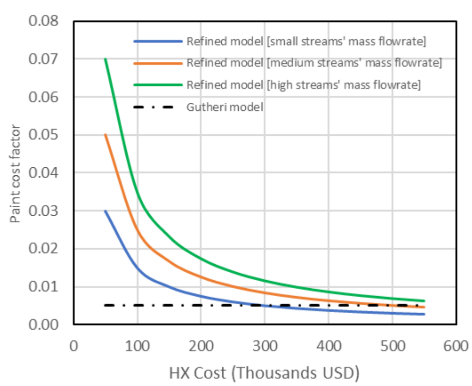
d. Piping (stainless steel) cost factor for streams with high corrosivity tendency



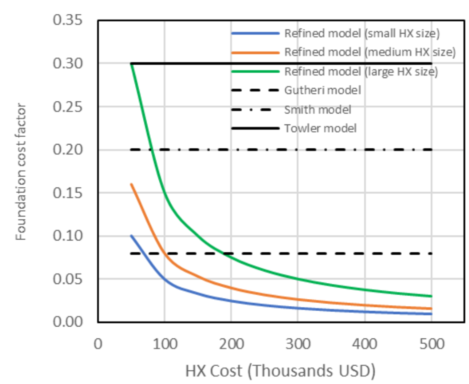
e. Instrumentation cost factor



f. Insulation cost factor

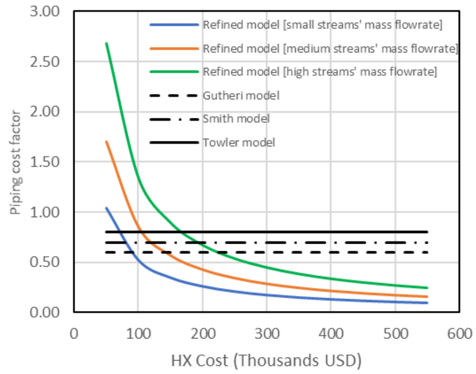


g. paint cost factor

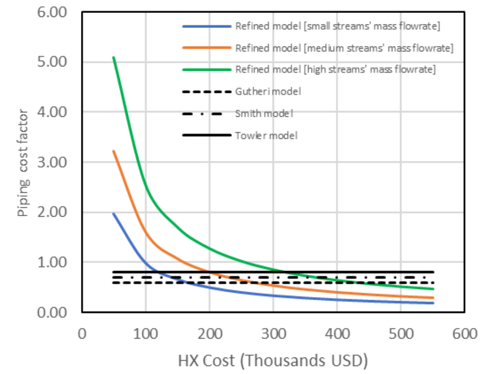


h. Foundation cost factor

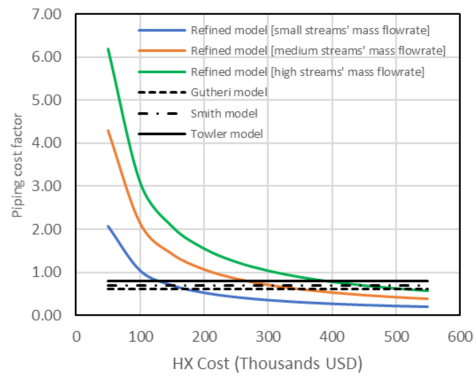
Figure 4.14. HX ISBL auxiliary equipment cost factors for liquid-liquid heat exchanging



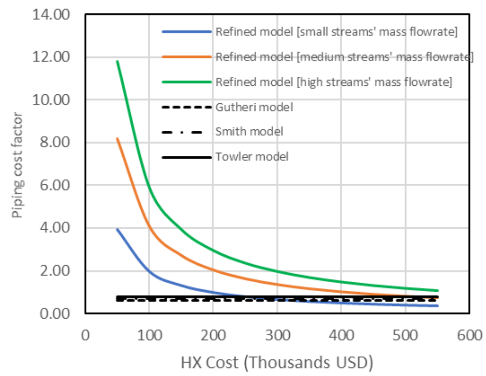
a. Piping (Carbon steel) cost factor for streams with low to medium corrosivity tendency



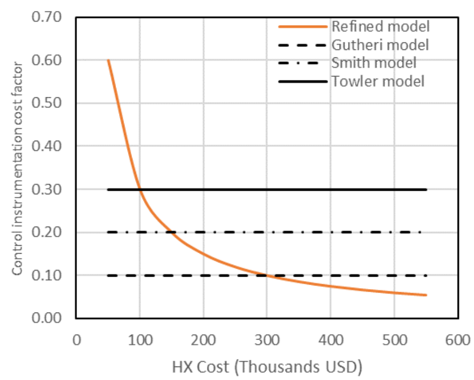
b. Piping (Carbon steel) cost factor for streams with high corrosivity tendency



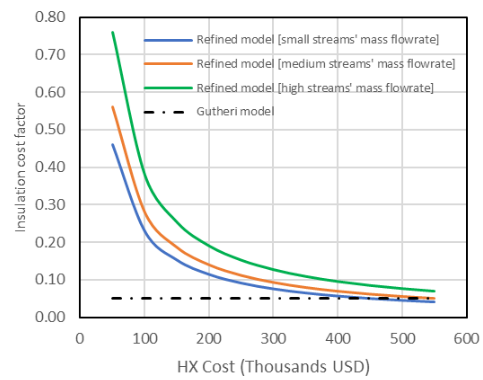
c. Piping (stainless steel) cost factor for streams with low to medium corrosivity tendency



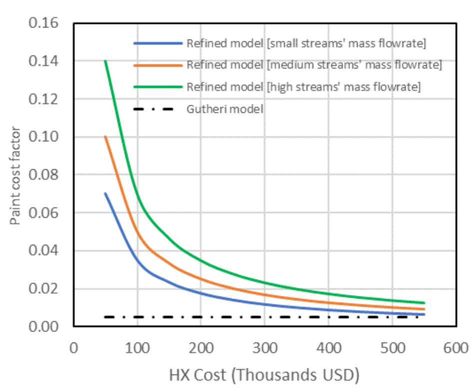
d. Piping (stainless steel) cost factor for streams with high corrosivity tendency



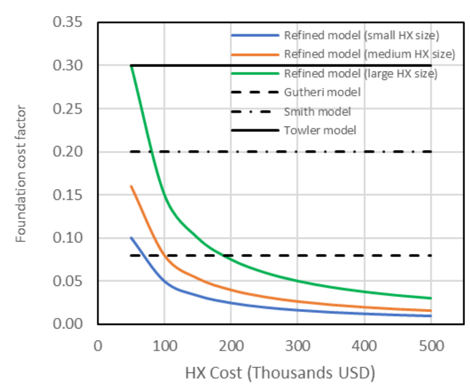
e. Instrumentation cost factor



f. Insulation cost factor



g. paint cost factor



h. Foundation cost factor

Figure 4.15. HX ISBL auxiliary equipment cost factors for liquid/gas-gas/liquid heat exchanging

- $f_{piping}(\frac{pump/compressor\ ISBL\ piping\ cost, USD}{pump/compressor\ cost, USD})$, $f_{instrumentation}(\frac{pump/compressor\ ISBL\ instrumentation, USD}{pump/compressor\ cost, USD})$, $f_{paint}(\frac{pump/compressor\ ISBL\ paint\ cost, USD}{pump/compressor\ cost, USD})$, $f_{insulation}(\frac{pump/compressor\ ISBL\ insulation\ cost, USD}{pump/compressor\ cost, USD})$ illustrate the costs of the auxiliary equipment items, as a percentage of the cost of the new pump/compressor, that need to be purchased in order to make pump/compressor operational as a OSBL of HRPs named "adding new HX unit" and "stream splitting-mixing and/or resequencing HX". *Figure 4.14* and Figure 4.15 depicted the quantitative value of these factors, which were calculated for a variety of situations super-structured in Figure *4.16*.

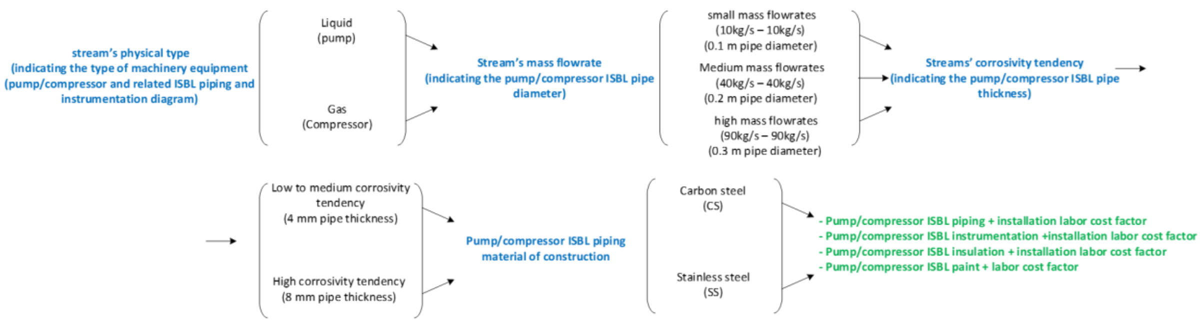


Figure 4.16. Superstructure of characteristics used for defining auxiliary equipment cost factors for pump/compressor

- $f_{paint}(\frac{piping-paint\ cost, USD}{piping\ cost, USD})$, $f_{insulation}(\frac{piping-insulation\ cost, USD}{piping\ cost, USD})$ illustrate the cost factors associated with piping system required for OSBL of HRP named "adding new HX" and ISBL of HRP named "stream splitting-mixing and/or resequencing of existing HX". figure 11 depicted the quantitative values of these factors, which were calculated for a variety of characteristics super-structured in Figure *4.17*.

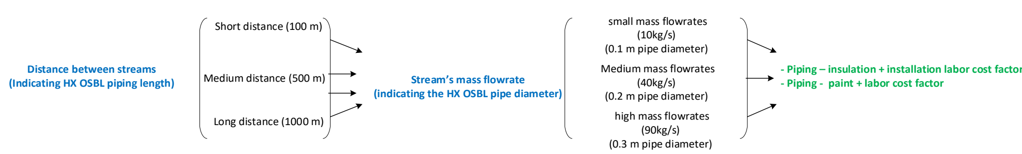
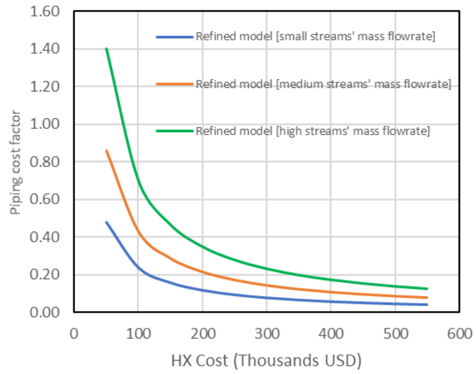
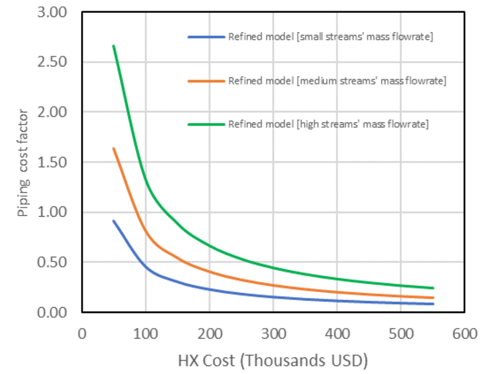


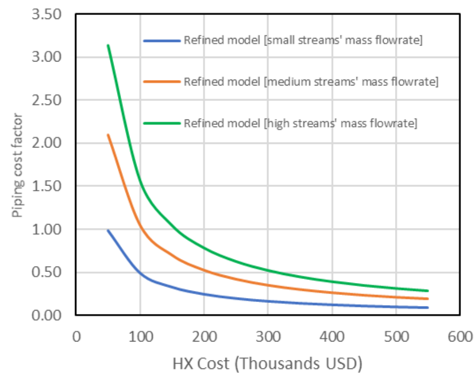
Figure 4.17. Superstructure of characteristics used for defining auxiliary equipment cost factors for piping system used as connection line between plant modules.



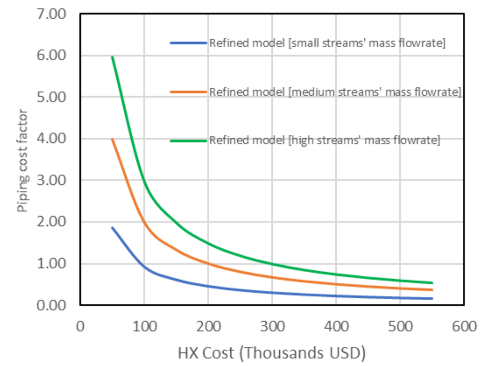
a. Piping (Carbon steel) cost factor for streams with low to medium corrosivity tendency



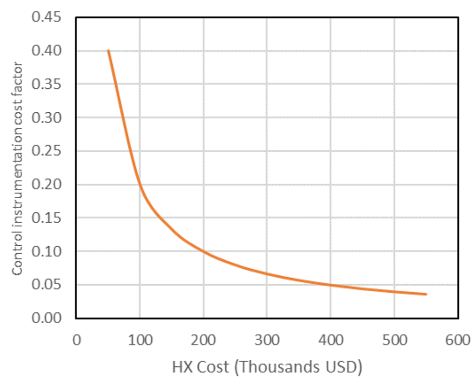
b. Piping (Carbon steel) cost factor for streams with high corrosivity tendency



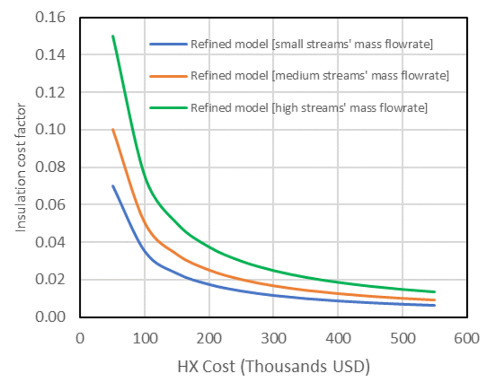
c. Piping (stainless steel) cost factor for streams with low to medium corrosivity tendency



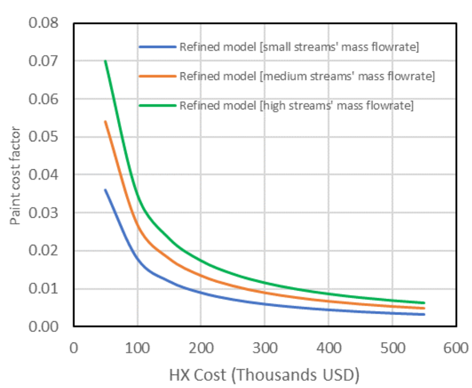
d. Piping (stainless steel) cost factor for streams with high corrosivity tendency



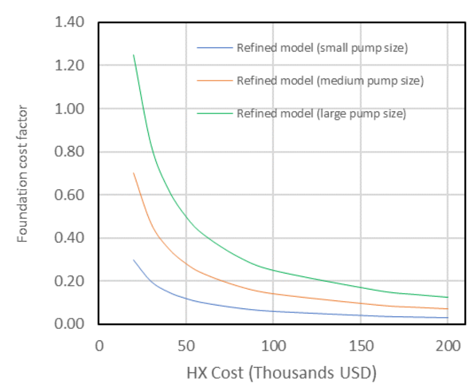
e. Instrumentation cost factor



f. Insulation cost factor

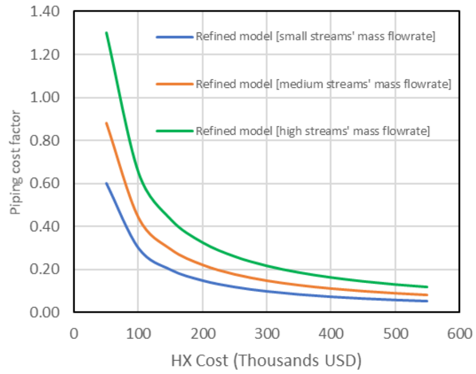


g. paint cost factor

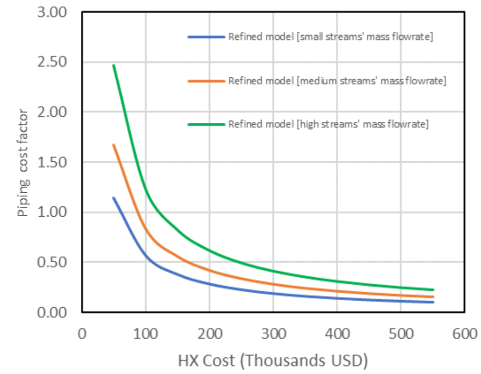


h. Foundation cost factor

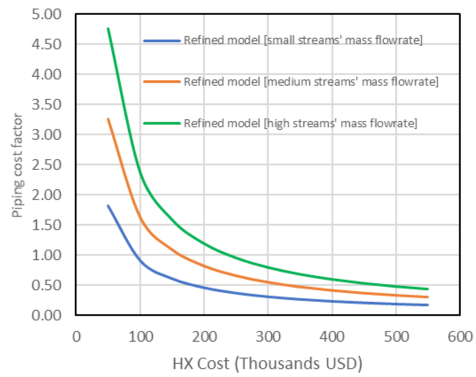
Figure 4.18. Pump ISBL auxiliary equipment items cost factors.



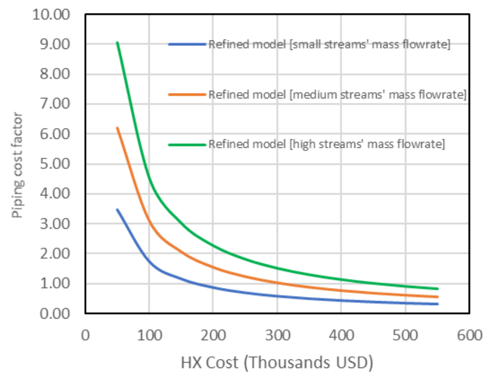
a. Piping (Carbon steel) cost factor for streams with low to medium corrosivity tendency



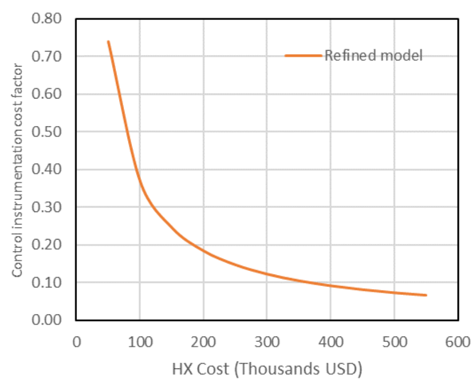
b. Piping (Carbon steel) cost factor for streams with high corrosivity tendency



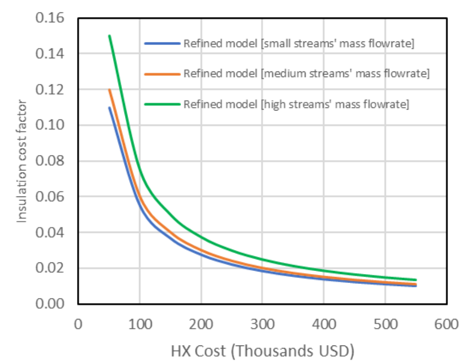
c. Piping (stainless steel) cost factor for streams with low to medium corrosivity tendency



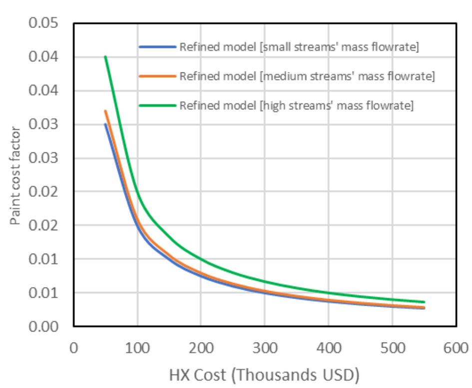
d. Piping (stainless steel) cost factor for streams with high corrosivity tendency



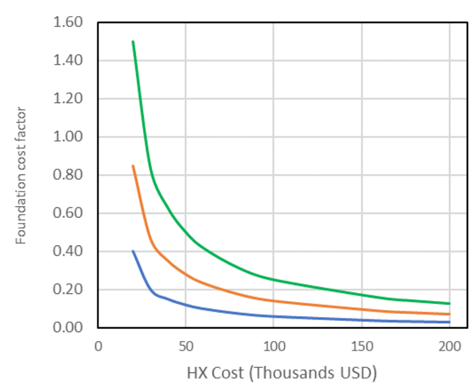
e. Instrumentation cost factor



f. Insulation cost factor

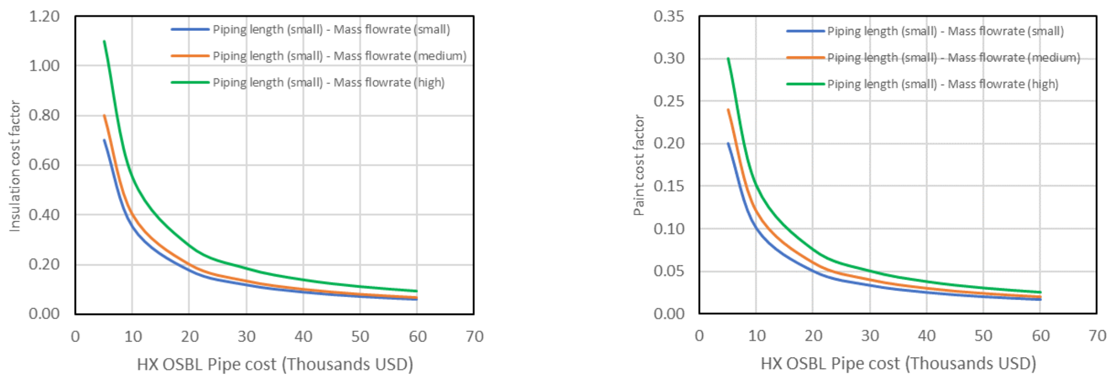


g. paint cost factor

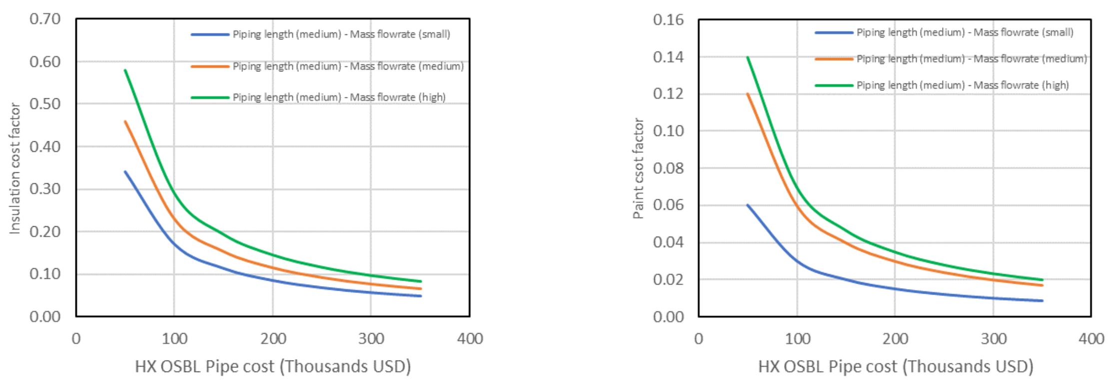


h. Foundation cost factor

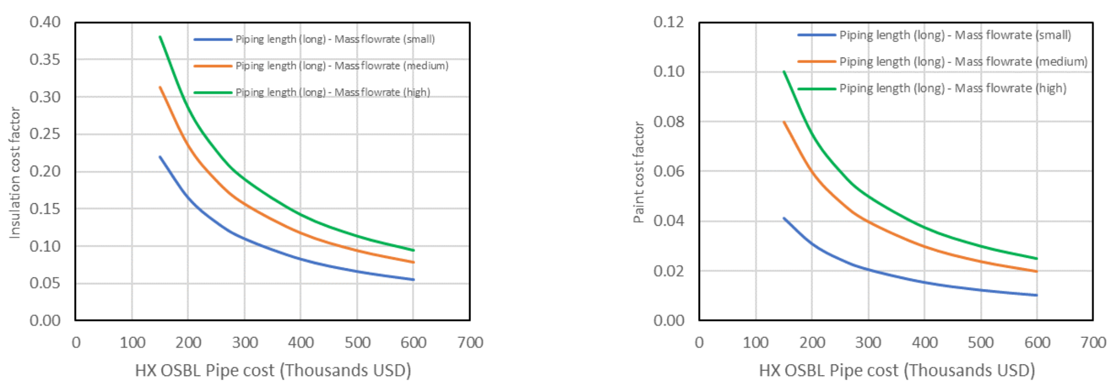
Figure 4.19. Compressor ISBL auxiliary equipment items cost factors.



a. Small piping length



b. Medium piping length



c. Long piping length

Figure 4.20. Auxiliary items' cost factors associated with piping system used as connection line between plant modules

TOCs saving

The objective of this section was to determine a guideline, Table 4.1, for decision makers to follow in order to select a reliable TOCs saving correlations after providing qualitative data for the following parameters that are available in the primary design stage: (i) type of fuel burning in steam boiler, (ii) type of steam saved (e.g., LP, MP, and/or HP) and the its generation pathway, (iii) energy saving capacity, and (iv) length of new piping system implied by HEN modifications. The plant process flow diagram (PFD) shows the qualitative information about the first two parameters. The information about the last two parameters can be found in the modified HEN grid diagram and through good engineering judgment. The parameters used in TOCs saving correlations are defined as follows: $Cost_{fuel}(\frac{USD}{Kj})$ represents the cost of the fuel burned in the steam boiler, $E^{i}_{saved-steam}(Kw)$ represents the amount of steam saved in utility-process HX, i, regardless of the steam pressure. $E_{saved-MP}(kW)$ and $E_{saved-LP}\,(kW)$ are the amounts of MP and LP steam saved in utility-process HX_i and HX_j. $Cost_{Elect.}\left(\frac{USD}{kwh}\right)$ is electricity selling price, $Elec_{HP\rightarrow MP}(kW)$ and $Elec_{HP\rightarrow LP}(kW)$ are the quantities of electricity produced after expanding HP steam into MP and/or LP steam using a steam turbine.

Table 4.1. TOCs saving.

Process Flow Diagram (PFD)	Modified HEN grid diagram - PFD	Modified HEN	Good engineering judgement	Suitable TOCs saving correlation
↓	↓	↓	↓	↓
Type of fuel burning in boiler	**Steam pressure saved and its generation pathway**	**Energy saving capacity**	**New piping length**	**TOCs saving correlation**
Expensive fuel $Cost_{fuel} \geq Cost_{NG}$	- Fuel → Boiler → HP_{steam} → HEN - Fuel → Boiler → MP_{steam} → HEN - Fuel → Boiler → LP_{steam} → HEN	$\geq 1\ MW$	$\leq 4000\, m$	$TOCs_{saving}\left(\frac{USD}{year}\right) = 31 \times 10^6 \times Cost_{fuel}\left(\frac{USD}{Kj}\right) \sum_{i=1}^{n} E^i_{saved-steam}(Kw)$
	- Fuel → Boiler → HP_{steam} → Steam turbine → MP_{steam} → HEN - Fuel → Boiler → HP_{steam} → Steam turbine → LP_{steam} → HEN	$\geq 1\ MW$	$\leq 4000\, m$	$TOCs_{saving}\left(\frac{USD}{year}\right) = \sum_{i=1}^{n}[31 \times 10^6 Cost_{fuel}\left(\frac{USD}{kj}\right) E_{saved-MP}(kW) - 8000 \times Cost_{Elect.}\left(\frac{USD}{kWh}\right) Elec_{HP\rightarrow MP}(kW)]_i + \sum_{j=1}^{m}[31 \times 10^6 Cost_{fuel}\left(\frac{USD}{Kj}\right) E_{saved-LP}(kW) - 8000 \times Cost_{Elect.}\left(\frac{USD}{kWh}\right) Elec_{HP\rightarrow LP}]_j$
Cheap fuel $Cost_{fuel} \leq Cost_{Biomass}$	- Fuel → Boiler → HP_{steam} → HEN - Fuel → Boiler → MP_{steam} → HEN - Fuel → Boiler → LP_{steam} → HEN	$\geq 1\ MW$	$\leq 4000\, m$	$TOCs_{saving}\left(\frac{USD}{year}\right) = 31 \times 10^6 \times Cost_{fuel}\left(\frac{USD}{Kj}\right) \sum_{i=1}^{n} E^i_{saved-steam}(Kw)$
	- Fuel → Boiler → HP_{steam} → Steam turbine → MP_{steam} → HEN - Fuel → Boiler → HP_{steam} → Steam turbine → LP_{steam} → HEN	$\geq 2\ MW$	$\leq 4000\, m$	$TOCs_{saving}\left(\frac{USD}{year}\right) = \sum_{i=1}^{n}[31 \times 10^6 Cost_{fuel}\left(\frac{USD}{kj}\right) E_{saved-MP}(kW) - 8000 \times Cost_{Elect.}\left(\frac{USD}{kWh}\right) Elec_{HP\rightarrow MP}(kW)]_i + \sum_{j=1}^{m}[31 \times 10^6 Cost_{fuel}\left(\frac{USD}{Kj}\right) E_{saved-LP}(kW) - 8000 \times Cost_{Elect.}\left(\frac{USD}{kWh}\right) Elec_{HP\rightarrow LP}]_j + 31 \times 10^6 \times Cost_{CW}\left(\frac{USD}{Kj}\right) \sum_{k=1}^{p} E^k_{saved-CW}(Kw)$
		$< 2\ MW$	$\leq 4000\, m$	$TOCs_{saving}\left(\frac{USD}{year}\right) = \sum_{i=1}^{n}[31 \times 10^6 Cost_{fuel}\left(\frac{USD}{kj}\right) E_{saved-MP}(kW) - 8000 \times Cost_{Elect.}\left(\frac{USD}{kWh}\right) Elec_{HP\rightarrow MP}(kW)]_i + \sum_{j=1}^{m}[31 \times 10^6 Cost_{fuel}\left(\frac{USD}{Kj}\right) E_{saved-LP}(kW) - 8000 \times Cost_{Elect.}\left(\frac{USD}{kWh}\right) Elec_{HP\rightarrow LP}]_j + [31 \times 10^6 \times Cost_{CW}\left(\frac{USD}{Kj}\right) \sum_{k=1}^{p} E^k_{saved-CW}(Kw)] - 8000 \times Cost_{Elect.}\left(\frac{USD}{kWh}\right) Elec_{pump-pipe}$

4.3 Benchmarking enhanced cost model against conventional factored-based cost models

This section was created to compare the global economic assessment of HRPs implied by SWEAMs to the conventional economic assessment approach, as well as the refined factored-based economic assessment approach to the conventional factored-based economic assessment approach. For the case study shown, the Bridge method was used to list all of the energy-saving projects (Table *4.2*), along with the different heat recovery targets.

Table 4.2. Case study – list of Bridges

No.	Bridge Modifications	Savings (kW)
1	$\{C_1^s h_1^r\}$	60
2	$\{C_1^s e_2^r, e_2^s h_1^r\}$	600
3	$\{C_1^s e_2^r, e_2^s h_1^r, e_1^s h_1^r\}$	720
4	$\{C_1^s e_1^r, e_1^s h_1^r\}$	800
5	$\{C_1^s e_2^r, e_2^s h_1^r, e_1^s h_1^r\}$	800
6	$\{C_1^s e_2^r, C_1^s e_1^r, e_1^s h_1^r, e_2^s h_1^r\}$	1100 (Maximum)

A modified HEN, including the modifications needed to meet energy saving recommendation, was generated (Figure *4.21*). This allows for the costing of each Bridge modification shown in Table *4.2*. The following are the presumptions upon which the HRP economic evaluation is based:

- Improved thermal integration between HEN process streams does not necessitate any major changes to existing HXs, which are adaptable enough to handle the new operating and thermal conditions.
- Direct process-process heat exchanging is used to implement the SWEAM suggestion known as "adding new HX."
- Carbon steel is chosen as the construction material for new equipment needed to implement topology changes necessitated by modified HEN.
- Based on shell and tube (floating head) HX, an estimate of the purchase price of the new HX, implied by the modified HEN, has been made.
- For the three reasons listed below, bridge implementation does not necessitate buying and installing a new pump. There are three assumptions made in this example: I new HXs are

sized based on the allowable pressure drop (1 bar) rather than the heat transfer coefficient of the streams; (ii) there are no elevation differences between the streams; and (iii) friction losses caused by the new piping system only increase plant pressure drops by a maximum of 1 bar.

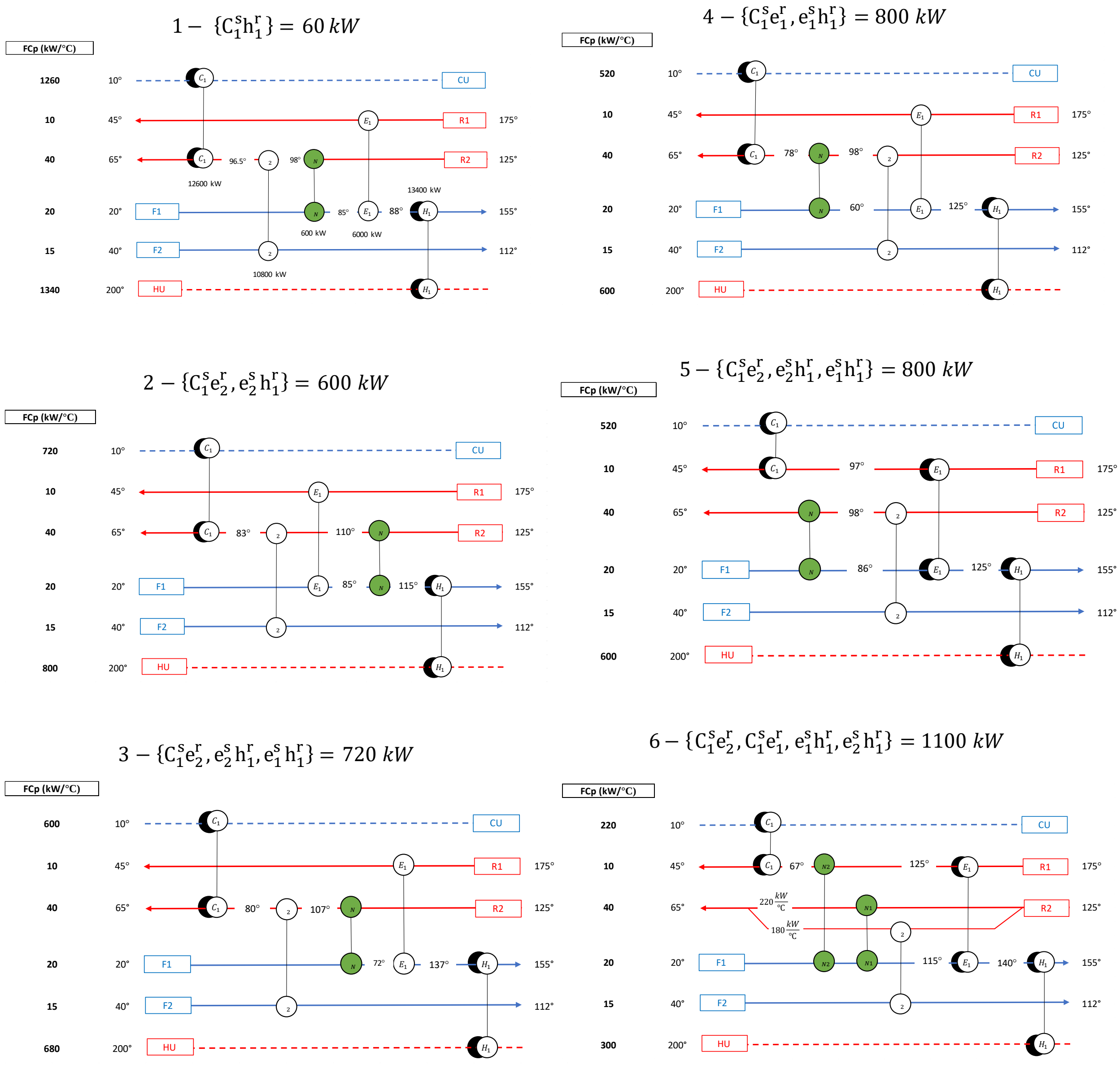


Figure 4.21. Case study – modified HEN grid diagrams.

Figure *4.22* compares the global costing approach of the HEN HRPs implied by Bridge and the conventional costing used in SWEAM's economic assessment, where only the cost of the HX is considered.

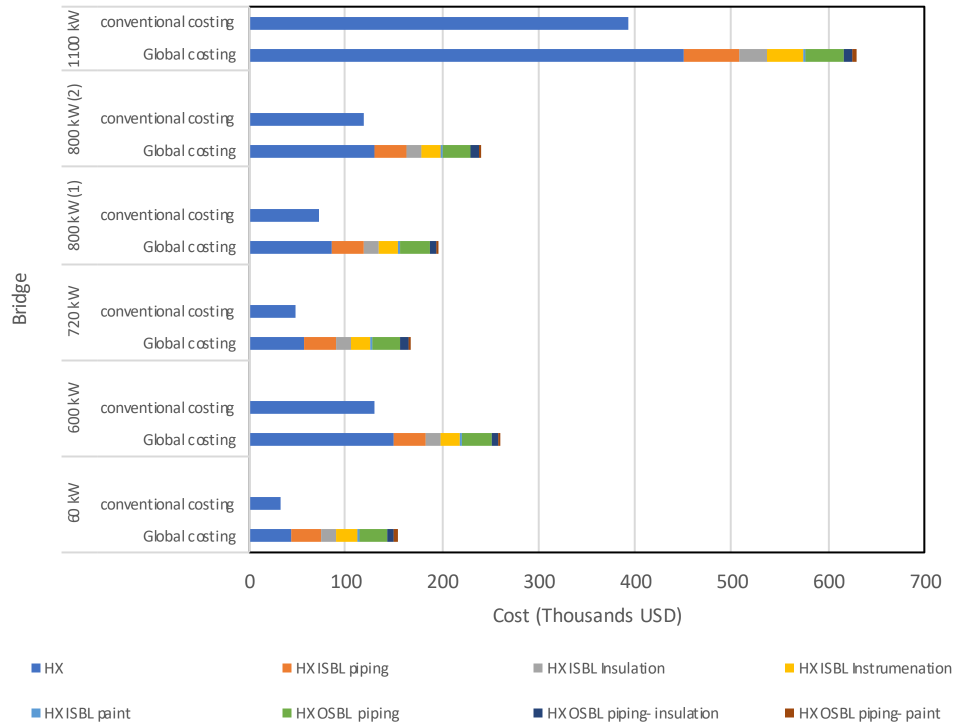


Figure 4.22. Case study – Global vs. conventional costing of HRPs implied by each Bridge modification.

This graph shows that each Bridge HRP's global cost is higher than its conventional cost. This is why: (i) conventional costing approach does not consider the impact of fouling coefficient on size and cost of the new HX, so the calculated values are underestimated, (ii) the cost of the equipment items required for making the new HX operational (e.g. ISBL piping and instrumentation) and related installation labor cost are not considered, and (iii) this approach does not include the OSBL module piping cost required for connecting new HX.

Figure *4.23* displays each Bridge's operating cost savings. As stated, the suggested global operating cost saving approach incorporates fuel and cooling water consumption reduction savings and addresses the negative effect of higher maintenance and electricity sales reduction caused by fuel consumption reduction. Due to subtracting electricity sales reduction from fuel and cooling water savings, conventional operating cost estimation results are higher than global operating cost estimation.

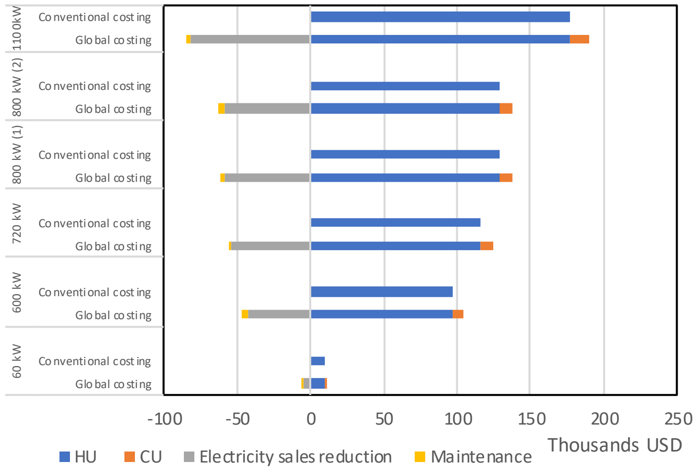


Figure 4.23. Case study – global vs. conventional TOCs saving implied by each Bridge.

Figure *4.24* compared the Internal Rate of Return (IRR) of each HRP's investment to show how global costing can change the number of profitable HRPs. According to the economic assessment results based on the conventional costing approach, all Bridge modifications are profitable except $\{C_1^s h_1^r\} = 60kW$. However, using global costing, only 2 HRPs have IRRs above the threshold (30%),$\{C_1^s e_2^r, e_2^s h_1^r, e_1^s h_1^r\} = 720kW$ and $\{C_1^s e_1^r, e_1^s h_1^r\} = 800kW$. This is as a result of the need for higher investment costs and lower operating cost savings when using the global costing approach.

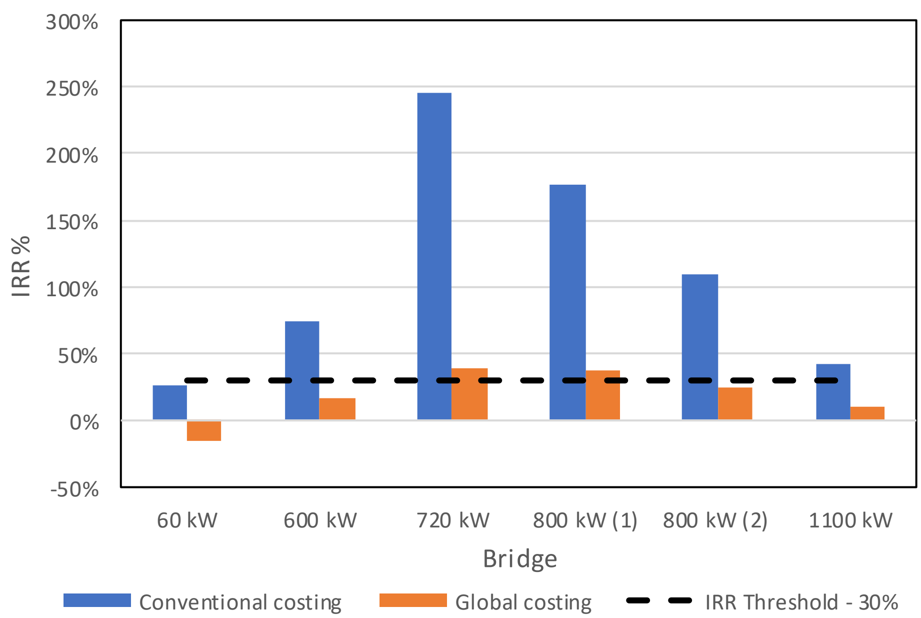


Figure 4.24. Case study - IRR for Bridge modifications (global costing vs. conventional costing)

It was stated that there is insufficient time and information during the primary design stage to conduct a global economic assessment of the HRP implied by SWEAM. In this regard, an improved factored-based costing approach was proposed, which has the capability of estimating the cost of the HRP's ISBL and OSBL auxiliary equipment as a percentage of the main equipment, which can be sized and costed based on information available during the preliminary design stage. Figure 4.25 compares the IRR of each HRP's investment to demonstrate how an improved factored-based cost model can change the number of profitable Bridge modifications with greater IRR than the threshold IRR (30%). Using the Gutheri factored-based cost model results in an underestimation of IRR for some bridges and an overestimation for others when compared to the results of the enhanced factored-based costing approach, which was characterized based on the global costing approach. This is because the Gutheri method uses the same cost factors to estimate the auxiliary equipment costs as a proportion of the HX purchase price. In the enhanced factored-based costing approach, however, the auxiliary cost factors were characterized based on the thermophysical properties of streams and the plant's topology. Consequently, using the Gutheri cost model causes decision makers to disregard the Bridge $\{C_1^s e_2^r, e_2^s h_1^r, e_1^s h_1^r\} = 800\ kW$ because its IRR is below the threshold; however, the enhanced cost model indicates that this project is profitable.

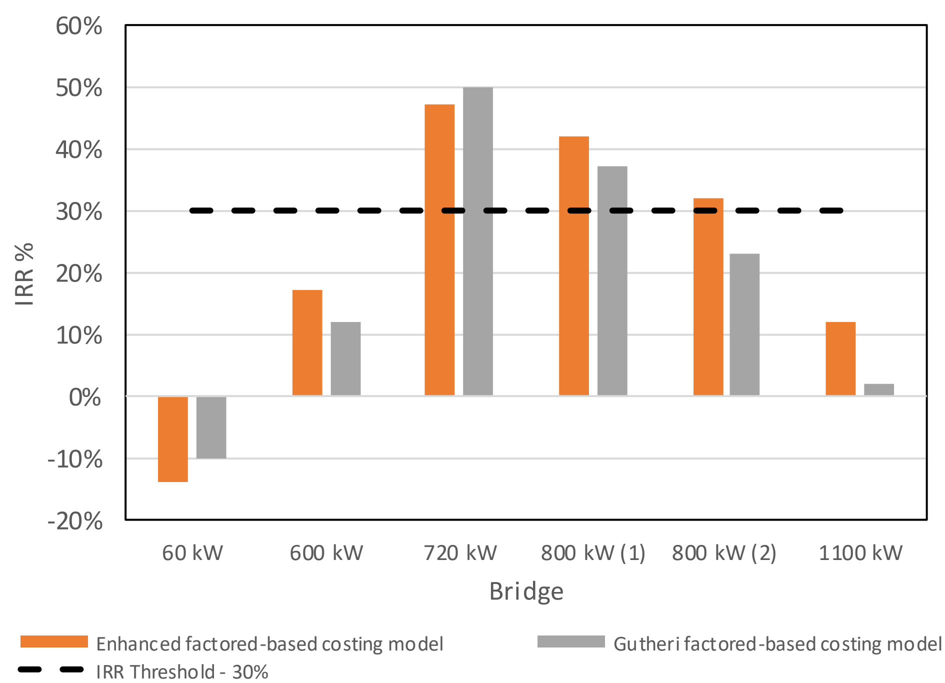


Figure 4.25. Case study – Comparing IRR of investment for Bridge modifications

CHAPTER 5 GENERAL DISCUSSION

As a result of the rising cost of fossil fuels, the ongoing depletion of fossil-based resources, and greenhouse gas emission reduction's regulations, owners of industries have realized that they must increase the thermal efficiency of their facilities if they wish to remain competitive with similar industries that are designed more efficiently and utilize more modern facilities. Retrofitting existing HEN is an important way to achieve energy and cost savings in process industries, among several options available for increasing energy efficiency in industries.

For the purpose of retrofitting HENs within individual processes and Total Sites, several systematic approaches and strategies (e.g., Pinch and Bridge) have been developed. In spite of their methodical nature, these methods fail to take design and cost considerations into account when identifying HEN retrofit projects. For instance, (1) the cost of the projects such as modifying existing HXs, splitting streams, and relocating existing HXs has been ignored, (2) the cost implications of considering process stream fouling tendency on the size and thus cost of new HX implied by SWEAMs have been overlooked, (3) As a result of retrofit projects, some modifications must be considered OSBL of each HRP to balance the HEN, which the design and cost of which have not been addressed, (4) The cooling water consumption reduction savings and negative effect of higher maintenance and electricity sales reduction caused by installing new equipment and fuel consumption reduction have not been addressed in economic assessment of heat recovery projects implied by SWEAMs.

These gaps stimulated the identification of key design and cost parameters that influence the economic assessment of HRPs implied by SWEAMs and the development of a global economic assessment model that incorporates these parameters. To demonstrate that the new global costing approach is a rigorous tool that provides the analyst with more precise economic data to help in the open-ended decision-making processes associated with the HEN retrofit, an example was provided to compare the global economic assessment of the HRPs to the conventional costing methodology addressed in SWEAM-based literatures, where only the cost of the HX was considered.

However, there is insufficient information and time at the preliminary design stage to conduct a rigorous economic assessment of HEN retrofit projects. Also, existing factored-based costing methods suitable for module-equipment costing are also untrustworthy due to their insensitivity to equipment design alternatives and plant topology. These gaps motivated to introduce enhanced factored-based costing approach that proposes a single relationship that correlates the purchase and installation costs of HRP's ISBL and OSBL equipment items. In this approach, the cost factors associated with the auxiliary equipment items of HX, the pump/compressor and the piping system used to connect two plant modules, were characterized based on the operating conditions that have an impact on their size. Finally, an example was provided to compare the refined factored-based cost model with the existing conventional factored-based costing approach addressed in the literature to demonstrate how the adoption of a good costing model may influence a decision maker's choice of an economically feasible HRP among the several projects suggested by SWEAMs.

CHAPTER 6 CONCLUSION

Increasing thermal integration between process streams within process units and the site as a whole can save energy and money, reduce carbon emissions, and increase the competitiveness of existing industries compared to those that are designed based on optimal energy consumption targets. Associated with site-wide energy analytics methods as a systemic tool for locating heat exchanger network retrofit projects, efforts have been focused on defining and/or refining visualization tools suitable for identifying thermal integration opportunities according to the first and second laws of thermodynamics. This is because the energy savings implied by each heat recovery project were regarded as the most important key performance indicators for selecting an acceptable project from a pool of multiple proposals, and do not take into account issues in conjunction with retrofit project design and costing. However, in order to choose between different retrofit projects or assess a retrofit project's viability, HEN Retrofit projects require a trustworthy design and cost estimate in the early design stages.

This paper has aimed to take into account design complexity and cost elements associated with each type of HEN topology modification to introduce enhanced parametric costing model suitable for economic assessment of heat recovery projects implied by site-wide energy analysis methods. In this regard, the relationship between SWEAM recommendations and HEN topology modifications was clarified through a critical review of SWEAMs. The outcomes of this step were used to define the global economic assessment of each HRP type, which correlates the cost components of the project's ISBL and OSBL equipment items. In addition, a global operating costs was introduced, which incorporated fuel and cooling water consumption reduction savings and addressed the negative effects of increased maintenance and decreased electricity sales caused by the reduction in fuel consumption. An example was given to compare the global costing approach to the conventional costing methodology addressed in literatures in order to demonstrate that the new global costing proposal is a rigorous tool that provides the analyst with more precise economic data to aid in open-ended decision-making processes. The findings revealed that using traditional costing results in winning a contract but incurring a financial loss, establishing the so-called "curse of the winner."

Literature proposes a factor-based cost model to estimate module-equipment costs at the preliminary design stage, when there is insufficient time and data to conduct a rigorous economic evaluation of HRPs. However, there are two major knowledge gaps associated with these modifications: (1) HX cost factors are only proposed for HX, whereas HEN topology modifications also include installing a pump/compressor to eliminate new pressure drop and a piping system to connect different modules of the plant. (2) HX cost factors are unreliable because they are not sensitive to operating conditions and plant topology. These gaps encouraged the development of a refined factored-based costing model, which was inspired by the global costing approach of four different HRPs. In addition, the cost factors associated with installing a new HX, pump/compressor, and piping system have been refined and quantified in accordance with the operating conditions and plant topology. Finally, a case study is provided to illustrate how the adoption of a good costing model may affect a decision maker's selection of a financially viable HRP among the various projects suggested by SWEAMs by comparing the refined factored-based cost model with the existing conventional costing approach addressed in the literature.

We need to know how to use structured data associated with SWEAMS costing projects systematically in order to take advantage of emerging computing tools, algorithms, and computers. As a recommendation for future work, an algorithmic costing framework suitable for use at the early stages of cost estimating can be defined on the basis of data-base, knowledge-base, and model-base information. It is worth noting that no one has considered how to use systematically structured data for costing heat recovery projects in conjunction with SWEAMs in the public literature.

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Appendix A ARTICLE 1: KEY PARAMETERS IMPACTING THE PROFITABILITY ASSESSMENT OF HEAT RECOVERY PROJECTS AT THE EARLY DESIGN STAGE

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Abstract

Heat exchanger network (HEN) projects in either the greenfield or retrofit context can be identified at the early design stage using site-wide energy analysis methods (SWEAMs), such as thermal Pinch Analysis or Bridge Analysis. This paper identifies key design parameters that influence the estimates of capital and operating costs of heat recovery projects (HRPs) for modifying existing HENs, needed in order to choose amongst the design alternatives implicated by SWEAMs. An example is provided that compares the economic assessment of HRPs using the practical if detailed method proposed here to the conventional costing estimation method and demonstrates how the new costing approach provides the analyst with more precise economic information to help in the decision-making processes associated with the HEN retrofit.

Keywords: Site-wide energy analytics methods (SWEAMs), Heat exchanger network (HEN), retrofit, Bridge method, Pinch method, investment cost, operating cost

1. Introduction

1.1 Background

Improving thermal integration between process streams through the retrofit of existing heat exchanger networks (HENs) is a well-known approach for economic and environmental improvements in existing plants [12]. For effective decision-making amongst possible options suggested by site-wide energy analysis methods (SWEAMs), HEN retrofit projects need reliable cost estimates in the early design stage to generate metrics such as internal rate of return (IRR). In this study, the key cost components that influence the economic assessment of HRPs are identified, and we introduce a more rigorous "global" costing approach than those typically employed.

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1.2 Literature review

This section discusses how literature have addressed the design and costing of HEN retrofit projects implied by site-wide energy analytics methods (SWEAMs).

Tjoe and Linnhoff [20] proposed the use of Pinch technology for HEN retrofit, where heat recovery projects are identified to remove cross pinch matches and reduce utility demand. The capital cost model used in this early work to evaluate retrofit projects considered the purchase cost of the new heat exchanger, and not the auxiliary equipment nor the installation of the HEN projects. Savings in total operating costs were based on estimates of the reduction in hot utility demand.

Carlsson et al. [22] noted that in the targeting stage, for early design decision-making, the most economic HRPs require the least amount of heat exchanging surface. However, a reliable costing approach must allow the decision maker to take into account a wide variety of variables that affect the project cost. In this regard, they suggested a novel costing approach for the targeting stage that takes into account the heat exchanger (HX) type and construction materials. The model also takes into account the cost of piping needed to tie-in the new HX to the existing process, as well as the cost of the pump needed to mitigate pressure drops caused by friction losses across the new HX and piping system. The costing methodology was used to cost pulp and paper mill HEN retrofit projects and was compared to existing published costing methods. According to the results, it was found that 32% of the total investment cost (TIC) for the retrofitted network is attributable to the purchase cost of new HXs, while the remaining investment is for the piping and pumps. Two additional criteria were also considered: maintenance costs and hot utility demand decreases.

To simplify the design of the modified HEN, Van Reisen et al. [23] proposed a path analysis approach for decomposing existing HENs into subnetworks, and the method used for designing the modified HEN of the Aromatics plant introduced by Tjoe and Linnhoff [20]. This study's capital cost model only considered the cost of the new HX, not the auxiliary equipment or HEN project installation. The model ignores the investment cost for other HEN modifications implied by modified HEN, such as modifying existing HX(s), stream(s) splitting-mixing, etc. Furthermore, the sole measure utilised to estimate operating cost reductions in improved HEN was fuel savings due to reduced hot utility consumption.

Asante and Zhu [60] found that conventional Pinch technology for retrofitting a HEN doesn't work for all types of retrofit projects, and developed a method commonly called Network Pinch. The new approach was subsequently utilised to identify HRPs and design a modified HEN for the Crude Oil Refinery plant. The heat recovery projects (HRPs) consisted of one new HX, resequencing of two HXs, one stream splitting and mixing, and the increased thermal duty of five existing HXs. In the economic analysis of the project, it was assumed that the just additional HXs would require investment, and that operational cost savings would be based on the decrease of fuel that must be consumed to generate steam as a hot utility stream.

Nordman and Berntsson [24] introduced the Advanced Composite Curves (ACCs) to identify economically feasible retrofit HEN projects. The ACCs do not provide a quantitative estimate of the cost of retrofitting, but rather a semi-quantitative estimate of how much heat would be cost-effective to recover through HEN retrofitting. Bengtsson et al. [40] used the ACCs in a case study at the Skoghall pulp and paper mill to determine the potential and cost of upgrading the existing HEN to release surplus heat at temperatures appropriate for pre-evaporation of the chemi-thermo-mechanical pulp mill effluent. They employed the Matrix technique introduced by Carlsson et al. [22] to identify the investment cost of heat recovery projects.

Pinch technology was utilised by Axelsson et al. [38] to study paper mills from an energy standpoint in order to identify HRPs that would reduce steam consumption. In this study, two major assumptions were made regarding the use of steam surplus: (i) the mill has access to a market where the energy surplus can be sold, and (ii) there is no external use of steam surplus, which implies expanding it in a steam turbine to generate electricity or blowing out steam to the atmosphere. The investment cost of the HRPs was calculated using a uniform purchase cost equation for new HXs, which is insensitive to HX type and construction material, and identical piping costs as a function of stream distance. Additionally, the operating cost changes were calculated by adding the cost of fuel needed to generate steam, the cost of electricity required to power the cooling water tower fans, and the negative value of revenue from selling excess steam. In another study, Axelsson et al. [39] employed pinch technology to investigate improvements to the HEN of bleached pulp mills in order to generate steam surplus for additional power generation or to make lignin extraction possible. The economic assessment of this study did not take into account the budgets that would be necessary for increasing /decreasing the area of the existing process - process and process - utility HXs. It also did not take into account the cost of the streams splitting-mixing implied by modified HEN grid diagram.

Applying pinch-based methods to multiple case studies in order to identify HRPs has been addressed over many studies by the research team at Chalmers Institute of Techjnology: Nordman et al. [41], Olsson et al. [42], Becker et al. [43], Hackl et al. [44], and Fornell et al. [45]. However, the approach used to estimate the economics of HEN modifications did not advance over the course of these studies.

Since 2012, published investigations in the area of using SWEAMs for HEN retrofitting have emphasized defining and/or refining visualization tools and/or numerical tools used to obtain energy saving targets, and design modified HEN based on thermodynamic criteria. Little attention has been paid to improve methodologies regarding economic aspects of HEN retrofit measures, despite their critical importance.

More recently, Bonhivers et al. [9, 28] proposed the Bridge Method, and concepts of an Energy Transfer diagram (ETD) and Network Table that represent and quantify heat saving possibilities by showing the heat degradation through process units and existing HXs. Bonhivers and co-workers published two papers to show the advantages of Bridge Analysis and how it could be used, alongside more conventional methods [29, 61]. It represents a significant advancement in SWEAMs. Others like Varbanov et al. [62] and Walmsley et al. [63] [33] have contributed to further developments of the Bridge Method, however to date, no attention has been paid to the economic aspect of HEN retrofit measures.

1.3 Objective of this paper

While the design and costing of retrofitting projects implied by SWEAMs have been treated in the literature, there are still some holes in the body of knowledge that are listed as follows:

- There have been few advances for estimating the cost of SWEAM-based recommendations for the modification of existing HXs, splitting streams, and relocating existing HXs reported in the literature.
- As a consequence of retrofit projects, to balance of the HEN, the system modifications and cost for these must be considered for the HX, new module piping and pump system. The cost of these system-level components has not been addressed in literature.

- The cost of supplying cold utility water, cost of pumping power required to circulate process streams in the HEN, and maintenance costs have not been addressed in the literature, considering the systems level.

This paper aims to address gaps in the literature by identifying the key design and cost parameters that impact the capital and operating costs implicated in recommendations emanating from the application of SWEAMs, at the early design stage.

For achieving this goal, Section 2 elucidates a relationship between SWEAMs recommendations (HRPs), and practical design solutions that show how HRPs can be manifested in modified HEN. This section also introduces the "global economic assessment" of the HRPs, which includes candidate key cost parameters that affect the global investment cost of the projects as well as the global operating cost savings implied by them. In order to identify key parameters, section 3 presents the results of a quantitative analysis that examines the effect of each candidate cost component listed in the previous section on the global costing of the projects when the design parameters of the HRPs are altered. Finally, in section 4 we concretize the results using a case study in which the results of the global economic assessment of HRPs are compared with those the typical costing approach used at the early design stage.

2. Global economic assessment of the HRPs implied by SWEAMs

Relationship between SWEAM recommendations and practical design solutions

With the objective of how to achieve minimum energy consumption targets, each SWEAMs use different information and methodologies to fulfill the necessary steps to identify heat recovery projects. For example, the classical Pinch method uses process stream supply and target temperatures as well as heat capacity flows to locate pinch point temperature on the existing HEN grid diagram. Then, it is possible to find and evaluate pinch violation matches that must be eliminated to reduce the flow rate of heat cascaded from hot utility to cold utility and then transferred across the pinch point temperature [11]. The Bridge Method uses thermophysical information associated with existing HX streams to plot the Energy Transfer Diagram or ETD, and uses the ETD in combination with Network Table and Heat-Exchanger Load Diagram (HELD) to identify and evaluate prime and composite Bridges that show (1) which existing HXs should be kept in their current locations, (2) which should be modified, (3) which should be moved, (4) which stream should be split, and (5) where new HXs should be placed [64].

Associated with design and operability constraints, SWEAM recommendations can imply different topology modifications, and consequently different modified HEN configurations [2, 13]. Figure 26 shows practical design solutions to illustrate how SWEAMs-recommended HRPs can manifest.

For instance, a process plant will typically be broken up into several logically distinct portions or zones. It might be necessary to keep these sections separate in order to facilitate things like starting up, shutting down, increasing operational flexibility, or improving safety. In these kinds of autonomous zones, also known as areas of integrity, the amount of heat that can be transported there is severely restricted. Since two locations cannot rely on each other for heating and cooling via direct heat recovery, indirect heat exchanging via an intermediate fluid must be selected to ensure operational independence when SWEAM recommends "inserting new HX."

As a heuristic, choosing “the best” topology modification, which are the set of HEN-based structural modifications implied by SWEAMs, generally requires the least change to the existing HEN. However, broader engineering judgment is required to assess the strengths and weaknesses of different possible topology modifications associated with an HRP. This judgement is open-ended, such as technology type implicated, risk, and should also be based on constraints associated with operational performance such as controllability, flexibility and special operations like start-up, shutdown, emergency, and maintenance.

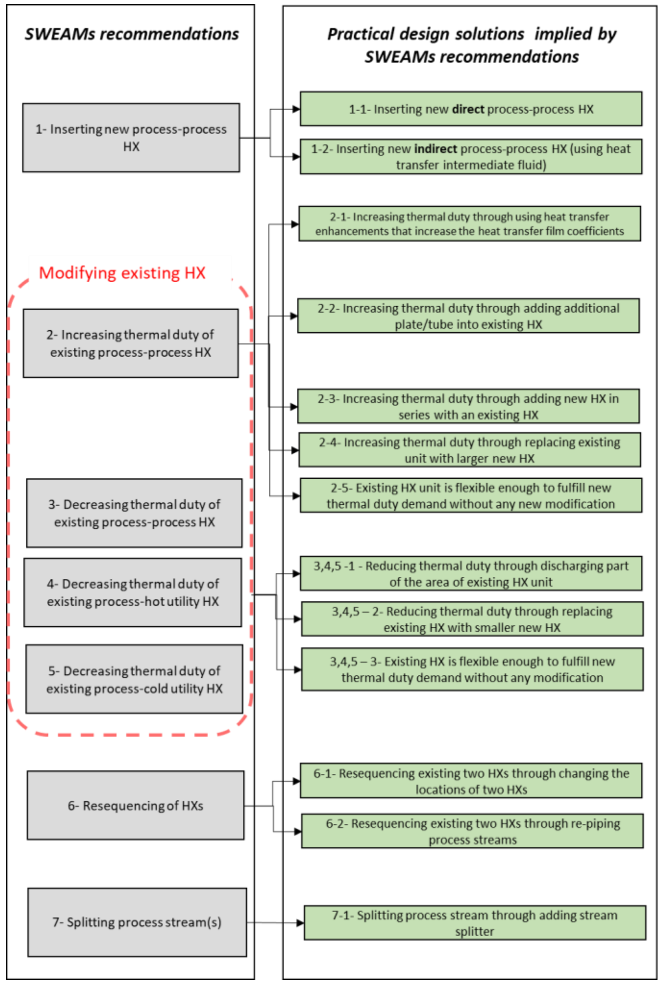


Figure 26. Relationship between SWEAM recommendations and potential design solutions

Key cost components impacting the economic assessment of the HRPs – "Global Investment Cost Estimate"

Figure 26 provides the basis used to define the "Global Investment Cost Estimate" we refer to in this paper. Equation 6 is implied by SWEAMs coupled with good engineering judgment. It correlates five main cost components including (i) cost of the new HX unit(s): $C^{Adding\ new\ HX\ unit}$, (ii) the cost of modifying an existing HX: $C^{Modifying\ existing\ HX}$, (iii) the cost of the resequencing existing HX(s) through stream re-piping: $C^{Resequencing\ existing\ HX}$, and (v) the cost of stream splitting-mixing: $C^{stream\ splitting-mixing}$. Depending on the size of the energy-saving project, the nature of the case study, and good engineering judgment, some or all of the above-mentioned cost components contribute to the direct cost component of the Global Investment Cost Estimate.

$$Direct\ TIC = \sum_{i=1}^{n} C_i^{Adding\ new\ HX\ unit} + \sum_{j=1}^{m} C_j^{Modifying\ existing\ HX} + \sum_{k=1}^{p} C_k^{Resequencing\ existing\ HX} + \sum_{l=1}^{q} C_l^{stream\ splitting-mixing} \quad \text{Equation 6}$$

The Global Investment Cost Estimate for a new HX (Equation 7) includes (i) **the Inside Battery Limits or *ISBL cost***, which is the summation of the HX purchase cost, axillary items required for erecting new HX in place and making it operational (e.g., ISBL piping, control instrumentation, insulation, etc.), and installation labor cost, and (ii) **the Outside Battery Limits or *OSBL cost***, which is the summation of the module piping system purchase cost required for connecting the new HX unit into the existing process, including pump/compressor purchase costs that may be required for eliminating pressure drop caused by HEN topology modifications [53].

$$C^{New\ HX\ unit} = \{C_{HX} + C_{foundation} + C_{piping} + C_{paint} + C_{insulation} + C_{Instrumentation} + C_{installation\ labor}\}_{HX\ ISBL\ costs} + \{C_{pump/compressor} + C_{foundation} + C_{piping} + C_{paint} + C_{insulation} + C_{instrumentation} + C_{labor}\}_{HX\ OSBL\ costs-pumping/compressing} + \{C_{piping} + C_{paint} + C_{insulation} + C_{installation\ labor}\}_{HX\ OSBL\ costs-piping\ system} \quad \text{Equation 7}$$

Equation 8 to Equation 12 represent the Global Investment Direct Cost Estimates for the SWEAM recommendation entitled "*modifying existing HX*," which varies depending on the type of practical design solution chosen for implementing the project in modified HEN.

- Modifying existing HX – Inserting heat transfer augmentation devices (HTADs)

$$C^{Modifying\ existing\ HX} = C_{HTADs} + C_{installation\ labor} \quad \text{Equation 8}$$

- Modifying existing HX – Discharging existing HX and replacing it with smaller/bigger one OR installing new HX in series with existing one

$$C^{Modifying\ existing\ HX} = \{C_{HX} + C_{foundation} + C_{piping} + C_{paint} + C_{insulation} + C_{Instrumentation} + C_{installation\ labor}\}_{New\ HX\ ISBL\ costs} \quad \text{Equation 22}$$

- Modifying existing HX – increasing number of tubes/plates of existing HX

$$C^{Modifying\ existing\ HX} = C_{additional\ tube/plate} + C_{installation\ labor} \quad \text{Equation 23}$$

- Modifying existing HX – discharging part of the area of existing HX

$$C^{Modifying\ existing\ HX} \approx 0\ (Assumed) \quad \text{Equation 24}$$

- Modifying existing HX – existing HX is flexible enough to fulfill new thermal duty demand without any modification

$$C^{Modifying\ existing\ HX} \approx 0\ \text{(Assumed)} \quad \text{Equation 12}$$

The Global Investment Cost Estimate of the SWEAM recommendations entitled "*Resequencing of HXs (using stream(s) re-piping"* and "*stream splitting-mixing"* are comprised of two major cost components (Equation 26): (i) the cost of a new module piping system, and (ii) the cost of a new module pump, each of which includes the cost of the main equipment, auxiliary items required to make them operational, and labor cost for installation.

$$C^{Resequencing\ existing\ HX} or C^{stream splitting-mixing} = \quad \text{Equation 26}$$
$$\{C_{piping} + C_{paint} + C_{insulation} + C_{labor}\}_{Module\ of\ new\ piping\ system\ costs}$$
$$+ \{C_{pump/compressor} + C_{foundation} + C_{piping} + C_{paint}$$
$$+ C_{insulation} + C_{Instrumentation}$$
$$+ C_{installation\ labor}\}_{module\ of\ new\ pumping/compressing\ unit\ costs}$$

Total Operating Cost (TOC) estimates with heat recovery projects - – "Global Operating Cost Estimate"

Equation 27 presents the four main cost components that contribute to the savings in Total Operating Costs as a consequence of lowering the process stream minimum approaching temperature (IMAT).

$$TOC_{saving} = \sum_{i=1}^{n} C_{HU}^{i} + \sum_{j=1}^{m} C_{CU}^{j} - \sum_{k=1}^{d} C_{Elec}^{k} - \sum_{l=1}^{f} C_{M}^{l} \quad \text{Equation 27}$$

Where C_{HU} and C_{CU} are cost savings associated with reduction of demands in utility-process HXs, i and j respectively. C_{Elec} is the cost of the electricity required to power machinery equipment items due to pressure drops brought on by the installation of new pipes as a result of energy efficiency projects, and C_M is the cost of maintenance resulting from the installation of equipment items. The cost of the hot utility stream, C_{HU}, must be accurately known in order to evaluate the proposed SWEAM's HRP's economics. Fuel costs, raw water costs, boiler feed water treatment costs (clarification, softening, demineralization, etc.), pumping costs, fan costs, and so on, must all be considered. The fuel cost has generally proven to be the most significant factor, typically accounting for as much as 90% of the total cost of steam [13].

3. Examining the impact of the key cost components on the capital and operating cost estimates of heat recovery projects (HRPs)

The global economic assessment of HRPs implied by SWEAMs takes into account all candidate cost factors influencing the capital cost of projects and the operating cost savings implied by increasing thermal integration among process streams. To identify the key cost components among them, this section is designed to conduct quantitative analysis on a large number of cases to examine the effect of each candidate cost component listed in the previous section on the global costing of the projects when the design parameters of HRPs are changed.

3.1 Total Investment Costs (TICs)

We first consider how key cost components identified in Section 2 affect the Global Investment Cost Estimate of the following HEN modifications when their equipment type, construction material, and size change for various cases including (i) Stream re-piping and /or stream splitting -mixing, (ii) Replacing existing HX unit with new smaller/bigger HX unit and/or installing new HX unit in series with existing HX unit, (iii) Inserting new HX unit.

Stream re-piping and/or stream splitting-mixing

Figure *4.3* Hypothetical case studies' super-structure in conjunction with HRP named "stream re-piping and/or stream splitting-mixing" depicts the superstructure of alternatives considered for design parameters affecting each cost component that are correlated in Equation 26 to yield the global TICs of HEN topology modification referred to as " Stream re-piping and/or stream splitting-mixing." In this superstructure, for the each design parameter, denoted by blue colors, hypothetical alternatives (specified in brackets) are chosen to cover the lower and upper limits of variations that may be encountered in actual plant operations. Also, quantities of insulation and paint required for piping system are chosen based on following assumptions: (i) the amount of insulation is computed based on silicate calcium (30 mm thick) as an insulation type which covered by an AL jacket, and (ii) the amount of paint is computed based on two prime coats plus two finish coats.

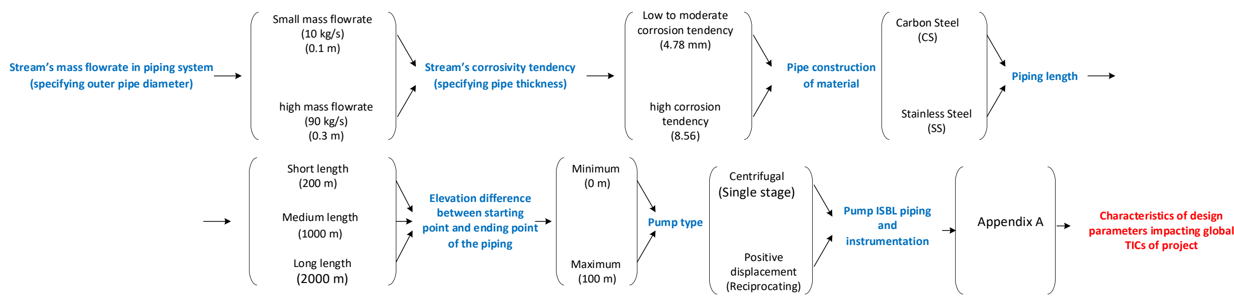
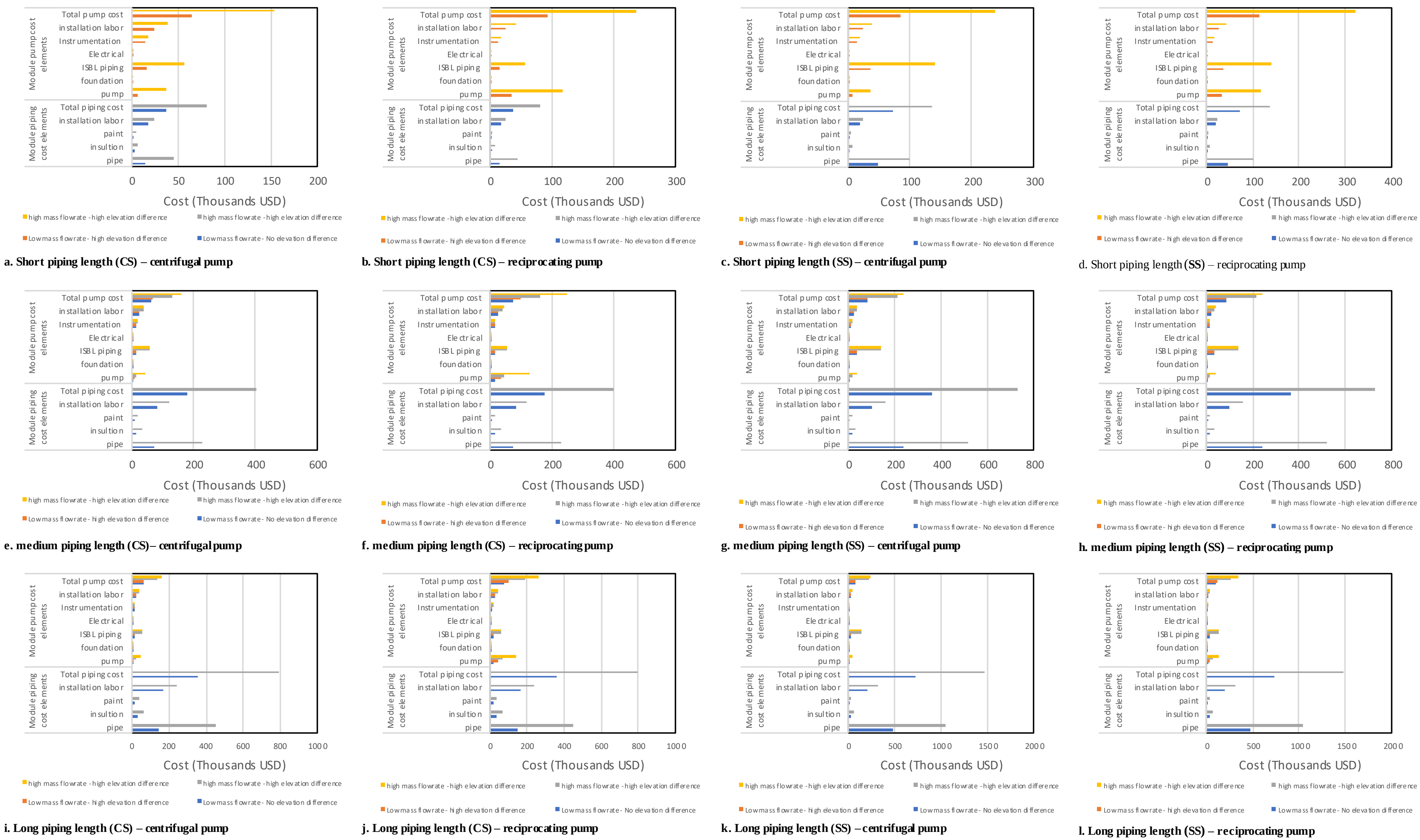


Figure 27. Assessment structure for heat recovery projects (HRPs) of type "stream re-piping and/or stream splitting-mixing"

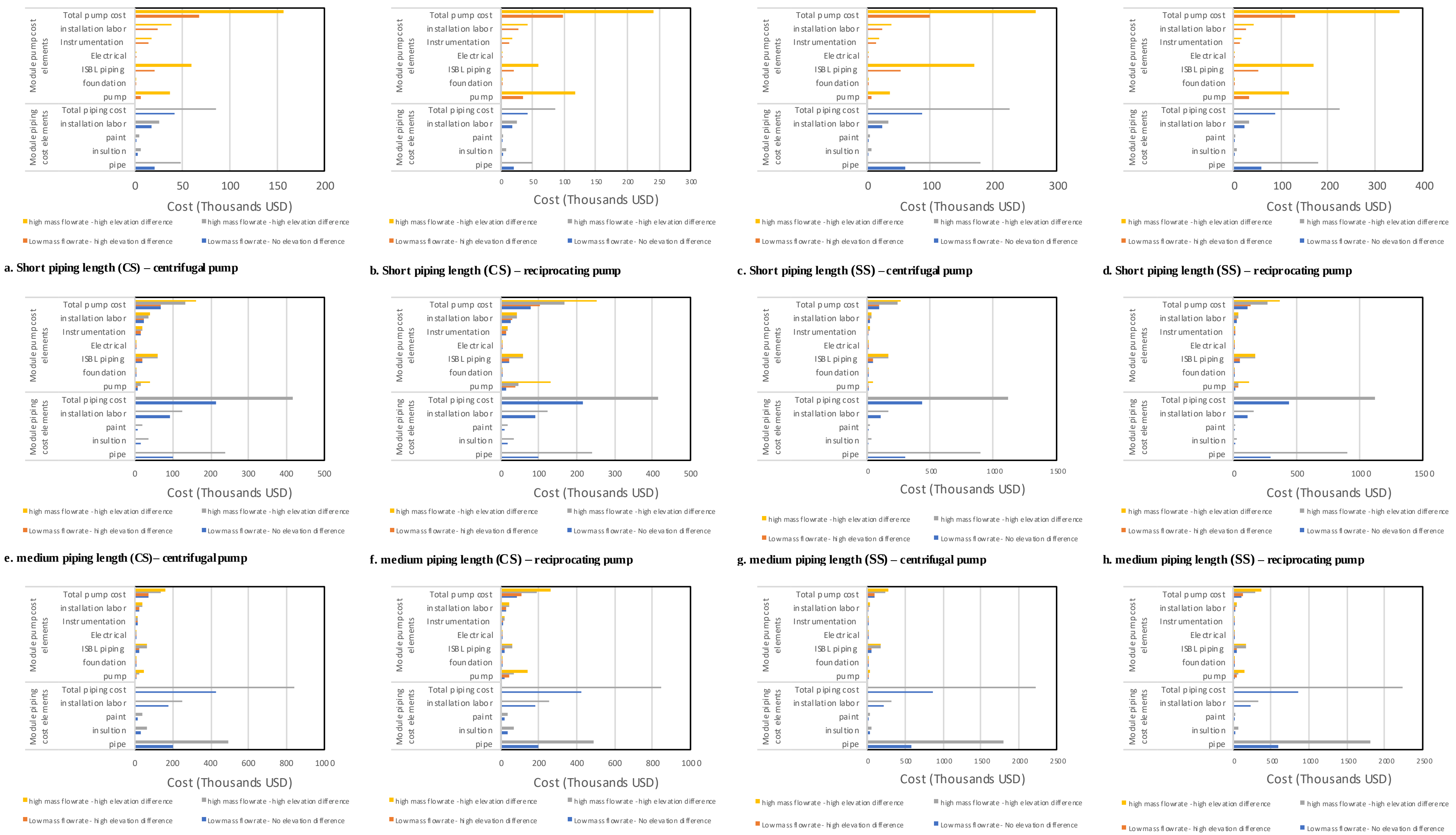
Choosing one alternative at a time for each design parameter from each bracket of figure 2 and combining them, with the aid of the mentioned assumptions, provides all the design information necessary to estimate the cost components affecting the global costing of this SWEAM recommendation, as shown in Figure 28 and Figure 29 when the corrosivity tendency of the stream is low and high, respectively.

A comparison of results reveals that, unless the piping length is small, the module new piping cost is significantly higher than the module new pump cost required for eliminating new pressure drop. Consequently, greater attention is required for sizing and costing this portion of the HEN topology modification implied by SWEAM. Also, among candidate cost components correlated in Equation 26, decision makers do not need to account for the cost components named *electrical cost and foundation cost* when estimating the cost of a module pump, as well as *paint cost* when estimating module piping cost if there is insufficient information to do so.



a. Short piping length (CS) – centrifugal pump
b. Short piping length (CS) – reciprocating pump
c. Short piping length (SS) – centrifugal pump
d. Short piping length (SS) – reciprocating pump
e. medium piping length (CS)– centrifugal pump
f. medium piping length (CS) – reciprocating pump
g. medium piping length (SS) – centrifugal pump
h. medium piping length (SS) – reciprocating pump
i. Long piping length (CS) – centrifugal pump
j. Long piping length (CS) – reciprocating pump
k. Long piping length (SS) – centrifugal pump
l. Long piping length (SS) – reciprocating pump

Figure 28. Estimate of investment cost of the HRP “stream splitting-mixing and/or stream repiping” (low to moderate stream corrosivity)



a. Short piping length (CS) – centrifugal pump

b. Short piping length (CS) – reciprocating pump

c. Short piping length (SS) – centrifugal pump

d. Short piping length (SS) – reciprocating pump

e. medium piping length (CS)– centrifugal pump

f. medium piping length (CS) – reciprocating pump

g. medium piping length (SS) – centrifugal pump

h. medium piping length (SS) – reciprocating pump

i. Long piping length (CS) – centrifugal pump

j. Long piping length (CS) – reciprocating pump

k. Long piping length (SS) – centrifugal pump

l. Long piping length (SS) – reciprocating pump

Figure 29. Estimate of total investment cost of the HRP “stream splitting-mixing and/or stream repiping” (high stream corrosivity).

Replacing existing HX with new smaller/bigger HX and/or installing new HX in series with existing HXFigure 4.6. Hypothetical case studies' super-structure in conjunction with HRP named "Replacing existing HX with new smaller/bigger HX and/or installing new HX in series with existing HX"

shows the superstructure of alternatives considered for design parameters affecting each cost component that are correlated in Equation 22 to yield the global TICs of HEN topology modification referred to "modifying existing HX" via a practical design solution referred to as "replacing existing HX with new smaller/bigger HX". The definitions of the items considered in this superstructure and the assumptions necessary for estimating the project's cost components are identical to those provided in the previous section.

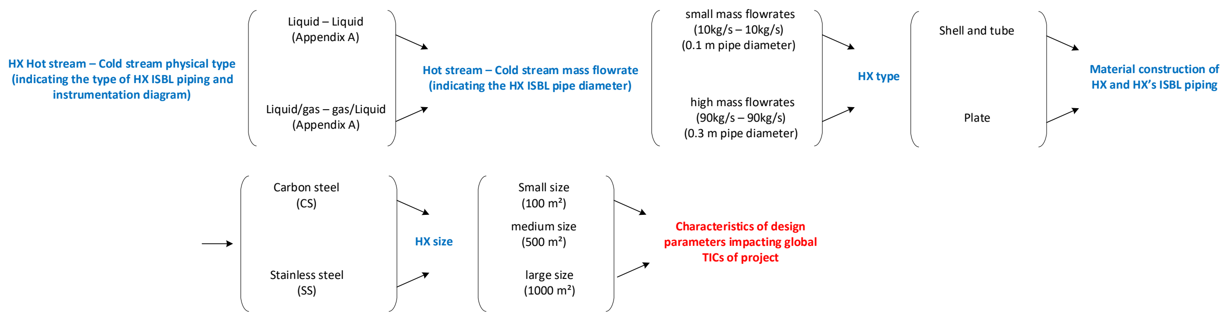
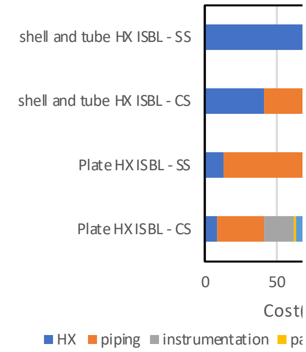


Figure 30. Assessment structure for heat recovery projects (HRPs) of type "Replacing existing HX with new smaller/bigger HX and/or installing new HX in series with existing HX"

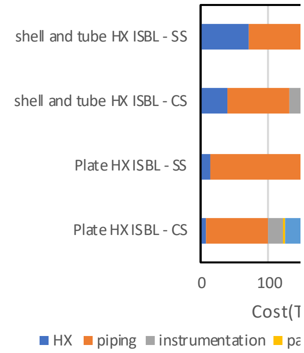
Choosing one option at a time for each design parameter in each bracket of Figure 4.6. Hypothetical case studies' super-structure in conjunction with HRP named "Replacing existing HX with new smaller/bigger HX and/or installing new HX in series with existing HX"

and combining them with the mentioned assumptions gives all the design information needed to estimate the cost components that affect the total cost of this SWEAM recommendation, as shown in Figure 31.

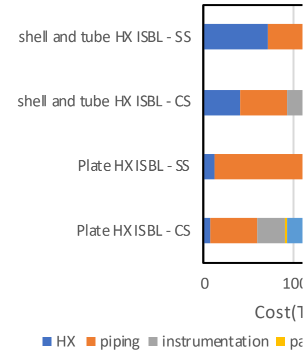
The following are the results of a critical examination of



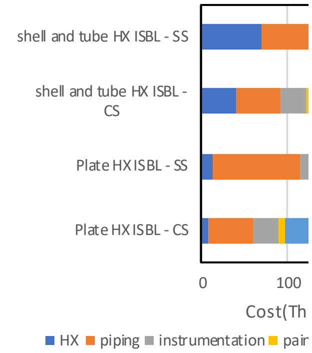
a. Liquid - Liquid heat exchanging |small streams' mass flowrate | small HX size



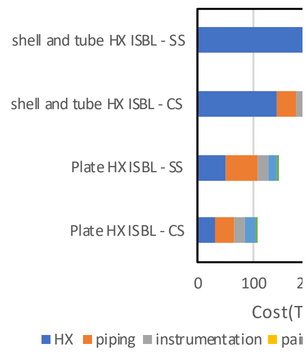
b. Liquid - Liquid heat exchanging |high streams' mass flowrate | small HX size



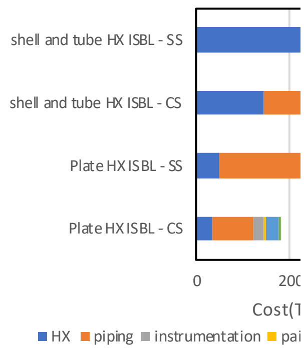
c. Gas - Gas heat exchanging |small streams' mass flowrate | small HX size



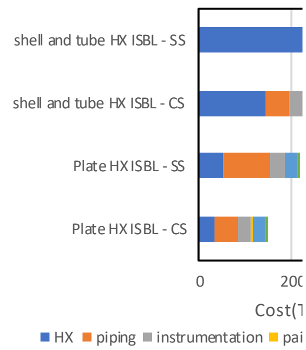
d. Gas - Gas heat exchanging |high streams' mass flowrate | small HX size



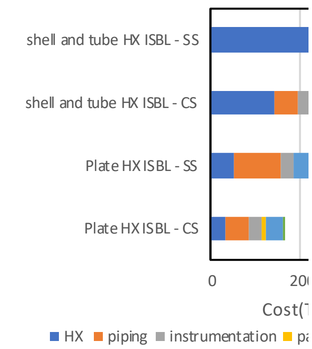
e. Liquid - Liquid heat exchanging |small streams' mass flowrate | medium HX size



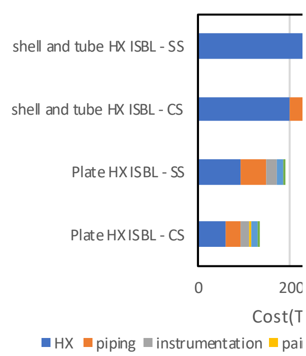
f. Liquid - Liquid heat exchanging |high streams' mass flowrate | medium HX size



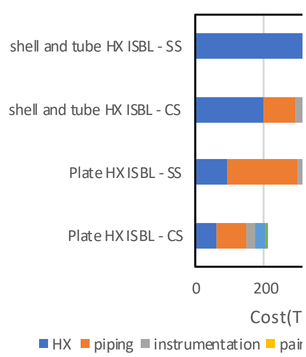
g. Gas - Gas heat exchanging |small streams' mass flowrate | medium HX size



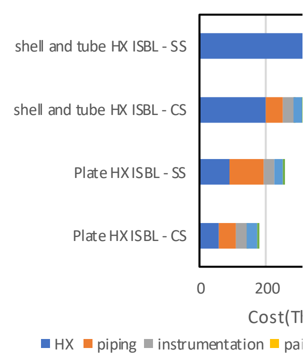
h. Liquid - Liquid heat exchanging |high streams' mass flowrate | medium HX size



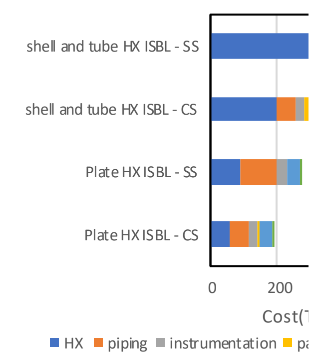
i. Liquid - Liquid heat exchanging |small streams' mass flowrate | large HX size



j. Liquid - Liquid heat exchanging |high streams' mass flowrate | large HX size



k. Gas - Gas heat exchanging |small streams' mass flowrate | large HX size



l. Liquid - Liquid heat exchanging |high streams' mass flowrate | large HX size

Figure *31*:

- Paint and civil costs are negligible compared to other cost components.

- Despite the size of the HX, the cost of the HX varies significantly based on the HX type and construction material; therefore, good engineering judgment is required to specify the HX type based on, for example, the operating conditions and thermophysical properties of the stream.
- The cost of ISBL piping and control instrumentation varies based on different P&IDs considered to make new HX operational, piping material of construction as well as diameter that changes based on stream mass flowrates, and remained constant when the size and type of the HX are altered.

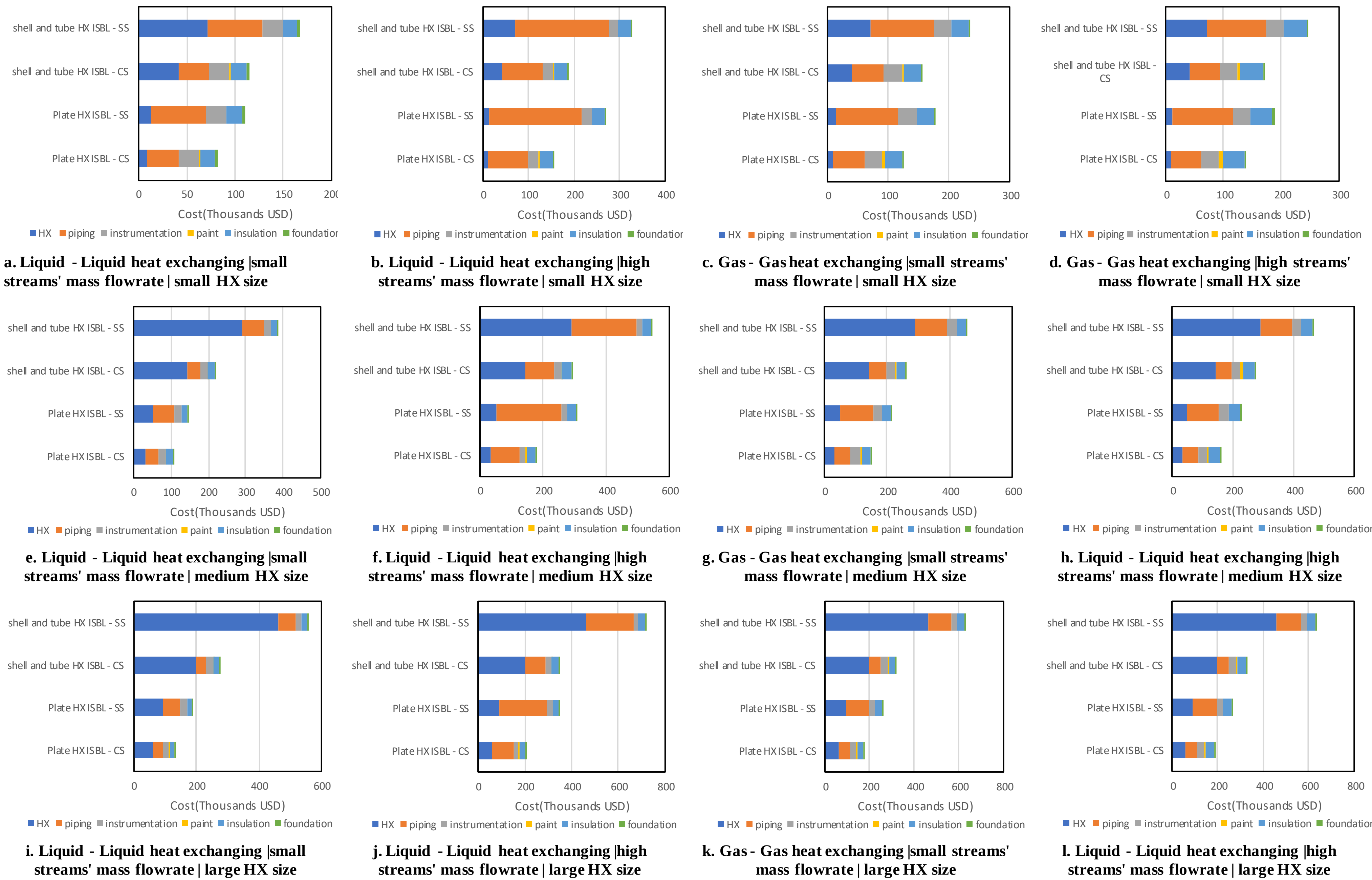


Figure 31. Estimate of total investment cost of the HRP "increasing/decreasing thermal duty of existing HX(s)" when replacing existing HX with new one is chosen.

Inserting new HX unit

Figure 32 depicts the superstructure of potential design parameters taken into account for each cost component that are correlated in Equation 7 to estimate the global TICs of HEN topology modification, known as "Inserting new HX unit".

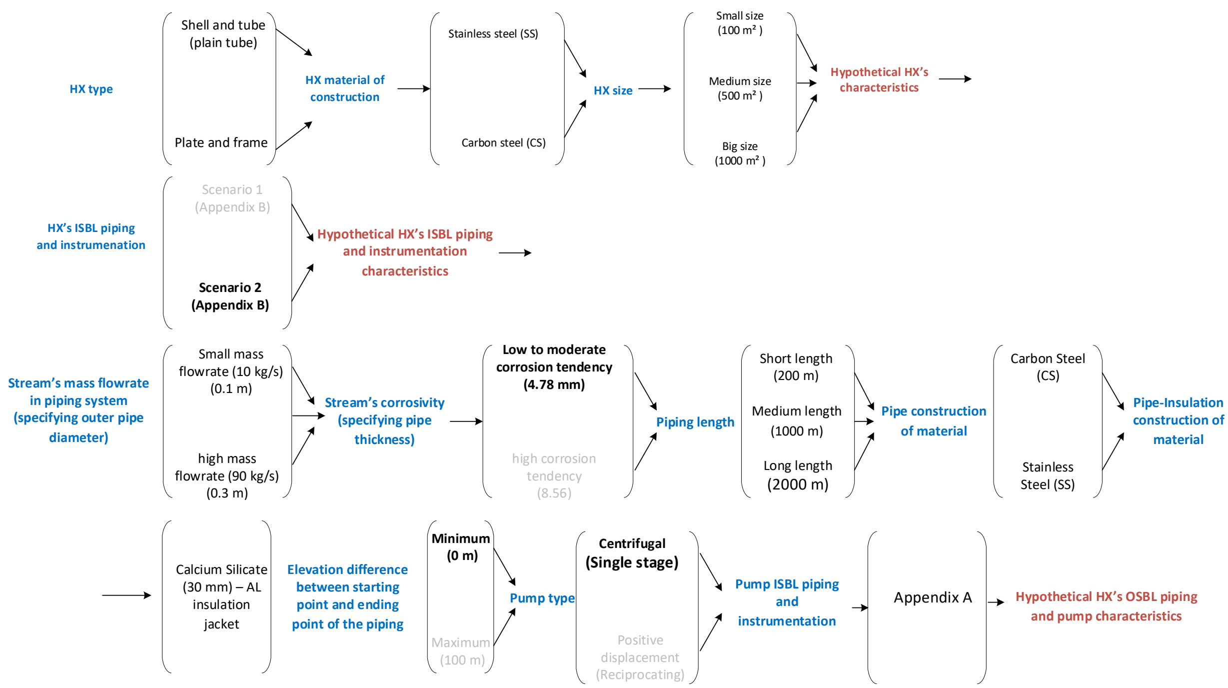
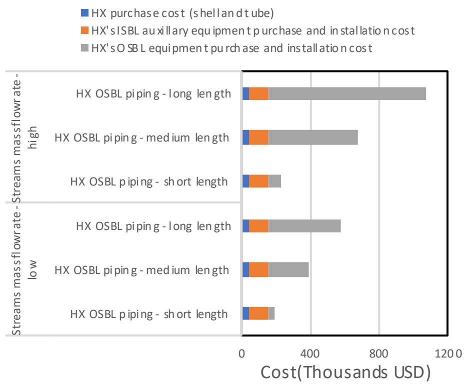
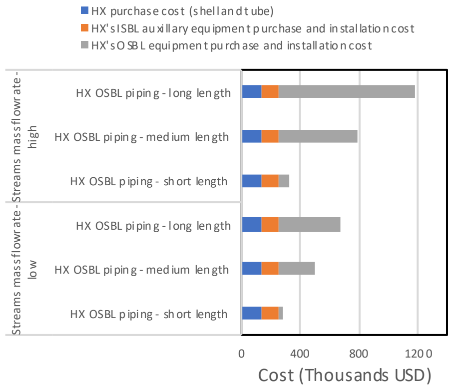


Figure 32. Assessment structure for heat recovery projects (HRPs) of type "Inserting new HX".

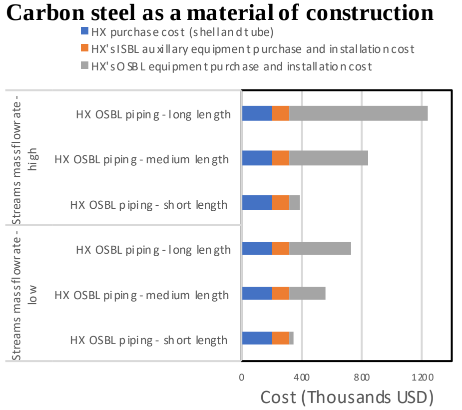
Figure 33 shows the results of a quantitative analysis done on a number of case studies characterized using information provided Figure 32. This figure demonstrates that when the size of the HX (SS) required for the new heat recovery between process streams is big and HX OSBL piping system (SS – 0.1 m diameter) is short, the contribution of HX cost to the global TICs of the project is a maximum of 60% for shell and tube type HXs, and 24% for plate type HXs. If distance between two streams imply using medium and/or long piping length, then the contribution of HX purchase costs to global TICs of project reduces by 40% and 30% for shell and tube HX, and by 12% and 8% for plate HX. In general, *Figure 33* demonstrates how the cost of the SWEAM project known as "inserting new HX" can be underestimated by simply taking into account the cost of the HX as the only cost component, as is done in published articles.



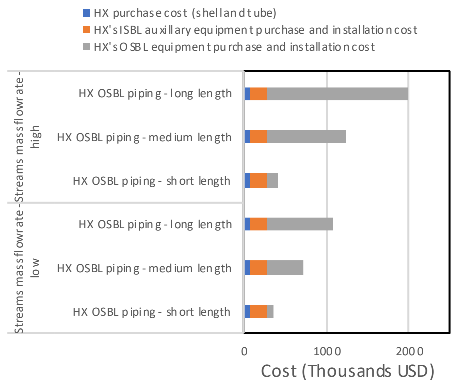
a. shell and tube HX type | small HX size | Carbon steel as a material of construction



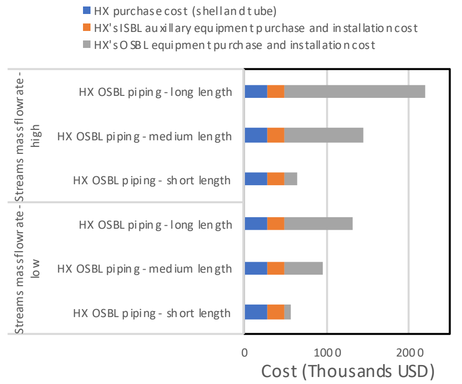
b. shell and tube HX type | medium HX size | Carbon steel as a material of construction



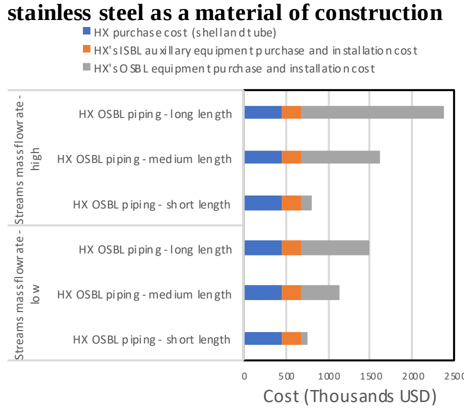
c. shell and tube HX type | large HX size | Carbon steel as a material of construction



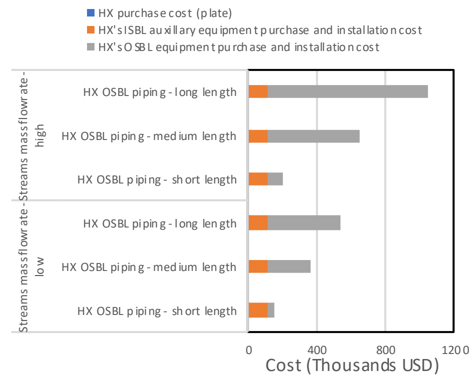
d. shell and tube HX type | small HX size | Stainless steel as a material of construction



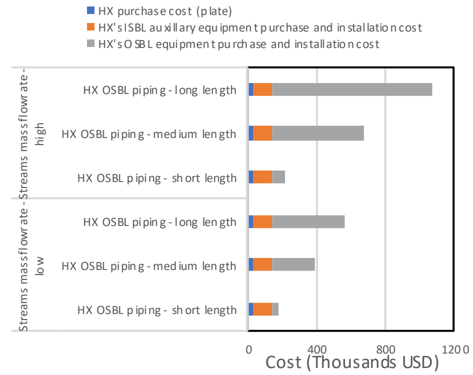
e. shell and tube HX type | medium HX size | stainless steel as a material of construction



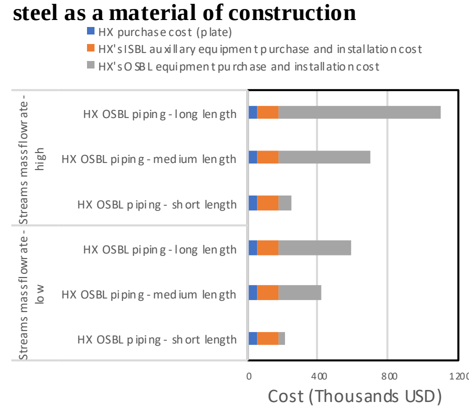
f. shell and tube HX type | large HX size | stainless steel as a material of construction



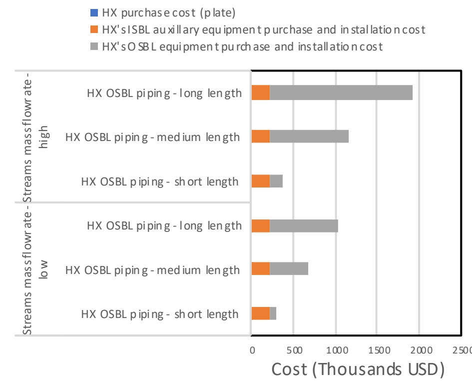
g. plate HX type | small HX size | Carbon steel as a material of construction



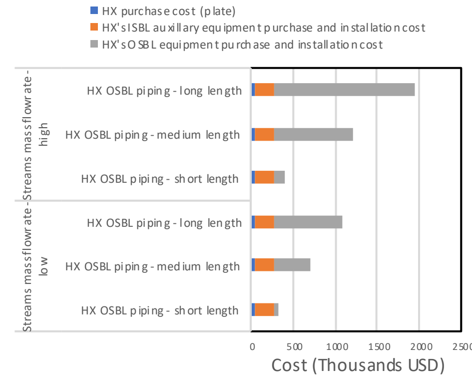
h. plate HX type | medium HX size | Carbon steel as a material of construction



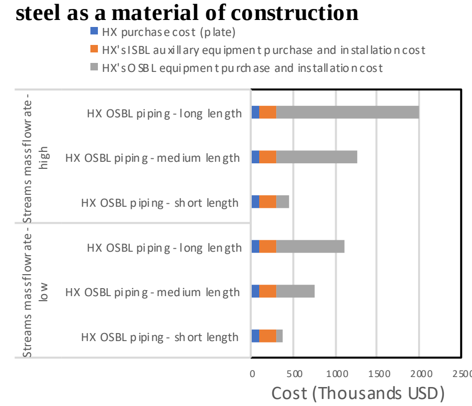
i. plate HX type | large HX size | Carbon steel as a material of construction



j. plate HX type | small HX size | Stainless steel as a material of construction



k. plate HX type | medium HX size | stainless steel as a material of construction



l. plate HX type | large HX size | stainless steel as a material of construction

Figure 33. Estimate of total investment cost of the HRP "adding new HX".

3.2 Total Operating Cost (TOC) savings

To compare the relative importance of global TOC components, Figure 2 is presented, which depicts hypothetical alternatives for design parameters that have an effect on cost components correlated in Equation 27. Figure 35 and Figure 36 depict the result of a quantitative analysis performed to determine which cost component estimation requires the most attention.

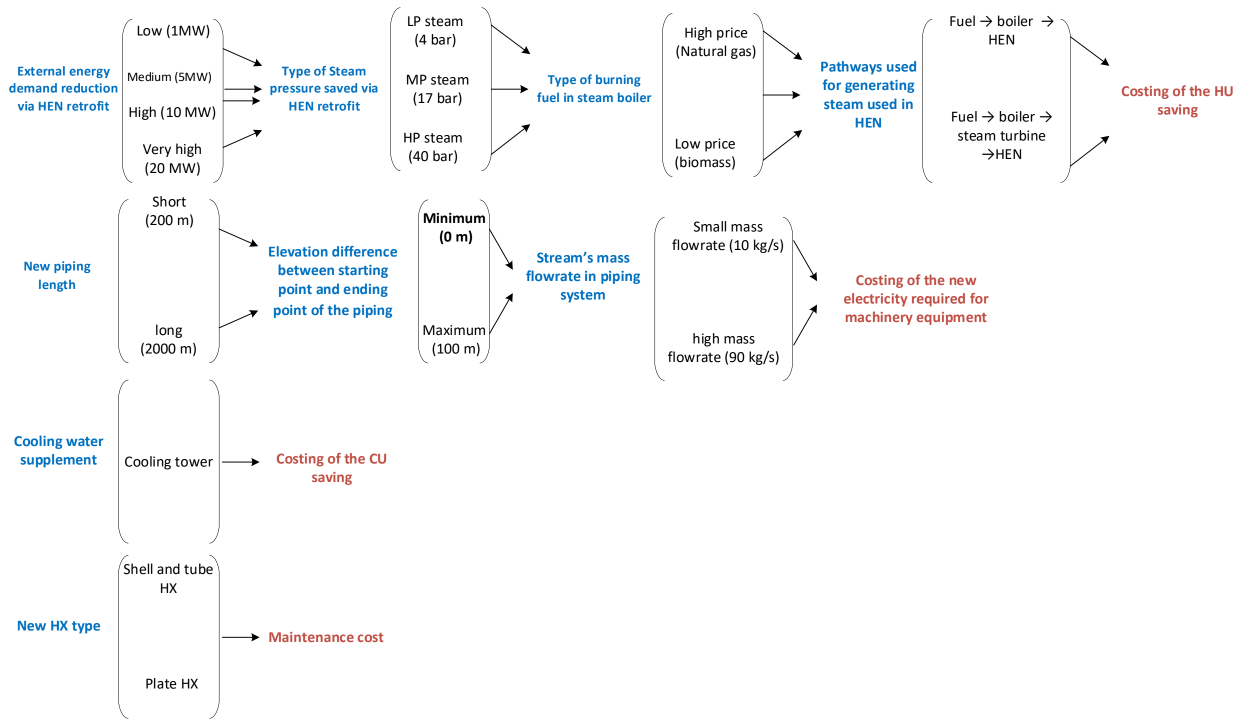
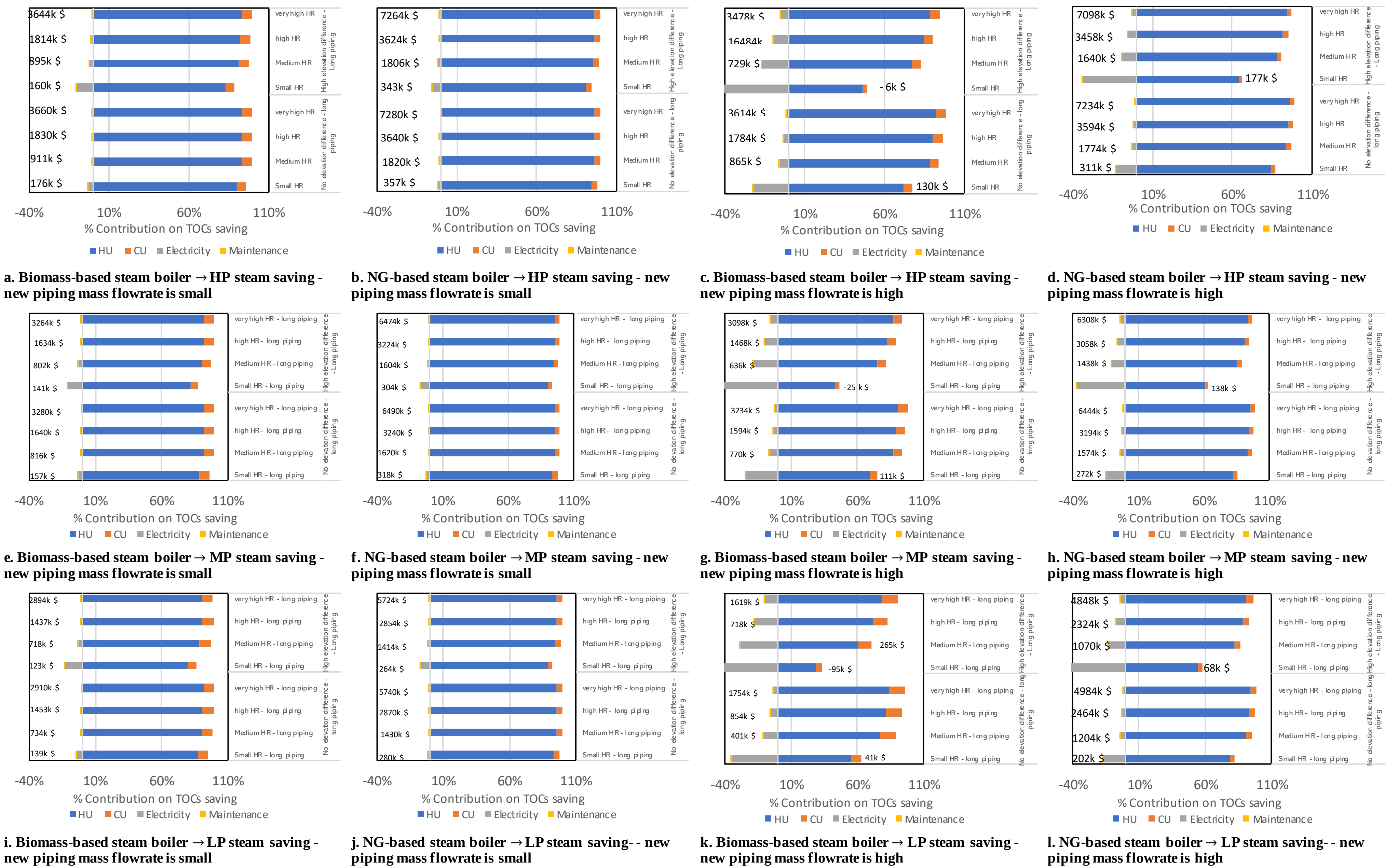


Figure 41. Assessment structure for global operating cost changes associated with heat recovery projects

We can observe the following results from Figures 10 and 11:

- It is important to specify the type of steam pressure saved in HEN (e.g. LP steam, MP steam, or HP steam) and the type of fuel burning in the steam boiler to generate steam for accurate estimate of TOC savings. Also, decision-makers must specify whether the saved steam comes directly from the steam boiler, or expands in the steam turbine before being used in the HEN. This is due to the fact that in the last scenario, the revenue from electricity sales must be subtracted from the fuel cost savings.



a. Biomass-based steam boiler → HP steam saving - new piping mass flowrate is small

b. NG-based steam boiler → HP steam saving - new piping mass flowrate is small

c. Biomass-based steam boiler → HP steam saving - new piping mass flowrate is high

d. NG-based steam boiler → HP steam saving - new piping mass flowrate is high

e. Biomass-based steam boiler → MP steam saving - new piping mass flowrate is small

f. NG-based steam boiler → MP steam saving - new piping mass flowrate is small

g. Biomass-based steam boiler → MP steam saving - new piping mass flowrate is high

h. NG-based steam boiler → MP steam saving - new piping mass flowrate is high

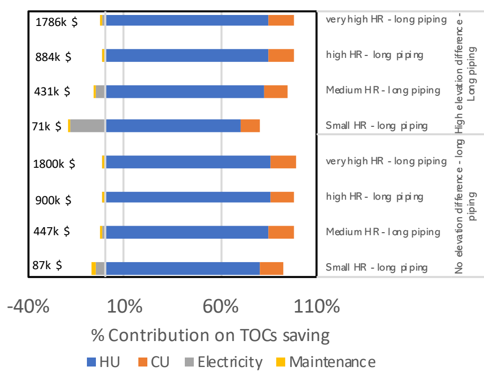
i. Biomass-based steam boiler → LP steam saving - new piping mass flowrate is small

j. NG-based steam boiler → LP steam saving- - new piping mass flowrate is small

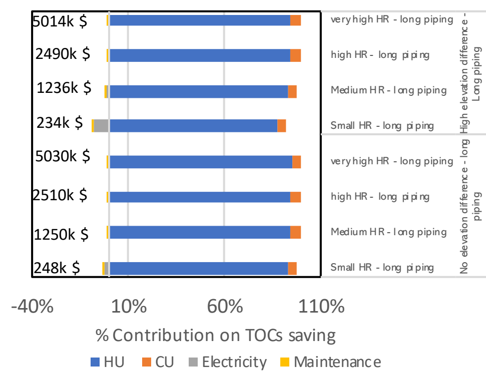
k. Biomass-based steam boiler → LP steam saving - new piping mass flowrate is high

l. NG-based steam boiler → LP steam saving- - new piping mass flowrate is high

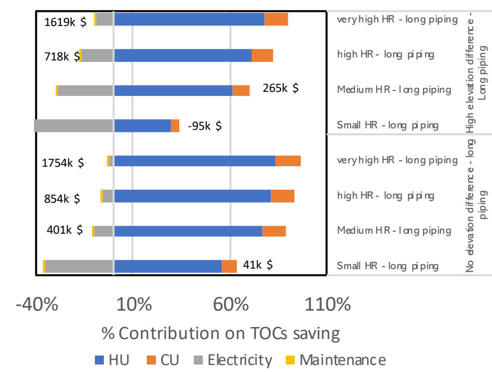
Figure 35. Estimate of total operating cost saving, when steam used in HEN comes directly from steam boiler



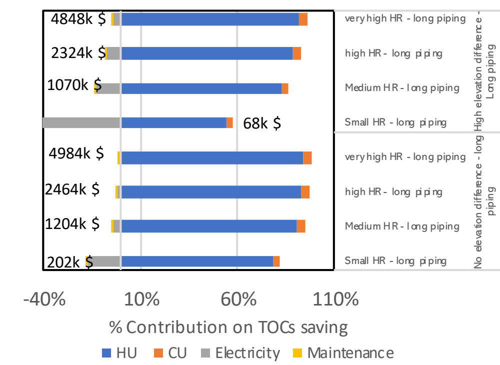
a. Biomass-based steam boiler → HP steam → Steam turbine → MP steam saving - new piping mass flowrate is small



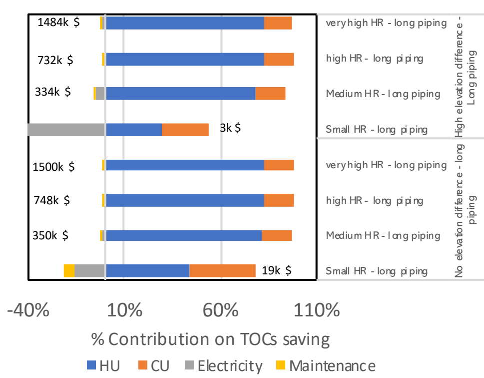
b. NG-based steam boiler → HP steam → Steam turbine → MP steam saving - new piping mass flowrate is small



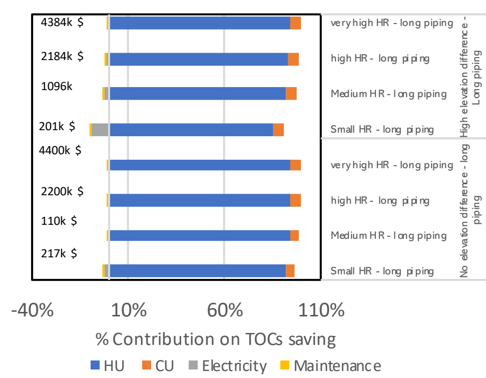
c. Biomass-based steam boiler → HP steam → Steam turbine → MP steam saving - new piping mass flowrate is high



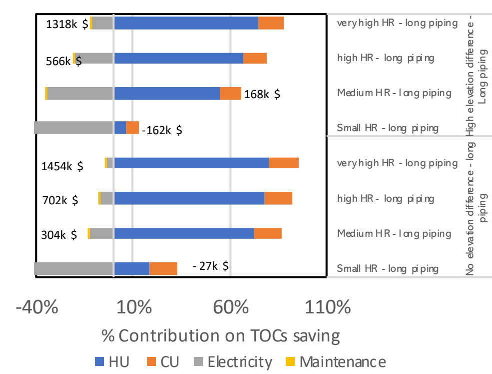
d. NG-based steam boiler → HP steam → Steam turbine → MP steam saving - new piping mass flowrate is high



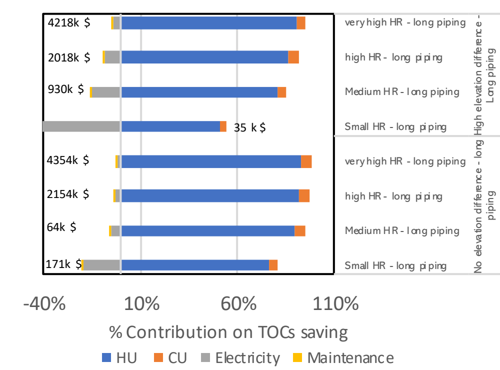
e. Biomass-based steam boiler →HP steam → Steam turbine → LP steam saving - new piping mass flowrate is small



f. NG-based steam boiler →HP steam → Steam turbine → LP steam saving - new piping mass flowrate is small



g. Biomass-based steam boiler →HP steam → Steam turbine → LP steam saving - new piping mass flowrate is high



h. NG-based steam boiler →HP steam → Steam turbine → LP steam saving - new piping mass flowrate is high

Figure 36. Estimate of total operating cost saving, when steam generated in steam boiler expanded in steam turbine before using in HEN

- It is crucial to consider the cost of the electricity required to pump the process stream(s) in the new piping system, especially When the decision maker faces the following conditions simultaneously during economic evaluation of a project: (i) the stream flow rate is high, (ii)the elevation difference between the new piping system's starting and ending points is high, (iii) the amount of HR suggested by SWEAM is low and/or medium, and (iv) the steam saved is provided by the following pathway: steam boiler –> steam turbine –> HEN.
- Despite the size of the HX, HX maintenance cost can be ignored by decision maker during global TOCs calculations. .
- The cost of the cold utility saved is significant compared to other cost components when the steam saved passes through the following pathway: cheap fuel (e.g. biomass) - based steam boiler -> steam turbine -> HEN.

4. Case study

To demonstrate the effectiveness of the global costing approach of HRPs at the early design stage, a process flowsheet consisting of four units was considered (Figure *44*): (1) Unit 1: E1-Heater-Reactor 1, (2) Unit 2: E2-Reactor2-Cooler-Separator 2, (3) Unit 3: hot stream generation unit, and (4) Unit 4: cold stream generation unit. The distance between streams that belong to the same unit and streams that belong to different units have nominally been assumed as 50 m and 200 m, respectively, and there are no elevation changes assumed between the four units. The hot utility is MP steam produced at the steam turbine, that expands HP steam generated by the combustion of 60% dry biomass. The cold utility stream is cooling water from a cooling tower.

Figure 45 presents the HEN associated with this process flowsheet, including two energy supplier streams (R1 and R2) which have the characteristics of light organic mixtures, two energy receptor streams (F1 and F2) which have the characteristics of heavy organic mixtures, and two process-process HXs (E1 and E2). The hot utility demand of the existing HEN is 1400 kW (shown by H1) and the cold utility demand is 1320 (shown by C1). It was assumed that (i) the temperature values assigned to each stream of the existing HEN grid diagram are associated with Exchanger Minimum Approach Temperature (EMAT) of 10 ℃, and (ii) the hot utility is steam at 200°C, while the cold utility is cooling water at 10°C.

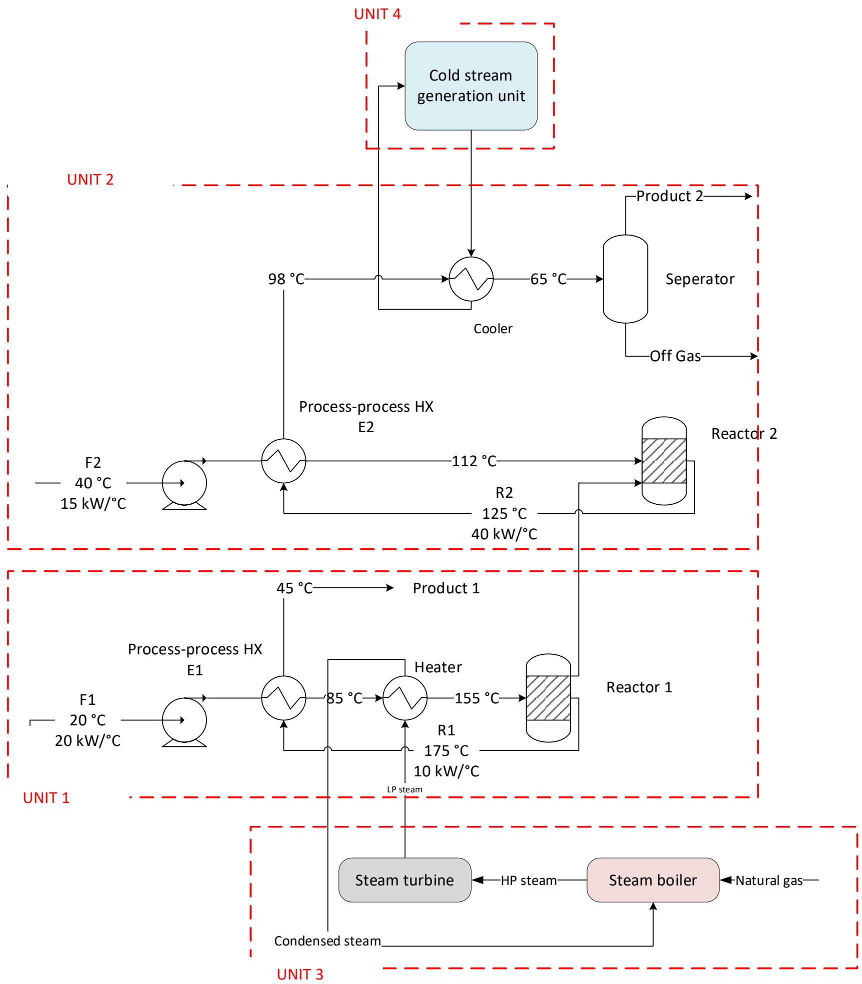


Figure 44. Case study - Process flowsheet

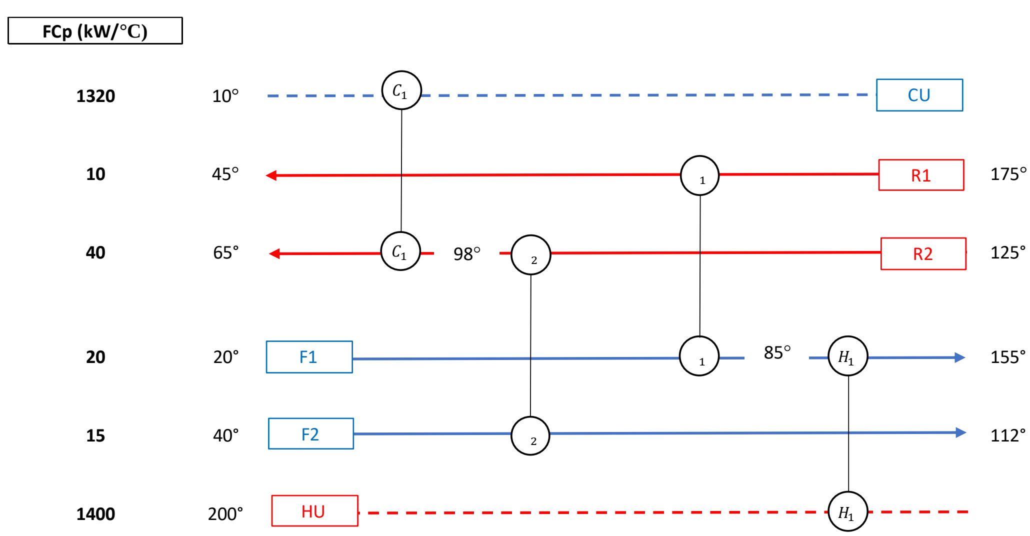


Figure 45. Case study - Existing heat exchange network (HEN)

The bridge method developed by Bonhiver et al. is used to obtain all feasible potential savings in external heating and cooling demands, as well as necessary HEN modifications, as shown in Figure 46 [9]. This method uses an energy transfer diagram (ETD) as a novel graphical tool for site-wide energy analysis to illustrates heat degradation between hot utility and environment caused by process operations and current HEN. This tool gives decision-makers a worldwide perspective of heat savings opportunities, allowing them to determine the path of HEN-HRPs named Bridges and the minimal HEN external heating and cooling requirements related to stream IMATs.

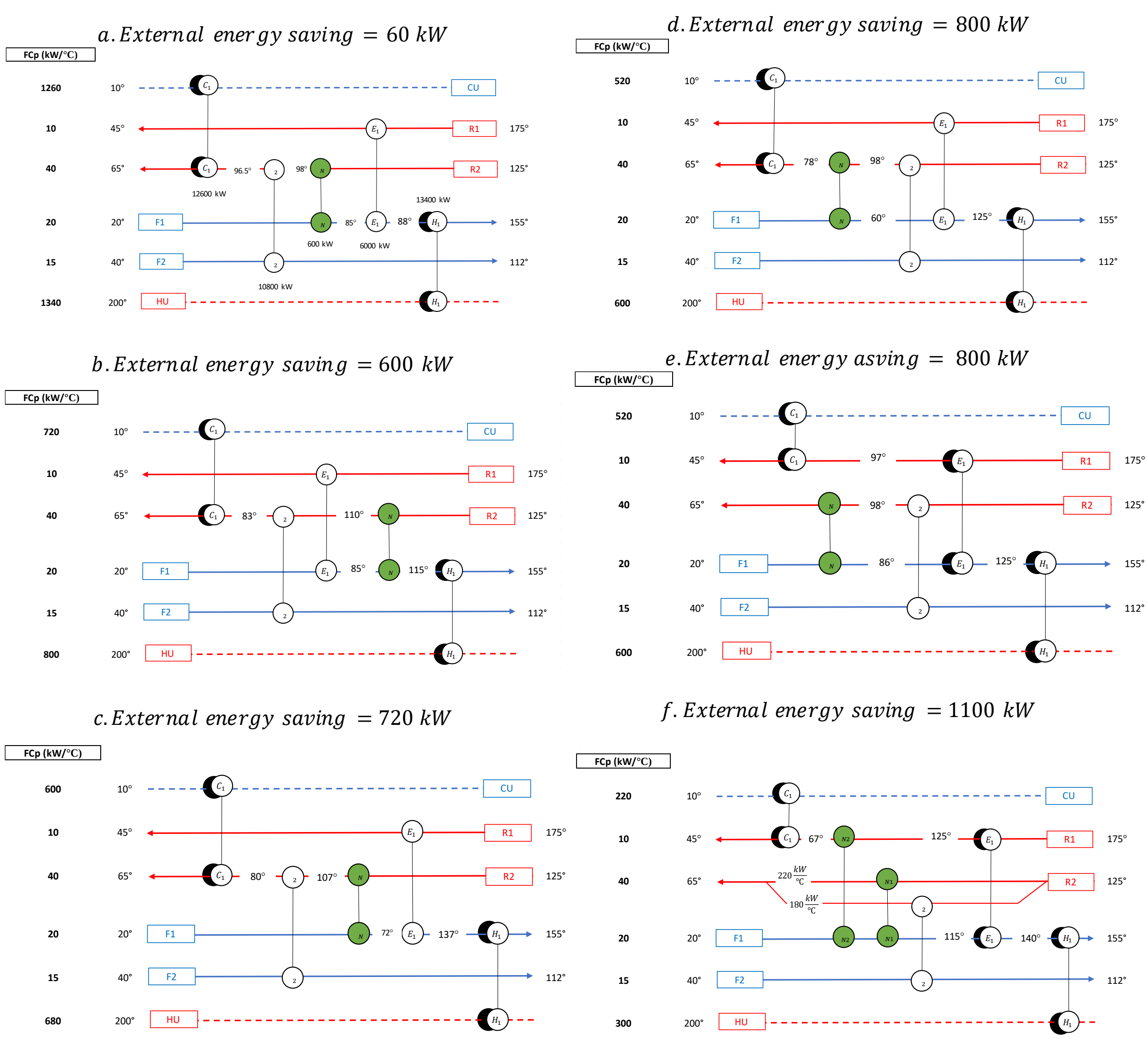


Figure *46*. Case study – Modified HEN grid diagrams in conjunction with various energy saving recommendations.

Figure 14 illustrates all HEN grid diagram modifications necessary to meet six distinct external energy reduction targets. According to this figure, "adding new HX" and "modifying existing HXs" are the only modifications required to meet five energy saving targets, with the exception of the 1100 kW external energy saving target. In this scenario, in addition to the aforementioned modifications, "stream splitting-mixing" is also necessary to achieve this target. The economic assessment of each six heat recovery projects is performed based on following assumptions:

- The existing HXs are flexible enough to meet new operating and thermal conditions brought on by increased thermal integration between HEN process streams.
- The SWEAM recommendation known as "inserting new HX" is implemented using direct process-process HX.
- Carbon steel is selected as the construction material for new equipment required to implement the topology changes. In addition, the P&ID presented in Appendix B (scenario 1) is assumed to estimate the cost of the ISBL pipework and instrumentation.
- The purchase price of the new HX is estimated based on shell and tube (floating head) HX.
- Bridge implementation does not imply purchasing and installing a new pump for the three reasons listed below: (i) new HXs are sized based on the allowable pressure drop (1 bar) rather than the heat transfer coefficient of the streams, (ii) there are no elevation differences between the streams, and (iii) friction losses caused by the new piping system increases the plant pressure drop by a maximum of 1 bar, which is within the range of the allowable pressure drop assumed for this example.

Figure *47* shows the results of a comparison between the global costing approach, introduced in this paper, and the conventional costing used in the economic assessment section of SWEAMs literatures, where only the cost of the HX is considered. The economic assessment is perfomed based on following assumptions:

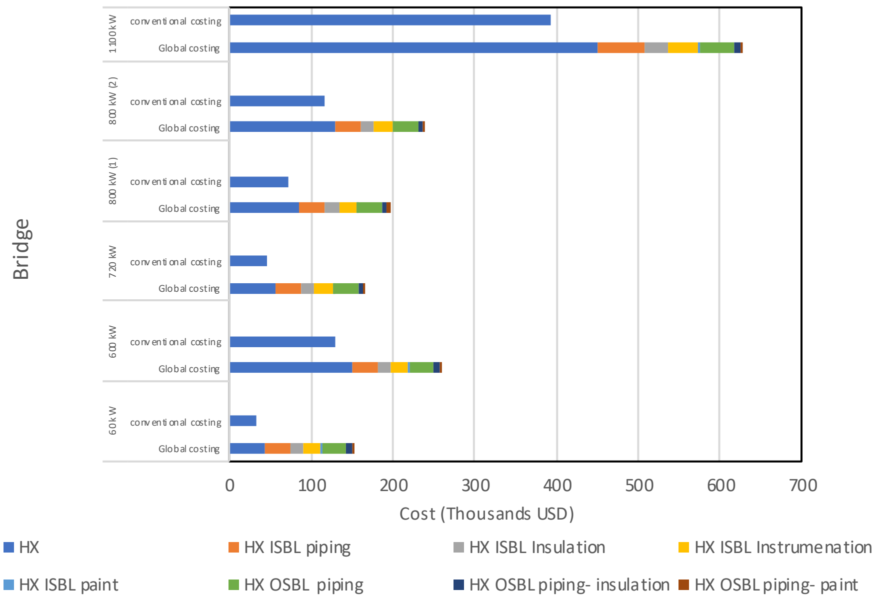


Figure 47. Case study - Global costing versus conventional costing of the heat recovery projects indicated by each Bridge

Figure *47* shows that the estimated cost of each Bridge using the global costing method is greater than the cost calculated using the conventional cost estimation method. This result is not surprising since (i) the conventional costing approach does not consider the impact of the fouling coefficient on size and cost of the new HX, (ii) the cost of the equipment items required for making the new HX operational (e.g. ISBL piping and instrumentation) and the installation labor cost, are not considered in the conventional costing approach, and (iii) this approach does not include the OSBL module piping cost for connecting new HX units with the plant.

Figure *48* shows the operating cost savings related to each Bridge. The suggested global operating cost saving approach not only incorporates savings related with fuel and cooling water consumption reduction, but also it addressed the negative effect of higher maintenance and electricity sales reduction caused by fuel consumption reduction. The conventional operating cost estimation approach results are higher than global operating cost estimation due to subtracting the electricity sales reduction from the summation of fuel and cooling water savings.

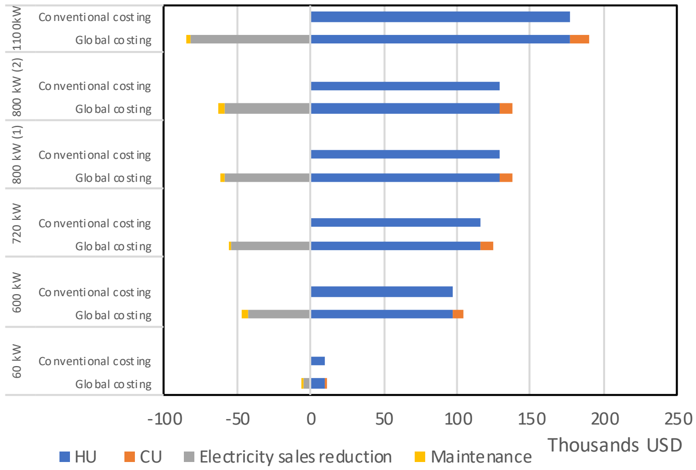


Figure 48. Case study – Total operating cost (TOC) savings

Figure *49*compares the Internal Rate of Return (IRR) of the 6 HRPs, and illustrates how using the global costing approach introduced in this study impacts the number of HRPs that are economically profitable. Using a global costing approach results in only three HRPs with higher IRRs than the target IRR of 20%. This is due to the fact that using the global costing approach establishes more rigorously the estimated investment and operating cost savings.

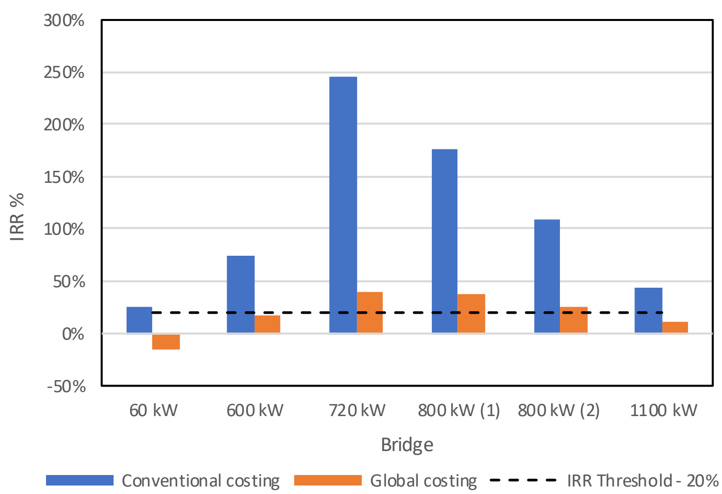


Figure 49. Case study – IRR for Bridge modifications considering global costing vs. conventional costing

Conclusions

This study proposed a global costing approach suitable for rigorous economic evaluation of the HRPs implied by SWEAM through completing following steps:

- Clarifying the relationship between each type of SWEAM recommendation, and required plant topology modification.
- Defining global investment cost and operating cost saving through identifying key parameters impacting economic assessment of the projects.

In order to show that the new global costing proposal is a rigorous tool that gives the analyst more precise economic data to aid in the open-ended decision-making processes, an example was given to compare global costing approach to the conventional costing methodology addressed in literatures. The results have shown that the more rigorous costing method will result in lower IRRs and less-attractive HEN projects. This is because that conventional costing approaches generally (1) underestimate the capital cost of retrofit projects and (2) overestimate the operating cost savings. Quantitative conclusion for the material up to the case study.

Appendix A

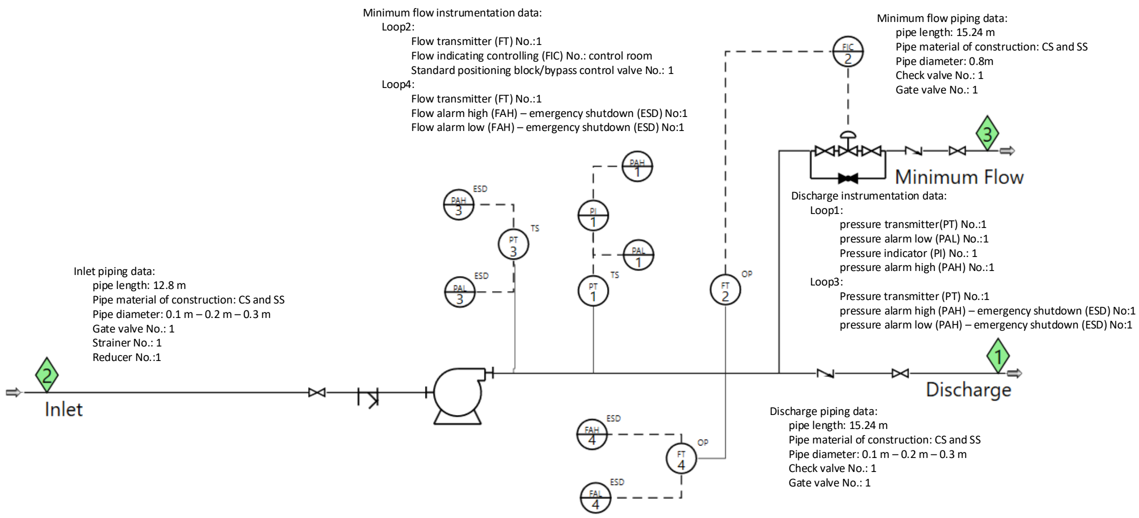


Figure A.1. Pump's P&ID.

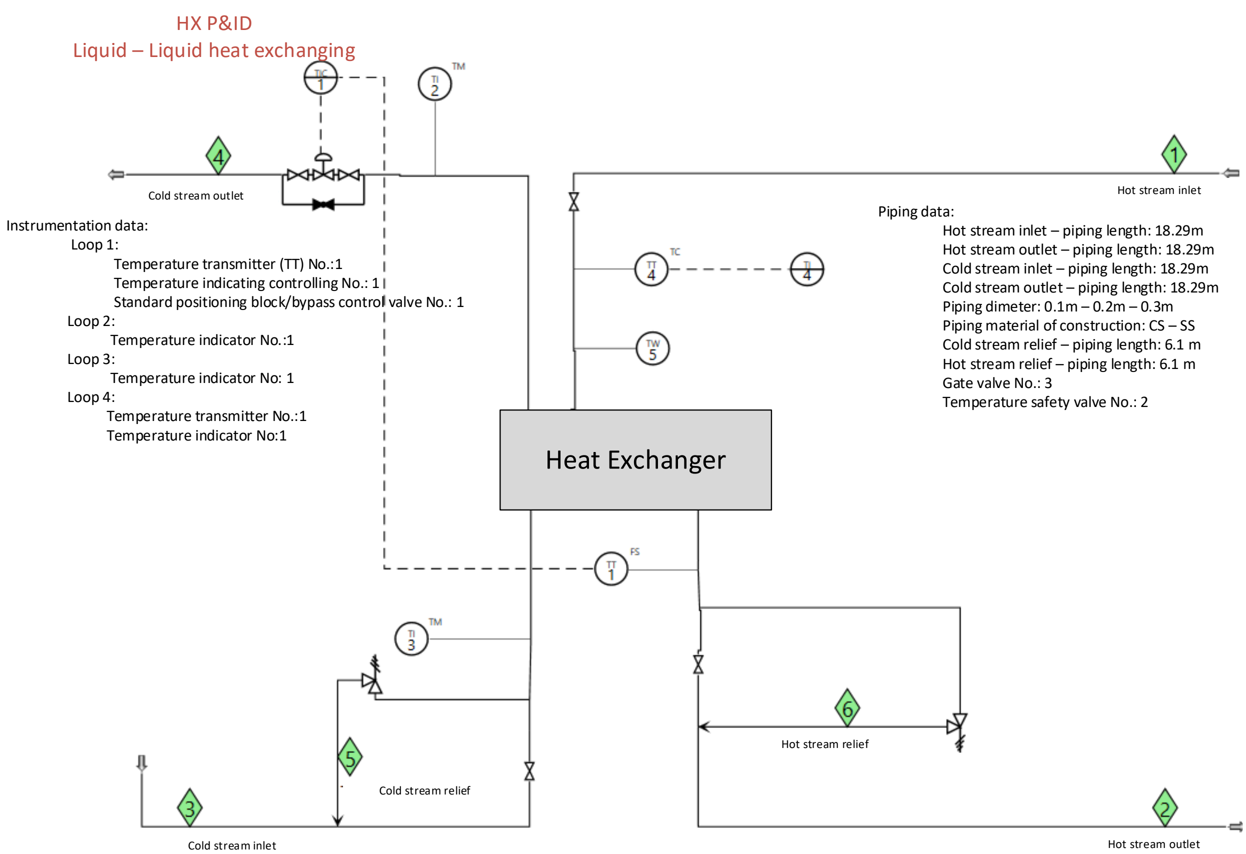


Figure A.2. HX's P&ID for Liquid-Liquid heat exchanging.

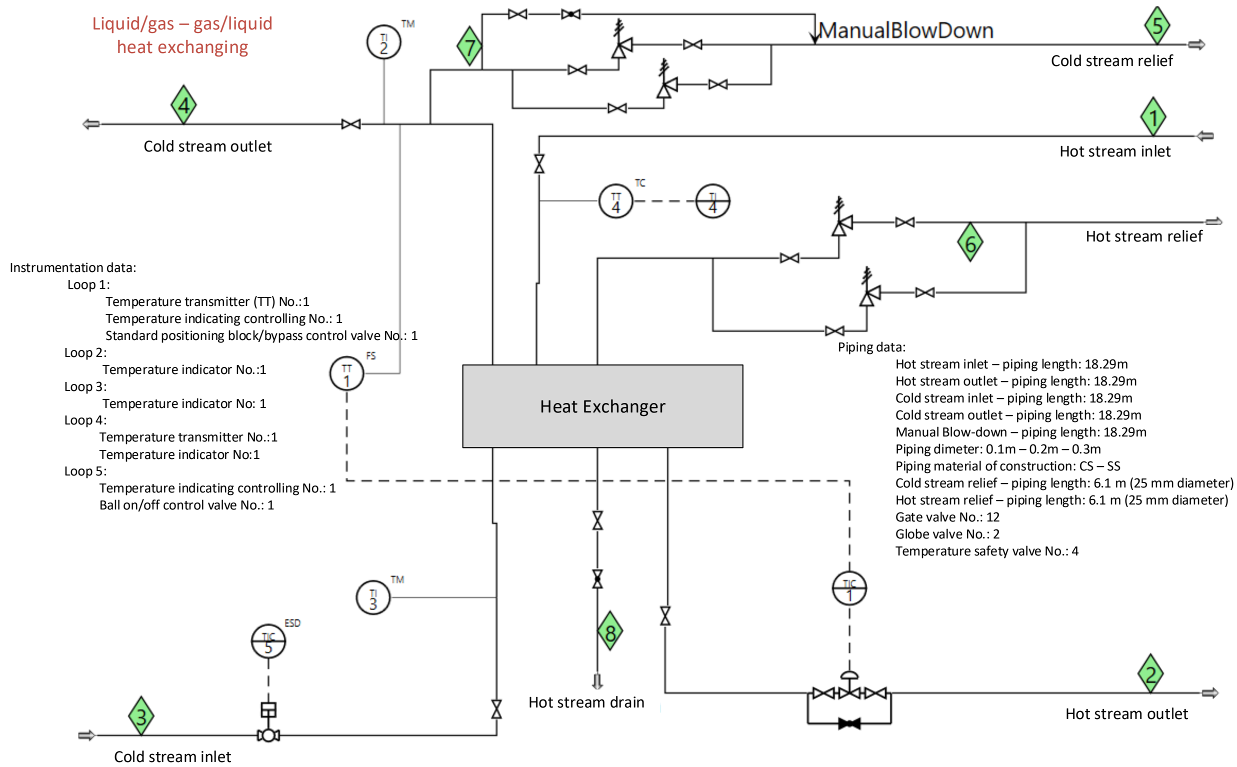


Figure A.3. HX's P&ID for Liquid/Gas – Gas/Liquid heat exchanging.

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Appendix B ARTICLE 2 : FACTOR-BASED COST MODEL FOR THE ECONOMIC ASSESSMENT OF HEAT RECOVERY PROJECTS AT THE EARLY DESIGN STATE

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Abstract

For decades, site-wide energy analysis methods such as the various forms of Pinch Analysis, and more recently the Bridge Method, have been used by industry for increasing energy integration between process streams through heat exchanger network (HEN) retrofit. Efforts to advance these methods have mainly concentrated on defining and/or refining the visualization tools used to obtain energy saving targets, and improved ways of identifying retrofit projects based on thermodynamic criteria. Little attention has been paid to the economic assessment of retrofit projects, which is critical to decision-making at the early design stage. The purpose of this study was to develop a global factored-based cost model suitable for costing heat recovery projects (HRPs) resulting from site-wide energy analysis methods (SWEAMs) at the early design stage. Following a review of HX parametric-cost models, the accuracy of different models is compared to a detailed cost model defined for shell-and-tube and plate heat exchangers (HXs). Then, a global factored-based cost model, inspired by the detailed costing of heat recovery projects, is proposed and quantified for different types of SWEAM recommendations. Finally, a case study is provided to concretize the method, and compare the "global" factored-based cost model introduced here with the existing conventional costing approach. We demonstrate how the adoption of the global costing model influences the decision-maker's selection of economically-feasible HRPs among the several projects suggested by SWEAMs.

Keywords: Site-wide energy analysis methods, heat exchanger network, retrofit, economic assessment

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1.1 Introduction

For decades, process integration methods have been demonstrated for improving site-wide energy efficiency in manufacturing processes [4, 20]. For example, energy savings of between 10% and 33% have been reported in case studies conducted in the petrochemical industry [19], between 53% and 75% in the chemical industry [65], and as high as 66% in the pulp and paper industry [12, 40]. Site-wide energy analysis methods (SWEAMs) are based upon the first and second laws of thermodynamics, and permit the identification of heat recovery projects (HRPs) [9, 20]. In order to establish whether HRPs are economically feasible, decision-makers need to assess the capital and operating costs of each HRP [66].

Heat exchanger network (HEN) modifications needed to meet the energy saving targets implied by SWEAMs can be complex, and include (i) adding new HX unit(s), (ii) modifying existing HX(s), (iii) resequencing existing HX(s), and (iv) splitting - mixing stream(s) [2]. Shahhosseini [66] presented a global costing approach that identified key design and cost parameters that influence the economic evaluation of fully implemented heat exchanger network (HEN) retrofit projects. At the primary design stage there is insufficient information and resources to conduct a rigorous economic assessment of HEN retrofit projects, and existing factor-based costing methods can be unreliable due to their lack of sensitivity to equipment design alternatives and plant topology [46, 49].

The main goal of this paper is to establish a practical method for improving the accuracy of capital and operating cost estimates of heat recovery projects (HRPs) at the early design stage, for better decision-making. We introduce a "global" factored-based cost model, and establish the factors to price HRPs that requires a minimum of data. This paper uses following structure:

- Parametric purchase cost models for heat exchangers are reviewed, including those by Corripio (1995) [48], Smith (2000) [13], Turton (2001) [49], Towler (2010) [50], and Seider (2013) [46].
- The accuracy of the cost models are benchmarked for shell-and-tube as well as plate HXs, and these against a detailed HX costing approach [59], evaluating how the accuracy of cost calculations changes as the heat transfer area of a HX is increased.
- The global factored-based cost model is introduced, including cost factors considering different HEN topology characteristics.

- The economic assessment of a case study is made to benchmark the global factored-based cost model versus a conventional cost model.

2. Literature review

2.1 A review of the parametric models for estimating the costs of heat exchangers

Heat exchanger capital costs without auxiliary equipment are typically expressed in terms of three formulations [14]:

- Power law formulation: $C_{HX} = aA^b$
- Power law with fixed contribution constant: $C_{HX} = a + bA^c$
- Logarithmic based (log or ln): $\ln(C_{HX}) = k_1 + k_2[\ln(A)] + k_3[\ln(A)]^2$

These three formulations indicate the "base case" purchase cost of a new HX at ambient operating conditions and carbon steel construction. The purchase cost of the HX is then modified to account for the type of heat exchanger, construction material, as well as operating temperature and pressure [46]. The goal of this section is to examine parametric models used for preliminary cost estimates of heat exchangers as a piece of equipment, and do not consider cost implications associated with purchasing auxiliary items required for installing purchased HX in place and make it operational.

Corripio model [48]

Corripio et al. correlated data from case studies to determine the basic cost model for a shell-and-tube configuration, considering a floating head made of carbon steel with a pressure of 100 $psig$ and a heat transfer surface (A) of 150 to 12000 ft^2.

$$C_{HX} = e^{\{8.551-0.30863[\ln(A)]+0.06811[\ln(A)]^2\}} \qquad \text{Equation 28}$$

Equations 2-4 offer correction factors to the variation of shell-and-tube costs. This component must be multiplied by the base cost correlation shown in Equation 28.

$$\mathrm{F_{Fixed\ head}} = \mathrm{e}^{\{-1.1156+0.0906[\ln(A)]\}} \qquad \text{Equation 29}$$

$$\mathrm{F_{U-tube}} = \mathrm{e}^{\{-0.9816+0.0830[\ln(A)]\}} \qquad \text{Equation 30}$$

$$\mathrm{F_{kettle-reboiler}} = 1.35 \qquad \text{Equation 31}$$

Corripio also suggested using Equation 32 to compute an operating pressure adjustment factor for pressures greater than 100 psig.

$$F_P = M_1 + M_2 \ln(A) \qquad \text{Equation 32}$$

When the operating pressure is between 100 and 300 $psig$ then $M_1 = 0.7771$ and $M_2 = 0.04981$, between 300 and 600 $psig$ then $M_1 = 1.0305$ and $M_2 = 0.07140$, between 600 and 900 $psig$ $M_1 = 1.1400$ and $M_2 = 0.12088$.

Smith model [13]

Smith et al. developed a parametric cost model for shell-and-tube heat exchangers manufactured from carbon steel having the following form:

$$C_{HX} = 1666.37(A)^{0.68} \qquad \text{Equation 33}$$

Equation 33 is applicable to situations in which the heat transfer area (A) is between 80 and 4000 m^2, the operating temperature is between 0 and 100 °C, and the operating pressure is between 0.5 and 7 bar. Smith's cost model considers correction factors to account for differences in (1) construction materials in each of the shell and tube components of the HX (*Table 3*), and (2) operating pressure (*Table 4*). Furthermore, when the working temperature is 300°C or 500°C, the base cost calculated in equation 1 must be multiplied by 1.6 and 2.1, respectively.

Table 3. Shell-and-tube heat exchanger construction material cost factors by Smith [13]

Material of construction Shell/tube	Correction factor
CS/CS	1.0
CS/Al	1.3
CS/Mo	2.1
CS/SS (low grade)	1.7
SS (low grade) /SS (low grade)	2.9

Table 4. Heat Exchanger operating pressure cost factors by Smith [13].

Operating pressure (bar)	Correction factor
0.01	2.0
0.1	1.3
0.5 to 7	1.0
50	1.5
100	1.9

Smith et al. have also provided a cost model for air-cooled HX made of CS, which is appropriate when the tube heat transfer area is between 200 and 2000 m^2.

$$C_{HX} = 1.56 \times 10^5 (\frac{A}{200})^2 \qquad \text{Equation 34}$$

Turton model [49]

Equation 35 indicates the relationship developed by Turton for the purchase cost of a new HX, C_{HX}, at ambient operating pressure and utilising carbon steel as a construction material.

$$C_{HX} = 10^{\{k_1 + k_2 \times \log(A) + k_3 \times [\log(A)]^2\}} \qquad \text{Equation 35}$$

Table 5 contains the data for the coefficients K_1, K_2, and K_3, as well as the maximum and lowest values of A (m^2) utilised in the correlation [49].

Table 5. Heat Exchanger cost parameters for Equation 35 by Turton [49]

Heat Exchangers		K_1	K_2	K_3	$A_{min}(m^2) - A_{max}(m^2)$
Scrapped wall		3.7803	0.8569	0.0349	2- 20
Teflon tube		3.8062	0.8924	-0.1671	1-10
Shell and Tube	Bayonet	4.2768	-0.0495	0.1431	10-1000
	Floating head	4.8306	-0.8509	0.3187	10-1000
	Fixed tube	4.3247	-0.3030	0.1634	10-1000
	U-tube	4.1884	-0.2503	0.1974	10-1000
	Kettle reboiler	4.4646	-0.5277	0.3955	10-100
Double pipe		3.3444	0.2745	-0.0472	1-10
Multiple pipe		2.7652	0.7282	0.0783	10-100
Flat plate		4.6656	-0.1557	0.1547	10-1000
Spiral plate		4.6561	-0.2947	0.2207	1-100
Air cooler		4.0336	0.2341	0.0497	10-10000
Spiral tube		3.9912	0.0668	0.2430	1-100

Equation 36 shows the relationship that takes into consideration the influence of variations in operating pressure and equipment construction material on the Turton cost model.

$$C_{HX,\text{global}} = F_P F_M C_{HX} \qquad \text{Equation 36}$$

The correction factors F_p and F_M are related to operating pressure and equipment construction material changes, respectively. F_p can be calculated through Equation 37.

$$F_P = 10^{\{C_1 + C_2 log_{10}^P + C_3 (log_{10}^P)^2\}} \qquad \text{Equation 37}$$

$P(barg)$ represents the stream operating pressures. *Table 6* shows the values for the coefficients C_1, C_2, and C_3 for various HX configurations, as well as the pressure ranges over which the constants values can be used. The construction material correction factors are given in *Table 7*.

Table 6. Heat exchanger operating pressure correction factors by Turton [49]

Heat Exchangers	C_1	C_2	C_3	$P_{min}(\text{barg}) - P_{max}(\text{barg})$
Scrapped wall	0	0	0	P<15
	0.6072	-0.9120	0.3327	40<P<100
	13.1467	-12.6574	3.0705	100<P<300
Teflon tube	0	0	0	P<15
Bayonet, Floating head, Fixed tube, U-tube, Kettle reboiler (both shell and tube)	0	0	0	P<5
	0.03881	-0.11272	0.08183	5<P<140
Bayonet, Floating head, Fixed tube, U-tube, Kettle reboiler (tube only)	0	0	0	P<5
	-0.00164	-0.00627	0.0123	5<P<140
Double pipe and Multiple pipe	0	0	0	P<40
	0.6072	-0.9120	0.3327	40<P<100
	13.1467	-12.6574	3.0705	100<P<300
Flat plate and Spiral plate	0	0	0	P<19
Air cooler	0	0	0	P<10
	-0.1250	0.15361	-0.02861	10<P<100
Spiral tube (both shell and tube)	0	0	0	P<150
	-0.4045	0.1859	0	150<P<400
Spiral tube (tube only)	0	0	0	P<150
	-0.2115	0.09717	0	150<P<400

Table 7. Heat exchanger construction material correction factors by Turton [49].

Heat Exchangers	Construction material	Correction factor, F_M
Double pipe, multiple pipe, Fixed tube sheet, floating head, U-tube, bayonet, kettle reboiler, scraped wall, and spiral tube	CS-shell/CS-tube	1
	CS-shell/Cu-tube	~1.4
	Cu-shell/Cu-tube	~1.7
	CS-shell/SS-tube	1.8
	SS-shell/SS-tube	~2.8
	CS-shell/Ni alloy tube	~2.7
	Ni alloy shell/ Ni alloy tube	~3.8
	CS-shell/Ti-tube	~4.6
	Ti-shell/Ti-tube	~11.4
Air cooler	CS tube	1
	AL tube	1.4
	SS tube	~2.9
Flat plate and spiral plate	CS	1
	Cu	~1.4
	SS	~2.45
	Ni alloy	~2.7
	Ti	4.6

Towler model [50]

Towler et al. propose Equation 38 for estimating the cost of the new HX [50].

$C_{HX} = a + bA^n$ Equation 38

where A denotes the heat transfer area for HX (m^2), and C_E denotes the HX costs in January 2010 (CEPCI = 532.9). Associated with different types of the HX, Table *8* contains data for the a, b, and n constants, as well as the maximum and minimum values of A for which Equation 38 is valid. Also, Equation 39 provides the refined Towler et al. cost model which is adjusted through multiplying F_M correction factor to consider construction material changes. *Table 9* shows the F_M cost factors in relation to plain carbon steel, which are independent of the equipment type.

$C_{HX,refined} = f_m C_{HX}$ Equation 39

Table 8. Heat Exchanger cost parameters for Equation 38 by Towler [50]

Heat Exchangers	a	b	n	$A_{min}(m^2) - A_{max}(m^2)$
U-tube shell and tube	28000	54	1.2	10-1000
Floating head shell and tube	32000	70	1.2	10-1000
Double pipe	1900	2500	1	1-80
Thermosiphon reboiler	30400	122	1.1	10-500
U-tube Kettle reboiler	29000	400	0.9	10-500
Plate and frame	1600	210	0.95	10-500

Table 9. Cost factors, f_m of equipment construction materials in comparison to carbon steel by Towler [50]

Material of construction	F_M
Carbon steel	1.0
Aluminum and bronze	1.07
Cast steel	1.1
304 stainless steel	1.3
316 stainless steel	1.3
321 stainless steel	1.5
Hastelloy C	1.55
Monel	1.65
Nickel and Inconel	1.7

Seider model [46]

Seider et al. used the cost model representation introduced by Corripio et al. [67] to correlate HX cost data in a graphical manner for fixed-head, floating head, U-tube and kettle shell-and-tube designs.

$C_{HX} = e^{\{N_1 + N_2[\ln(A)] + N_3[\ln(A)]^2\}}$ Equation 40

Where $A(ft^2)$ is the heat transfer area, which varies between 150 and 12000 ft^2. *Table 10* shows the values of the correlation constants N_1, N_2, and N_3.

Table 10. Heat Exchanger cost parameters for Equation 40 by Seider

Heat Exchangers		N_1	N_2	N_3
Shell and tube	Floating head	12.0310	-0.8709	0.09005
	Fixed head	11.4185	-0.9228	0.09861
	U-tube	11.5510	-0.9186	0.09790
	Kettle vaporizer	12.3310	0.08709	0.09005

When the working pressure and construction material are set to ambient pressure and carbon steel, the mentioned equations are valid. Equation 42 and Equation 43 provide a correlation to evaluate the operating pressure correction factor, f_p, and the construction material correction factor, f_m, which are required to adjust the base cost of shell-and-tube HXs due to changes in operating pressure on only the shell side and construction materials on both the shell-and-tube sides.

$$C_{HX,refined} = f_m f_p C_{HX} \quad \text{Equation 41}$$

$$f_m = a + (\frac{A}{100})^b \quad \text{Equation 42}$$

$$f_p = 0.9803 + 0.018\left(\frac{P}{100}\right) + 0.0017(\frac{P}{100})^2 \quad \text{Equation 43}$$

Equation 43 is true for operating pressure ranges of $100 - 200\ psig$. The constants a and b are shown in Table 9 for various combinations of tube and shell construction materials.

Additionally, Seider et al. propose a correction factor to account for differences in tube length, which is irrelevant in the context of this research since there is insufficient knowledge at the start of the design stage to define detailed HX mechanical design parameters [46].

Table 11. Heat Exchanger cost parameters to estimate construction material correction factor by Seider [46]

Materials of construction Shell/Tube	a	b
CS/CS	0.00	0.00
CS/Brass	1.08	0.05
CS/SS	1.75	0.13
CS/Mo	2.1	0.13
CS/Ti	5.2	0.16
Cs/Cr-Mo steel	1.55	0.05
Cr-Mo steel/Cr-Mo steel	1.70	0.07
SS/SS	2.70	0.07
Mo/Mo	3.3	0.08
Ti/Ti	9.6	0.06

Seider et al. provided a cost correlation for double pipe HX based on cost data.

$$C_{HX} = e^{\{7.2718+0.16[\ln(A)]\}} \quad \text{Equation 44}$$

The base cost estimate is for one particular baseline double pipe HX configuration: a carbon-steel structure of material for pressures up to 600 $psig$ with an area measured in ft^2. Also, the base cost may be changed by multiplying by 2 and 3 when the outer pipe is CS and the inner pipe is SS, and when both pipes are SS, respectively. When the operating pressure varies from 600 to 3000 psig, the pressure factor, which is associated as Equation 45, may be used to adjust the double pipe base cost correlation.

$$F_P = 0.8510 + 0.1292\left(\frac{P}{600}\right) + 0.0198\left(\frac{P}{600}\right)^2 \quad \text{Equation 45}$$

Seider et al. also used cost data from 2013 to generate the cost correlation of an air-cooled fin-fan HX made of CS (Equation 46), as well as three kinds of compact HXs made of SS: plate and frame (Equation 47), spiral plate (Equation 48) and spiral tube (Equation 49).

$$C_{HX} = 2835A^{0.40} \quad \text{Equation 46}$$

$$C_{HX} = 10070A^{0.42} \quad \text{Equation 47}$$

$$C_{HX} = 7030A^{0.42} \quad \text{Equation 48}$$

$$C_{HX} = e^{\{8.2015+0.4343[\ln(A)]+0.03812[\ln(A)]^2\}} \quad \text{Equation 49}$$

Equation 46 to Equation 49 are applicable for heat transfer area ranges of 40-150000 square feet, 150-15000 square feet, 20–2000 square feet, and 1-500 square feet, respectively.

2. “Module heat exchanger” cost models

Auxiliary equipment is needed to make the new purchased HX purchase functional. These auxiliary equipment components, named as HX inside battery limit (ISBL), include the following: (i) piping system for hot and cold HX-sides, paint and insulation; (ii) foundation; and (iii) control and instrumentation. Preliminary costing for “module HX”, which refers to HX as a piece of equipment accompanied by its ISBL auxiliary items, can employ factored-based cost methods.

Table 12 summarises the data for the factors used in Equation 2.12 as provided by Gutheri [54], Smith et al. [13], and Towler et al. [50].

$$C_{MC-HX} = C_{HX} \sum (f_{Piping} + f_{civil} + f_{Instrumentation} + f_{paint} + f_{insulation})$$ Equation 50

Table 12. Heat exchanger module cost factors

Cost Model	Module – HX cost factors				
	f_{piping}	f_{paint}	$f_{insulation}$	f_{civil}	$f_{instrumentation}$
Gutheri model (1969)	0.456	0.005	0.049	0.081	0.102
Smith model (2000)	0.7	-	-	0.4	0.2
Towler model (2010)	0.8	0.1	-	0.3	0.3

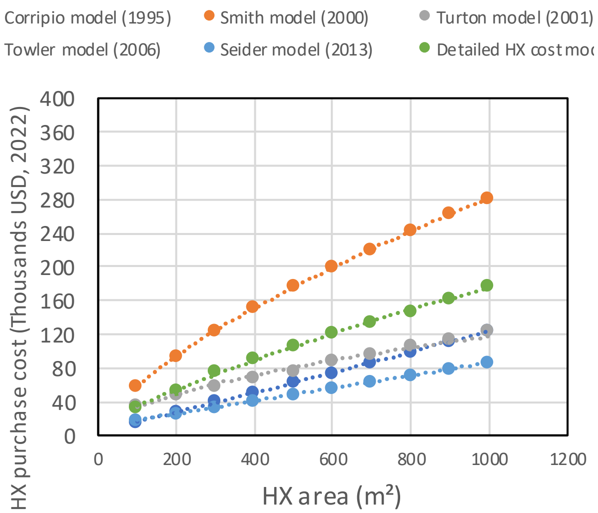
3. Results and discussion

3.1 Benchmarking HX parametric cost models against detail HX cost

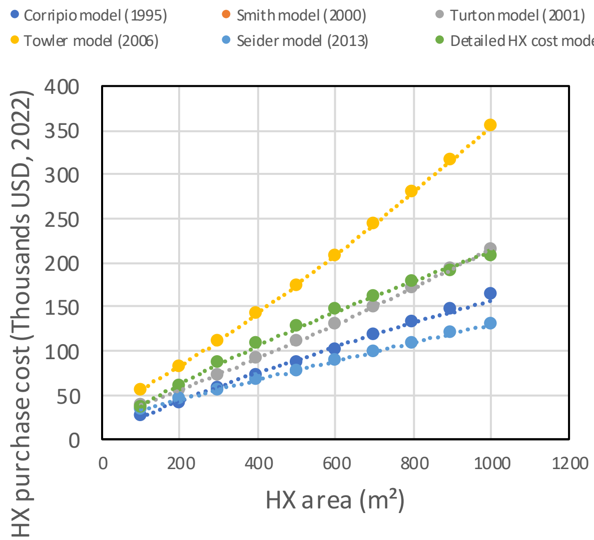
In this section the different heat exchanger cost estimates are benchmarked, ie Corripio model (1995) [48], Smith model (2000) [13], Turton model (2001) [49], Towler model (2010) [50], and Seider model (2013) [46] against the detailed heat exchanger cost model [59].

Figure 50 and 2 show the results of benchmarking in order to provide a general guideline for decision-makers looking to select an appropriate HX costing model for plate as well as shell and tube HX (fixed head, floating head, and U-tube) constructed from CS and SS, which are the most commonly used HXs in industries. *Figure 50* shows that the Turton cost model results are the most reliable relative to the detailed HX cost model results when a shell-and-tube HX type constructed from CS is considered. This is true for the cases of fixed head, floating head, or U tube type. However, if a stainless steel tube-side construction of material is considered, then the appropriate cost model for the HX would be (i) Smith model for fixed head, or (ii) Towler model for Floating head and U-tube. This observation can be attributed to two primary factors: (1) the accuracy of the vendor HX quotes, used as the basis for developing each model, and (2) the type of mathematical model used to express the relationship between HX purchase cost and HX surface area.

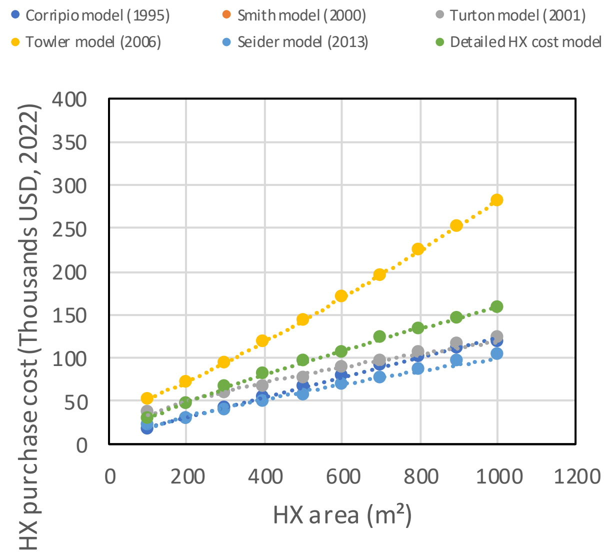
Figure 51 demonstrates that when the type of HX is changed to a Plate type constructed from SS or CS, the estimations associated with the Towler cost model results are the closest to the detailed cost model.



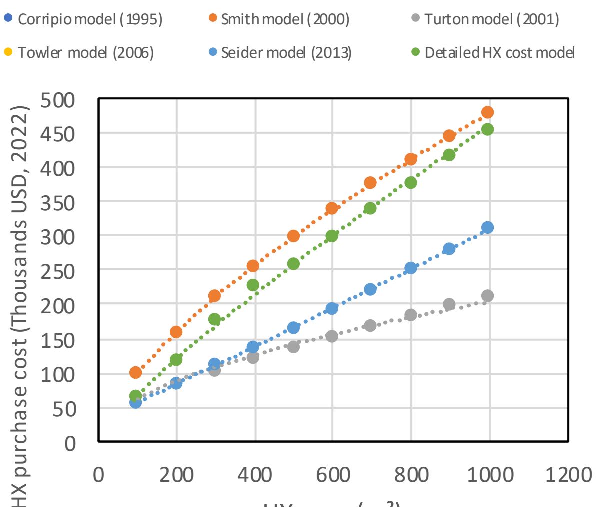
a. Shell-and-tube HX (Fixed head) – carbon steel



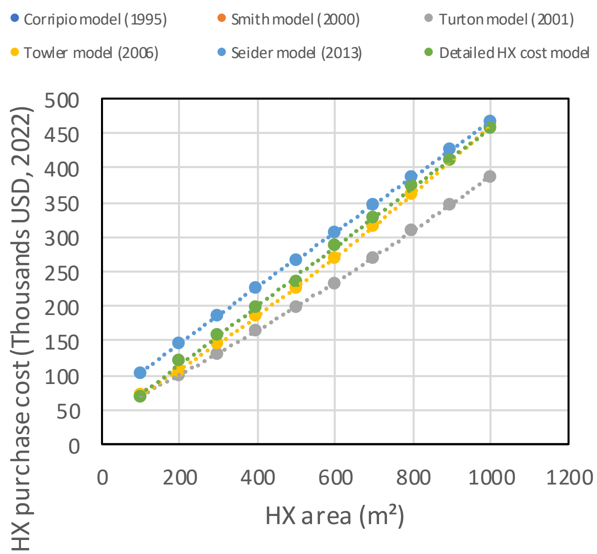
c. Shell-and-tube (Floating head) – carbon steel



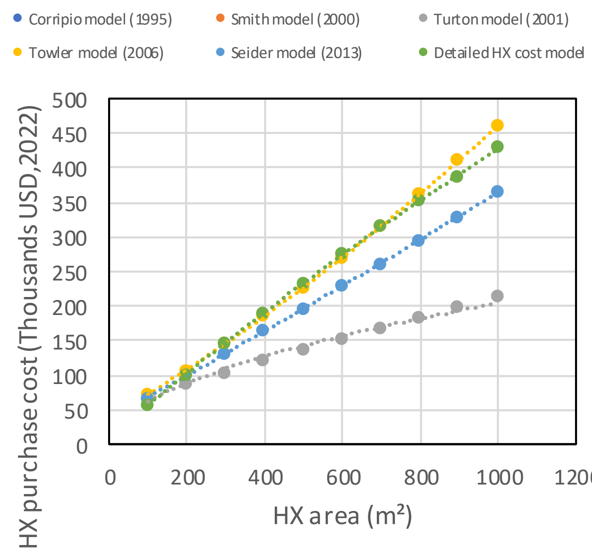
e. Shell-and-tube (U tube) – carbon steel



b. Shell-and-tube HX (Fixed head) – stainless steal

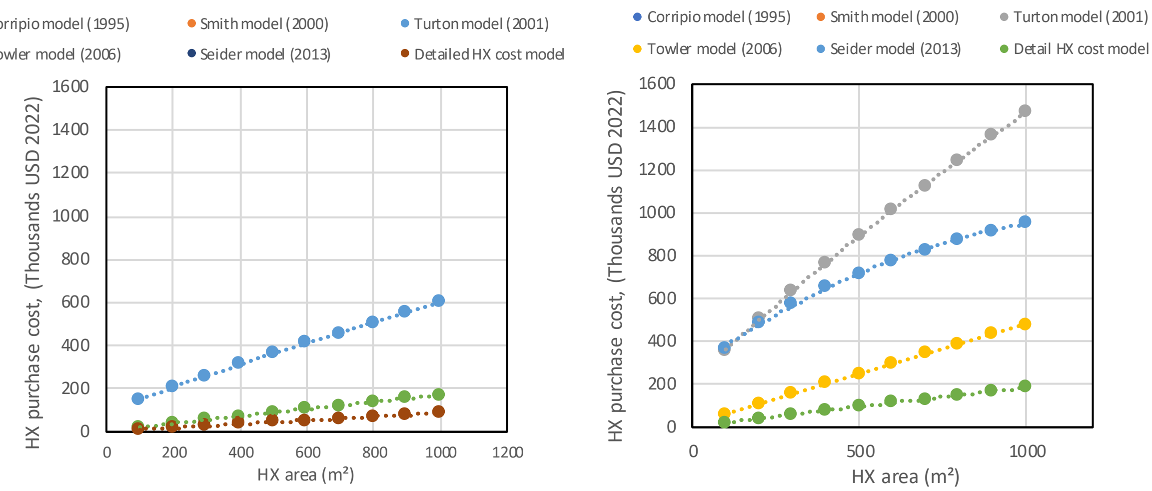


d. Shell-and-tube (Floating head) – stainless steel



f. Shell-and-tube (U tube) – stainless steel

Figure 50. Benchmark of HX parametric cost models versus detailed costing results – example of shell-and-tube HX



a. Plate HX – Carbon steel b. Plate HX – Stainless steel

Figure 51. Benchmark of HX parametric cost models versus detailed costing results – Example of plate HX

3.2 Enhanced factor-based cost model

To define the enhanced factor-based cost model, this section first clarifies the list of HEN modifications implied by SWEAMs, as well as the practical design solutions available for implementing them in plant. The type of HEN topology modifications required to fully implement each SWEAMs recommendation is then clarified, which aids in identifying and correlating all key cost components that contribute to the total investment cost of the HEN modification, referred to as the "global investment cost." This model serves as the foundation for introducing an improved factor-based cost model suitable for the preliminary design stage of HRPs implied by SWEAMs.

Heat Recovery Project Recommendations from Site-Wide Energy Analysis Methods

With the objective of getting as close as possible to the energy consumption targets, each SWEAM uses different information and methodologies as well as good engineering judgment to identify HEN grid diagram modifications, known as a “SWEAMs recommendation”. In general, these modifications can be categorized into four main groups; (1) Adding new HX(s), (2) Modifying existing HX(s), (3) Resequencing of existing HX(s), and (4) stream(s) splitting-mixing. These modifications do not have any information regarding how the HEN modifications can manifest themselves in plants. Shahhosseini [66] elucidated the relationship between SWEAM recommendation and associated practical design solutions and mapped them using Figure 52.

HEN topology modification

Figure 52 demonstrates that the type of topology modifications that are implied by SWEAM recommendations depends on the practical design solution(s) that decision-makers choose in order to fulfill requirements. In order to select an economical design, it is necessary to select one that calls for the current HEN topology to undergo the fewest number of topology modifications possible. This is a design philosophy that must be adhered to. However, the feasibility of many practical design alternatives associated with a single SWEAMs recommendation also needs to be evaluated based on known qualitative practical constraints. In this regard, engineering judgment is essential in determining which topology modifications are required in conjunction with the recommendations of SWEAM.

Global investment cost of SWEAM recommendations

Equation 51 can be regarded as the relationship between the cost of four main SWEAM recommendation categories that depending on the size of the energy-saving project, the nature of the case study, and good engineering judgment, some or all of them contribute to the estimation of cost of the HRP.

$$TICs_{HRP} = \sum_{i=1}^{n} C^{i}_{Adding\ new\ HX\ unit} + \sum_{j=1}^{m} C^{j}_{modifying\ existing\ HX} + \sum_{k=1}^{s} C^{k}_{Resequencing\ exsiting\ HX} + \sum_{d=1}^{p} C^{d}_{stream\ spliting-mixing} \quad \text{Equation 51}$$

In conjunction with each HRP, in this equation, i represents the number of newly required HX(s), j represents the number of existing HX(s) requiring modification, k represents the number of stream re-piping required for HX(s) relocation, and d represents the number of stream splitting-mixing projects. Associated with each type of SWEAM recommendation, Shahhosseini [66] identified and then correlated key cost components that impact the total installed costs of HX modifications, and defined the term “global costing of SWEAM recommendations” (Figure 52).

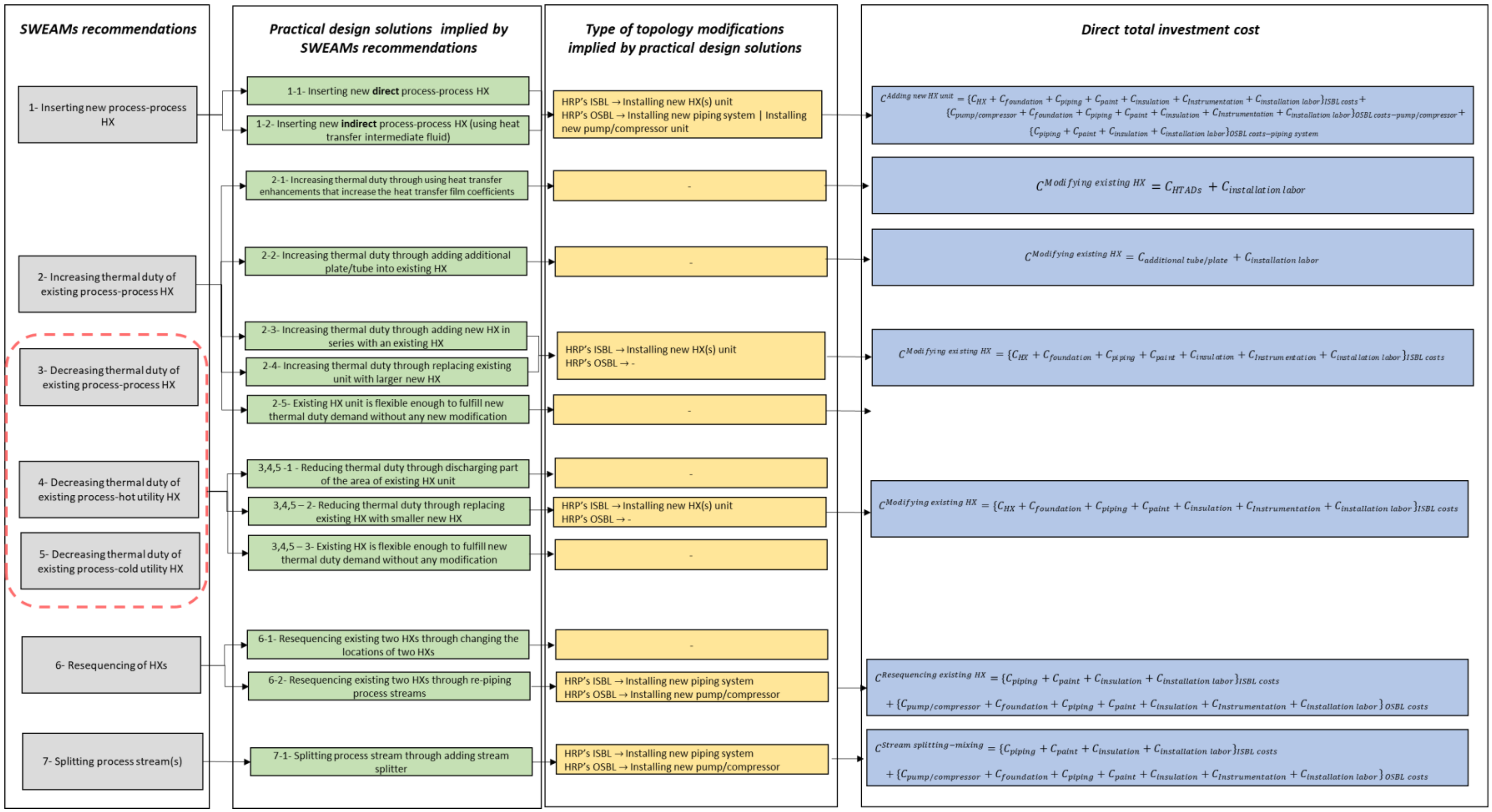


Figure 52. Relationship between SWEAM recommendations, practical design solutions, HEN topology modifications, and Total Investment Cost formulation.

Global costing is considered as an inspiration in this paper for defining the factored-based cost model (Equation 52-26) which is suitable for SWEAM recommendation costing at the early design stage that just there is enough information for sizing and costing of HX, pump/compressor and piping required for connecting new HX with other modules of the plant.

- Inserting new HX

$$C^{Adding\ new\ HX\ unit} = \{C_{HX} + C_{HX}[f_{foundation} + f_{piping} + f_{paint} + f_{insulation} + f_{Instrumentation}]\}_{ISBL\ cost-HX\ unit} + \{C_{pump/compressor} + C_{pump/compressor}[f_{foundation} + f_{piping} + f_{paint} + f_{insulation} + f_{Instrumentation}]\}_{OSBL\ cost-pump/compressor\ unit} + \{C_{piping} + C_{piping}[f_{paint} + f_{insulation}]\}_{OSBL\ cost-piping\ system}$$ Equation 52

- Modifying existing HX – discharging existing HX unit and replace it with a smaller/bigger HX unit

It is assumed that the OSBL equipment items, such as the piping system and pump/compressor, are usable for the new HX unit after the discharge of the existing HX unit.

$$C^{Modifying\ existing\ HX} = \{C_{HX} + C_{HX}[f_{foundation} + f_{piping} + f_{paint} + f_{insulation} + f_{Instrumentation} + f_{installation\ labor}]\}_{ISBL\ cost-HX\ unit}$$ Equation 53

- Resequencing of existing HX(s) and/or stream(s) splitting – mixing

  It is assumed that resequencing of existing HX(s) is accomplished through stream(s) re-piping, and new piping system can use existing pipe-rack.

Equation 54

$$C^{Resequencing\ existing\ HX}\ and/or\ C^{stream\ splitting-mixing}$$
$$= \{C_{piping} + C_{piping}[f_{paint} + f_{insulation}]\}_{ISBL\ cost-piping\ system}$$
$$+ \{C_{pump/compressor} + C_{pump/compressor}[f_{foundation} + f_{piping} + f_{paint} + f_{insulation} + f_{Instrumentation}]\}_{OSBL\ cost-pump/compressor\ unit}$$

where:

- $\boldsymbol{C_{HX}}$ is the estimate of cost to buy a new HX based on parametric models. Using engineering judgment, it is possible to choose the type of HX and the material it is made of based on the nature of the hot and cold streams and the operating conditions. In this step of the design process, the allowable pressure drops of the system and data used to find HRPs are both pieces of information that can be used to estimate the size of the HX.
- $\boldsymbol{f_{piping}}\left(\frac{\boldsymbol{HX\ ISBL\ piping\ cost,USD}}{\boldsymbol{HX\ cost,USD}}\right)$, $\boldsymbol{f_{instrumentation}}\left(\frac{\boldsymbol{HX\ ISBL\ instrumentation,USD}}{\boldsymbol{HX\ cost,USD}}\right)$, $\boldsymbol{f_{paint}}\left(\frac{\boldsymbol{HX\ ISBL\ paint\ cost,USD}}{\boldsymbol{HX\ cost,USD}}\right)$, $\boldsymbol{f_{insulation}}\left(\frac{\boldsymbol{ISBL\ insulation\ cost,USD}}{\boldsymbol{HX\ cost,USD}}\right)$ show the new HX ISBL cost factors that represent the cost of the auxiliary equipment items as a percentage of the new HX purchase cost. The quantitative value of these factors, calculated for a number of operating conditions in Figure 53, is shown in Figure 54 and Figure 55. Heat exchanger P&IDs have been assumed to refine these factors in two distinct scenarios—liquid-liquid heat exchanging and liquid/gas-gas/liquid heat exchanging (shown in Appendix A).

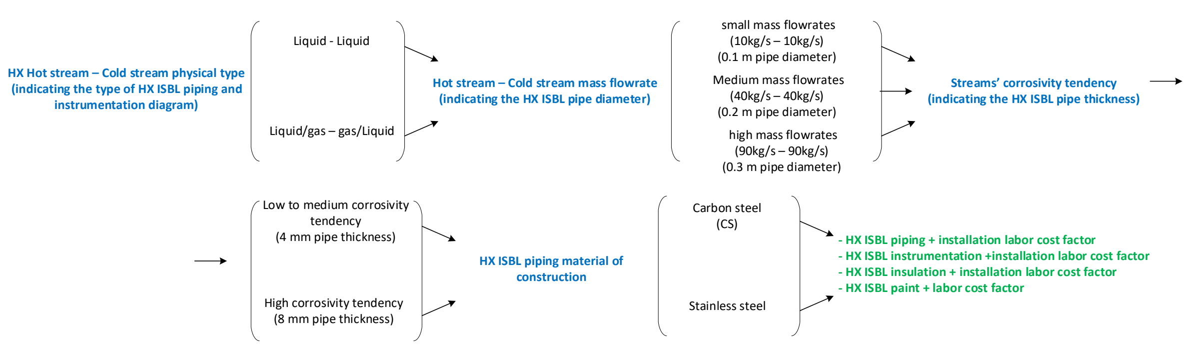
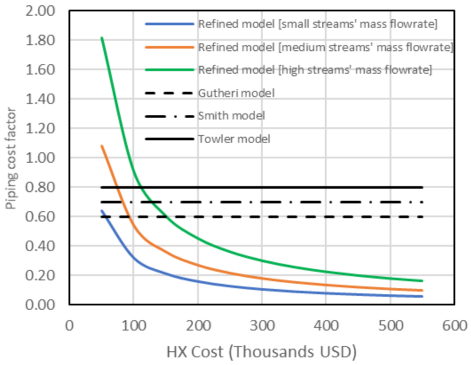
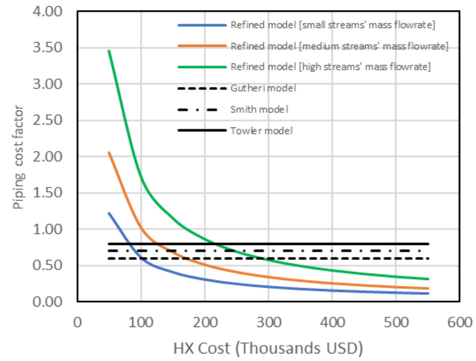


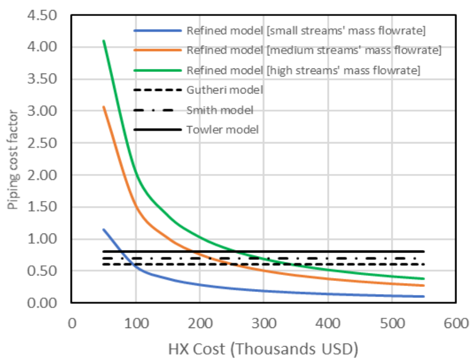
Figure 53. Assessment structure to quantify cost factors associated with the new HX ISBL equipment items



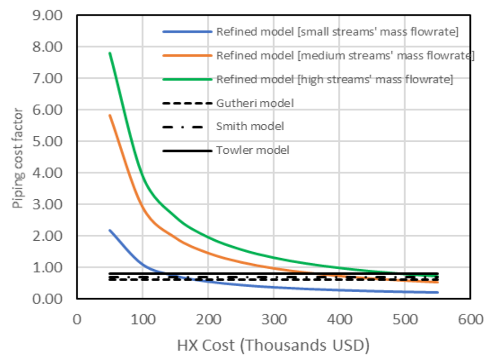
a. Piping (Carbon steel) cost factor for streams with low to medium corrosivity tendency



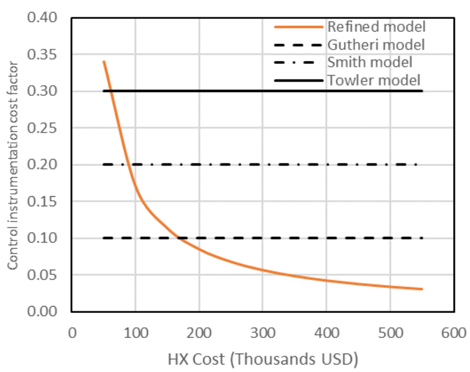
b. Piping (Carbon steel) cost factor for streams with high corrosivity tendency



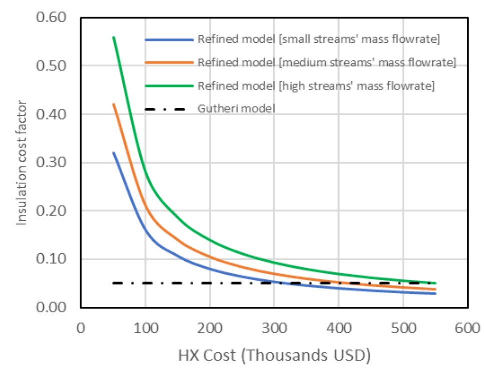
c. Piping (stainless steel) cost factor for streams with low to medium corrosivity tendency



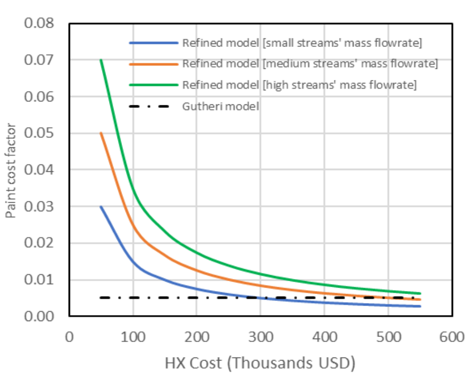
d. Piping (stainless steel) cost factor for streams with high corrosivity tendency



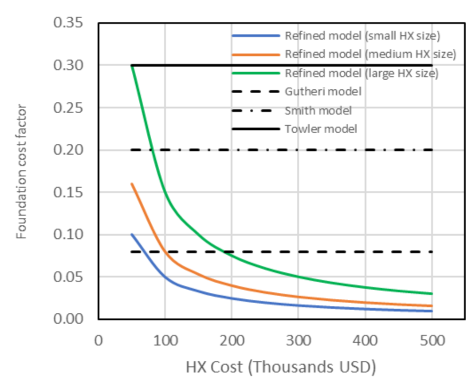
e. Instrumentation cost factor



f. Insulation cost factor

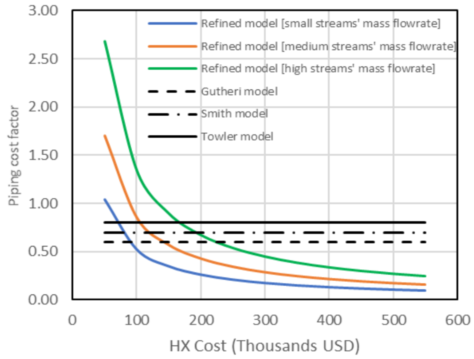


g. Paint cost factor

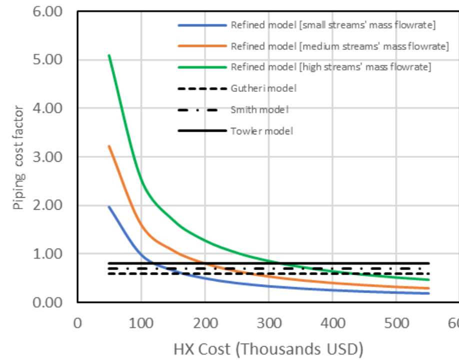


h. Foundation cost factor

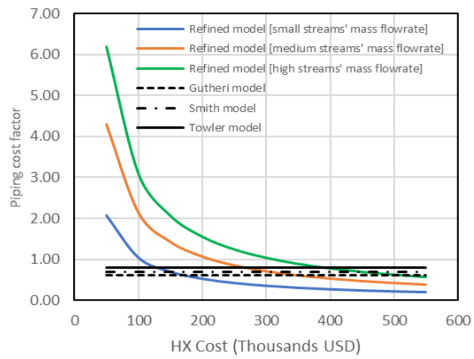
Figure 54. Cost factors associated with HX ISBL cost factors (liquid-liquid heat exchange)



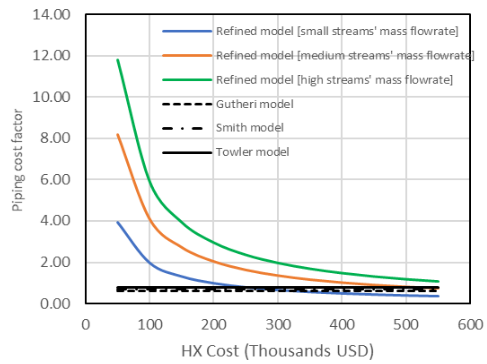
a. Piping (Carbon steel) cost factor for streams with low to medium corrosivity tendency



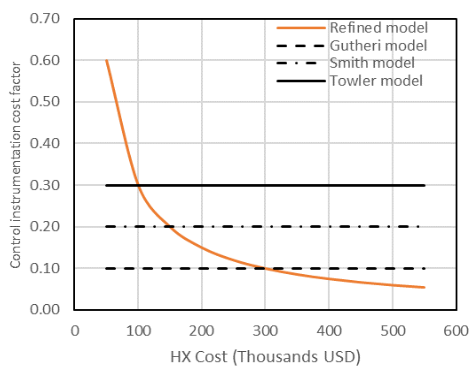
b. Piping (Carbon steel) cost factor for streams with high corrosivity tendency



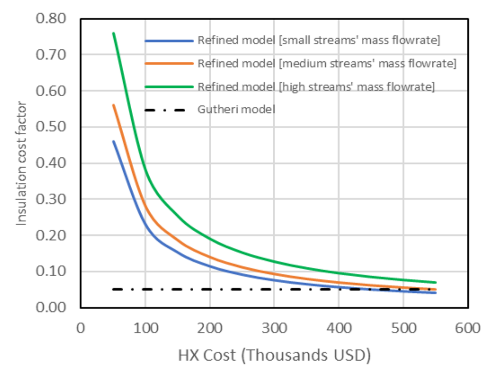
c. Piping (stainless steel) cost factor for streams with low to medium corrosivity tendency



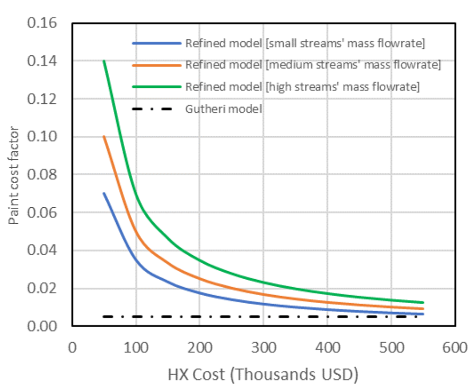
d. Piping (stainless steel) cost factor for streams with high corrosivity tendency



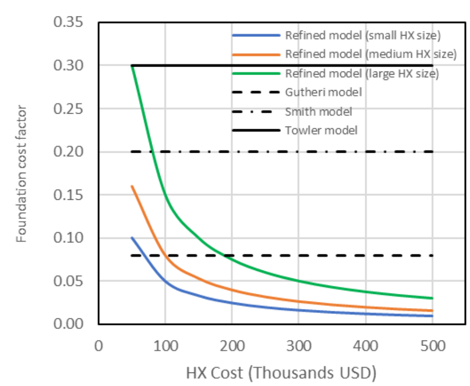
e. Instrumentation cost factor



f. Insulation cost factor



g. paint cost factor



h. Foundation cost factor

Figure 55. Cost factors associated with HX ISBL cost factors (liquid/gas-gas/liquid heat exchange)

- $C_{pump/compressor}$ shows the cost of the pump/compressor needed to eliminate pressure drop caused by new piping system friction losses and elevation changes when the HRPs are followed: (i) Adding new HX, (ii) Resequencing existing HX by re-piping streams and/or stream splitting-mixing.
- $f_{piping}(\frac{pump/compressor\ ISBL\ piping\ cost,USD}{pump/compressor\ cost,USD})$, $f_{instrumentation}(\frac{pump/compressor\ ISBL\ instrumentation,USD}{pump/compressor\ cost,USD})$, $f_{paint}(\frac{pump/compressor\ ISBL\ paint\ cost,USD}{pump/compressor\ cost,USD})$, $f_{insulation}(\frac{pump/compressor\ ISBL\ insulation\ cost,USD}{pump/compressor\ cost,USD})$ show the new pump/compressor ISBL cost factors that represent the cost of the auxiliary equipment items as a percentage of the new pump/compressor purchase cost. The quantitative value of these factors, calculated for a number of operating conditions which super-structured in Figure 56, is shown in and *Figure 58* and Figure 59. The P&ID for the pump and compressor that was used to calculate the cost factors for the ISBL auxiliary equipment items is shown in Appendix B.

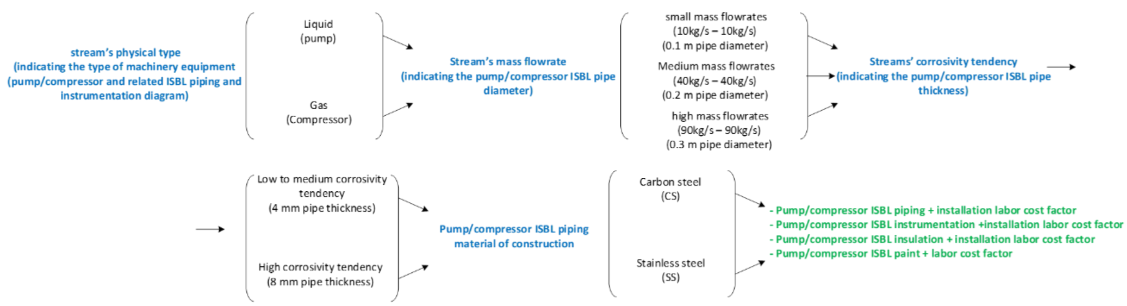


Figure 56. Assessment structure to quantify cost factors associated with the new pump/compressor auxiliary equipment items

- $f_{paint}(\frac{piping-paint\ cost,USD}{piping\ cost,USD})$, $f_{insulation}(\frac{piping-insulation\ cost,USD}{piping\ cost,USD})$ illustrate the cost factors associated with piping system required for OSBL of HRP named "adding new HX" and ISBL of HRP named "stream splitting-mixing and/or resequencing of existing HX". *Figure 60* depicted the quantitative values of these factors, which were calculated for a variety of characteristics super-structured in *Figure 57*.

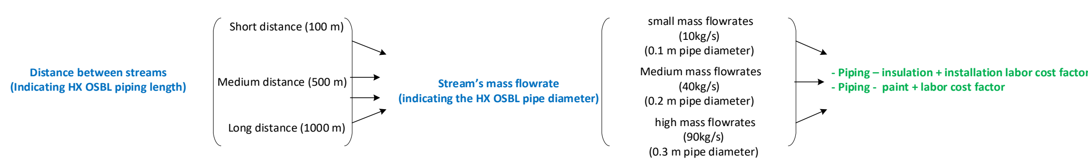
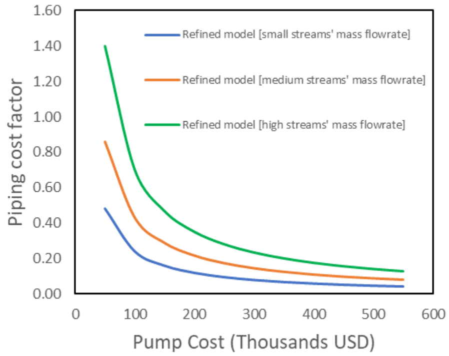
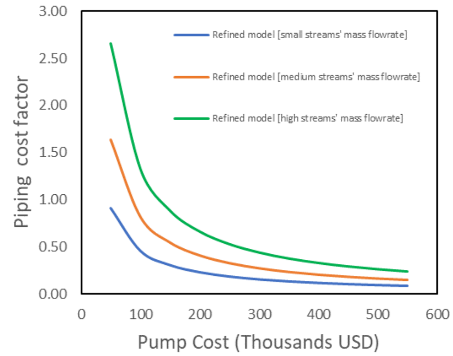


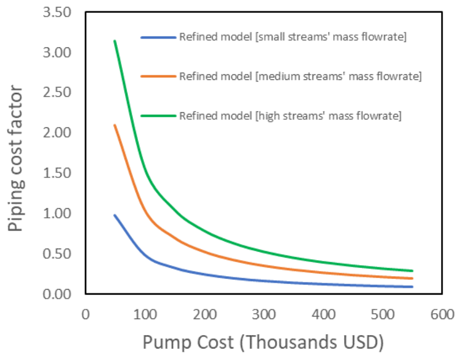
Figure 57. Assessment structure to quantify OSBL piping system auxiliary equipment items.



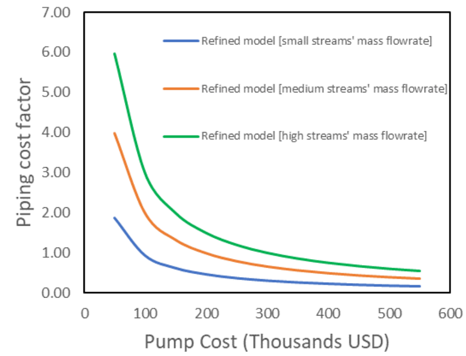
a. Piping (Carbon steel) cost factor for streams with low to medium corrosivity tendency



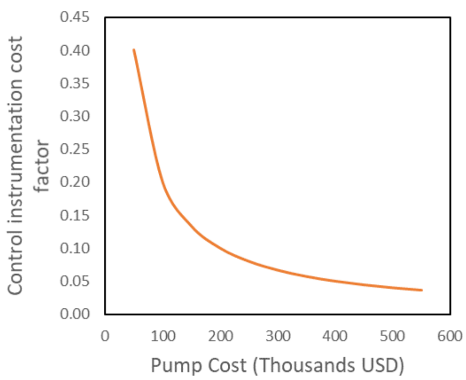
b. Piping (Carbon steel) cost factor for streams with high corrosivity tendency



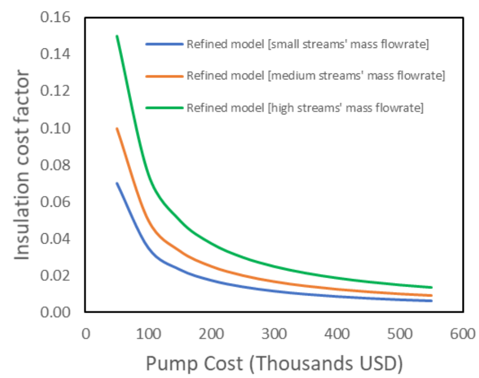
c. Piping (stainless steel) cost factor for streams with low to medium corrosivity tendency



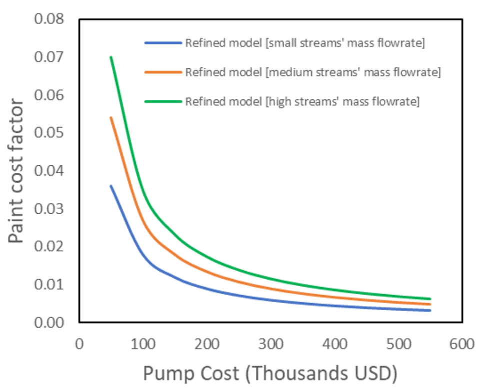
d. Piping (stainless steel) cost factor for streams with high corrosivity tendency



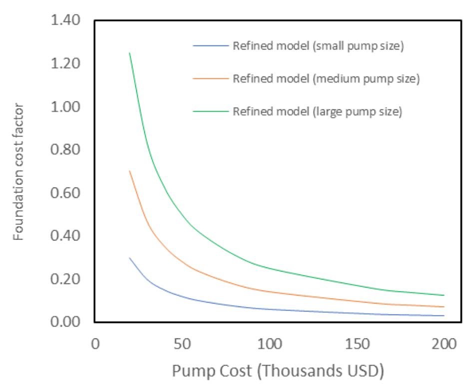
e. Instrumentation cost factor



f. Insulation cost factor

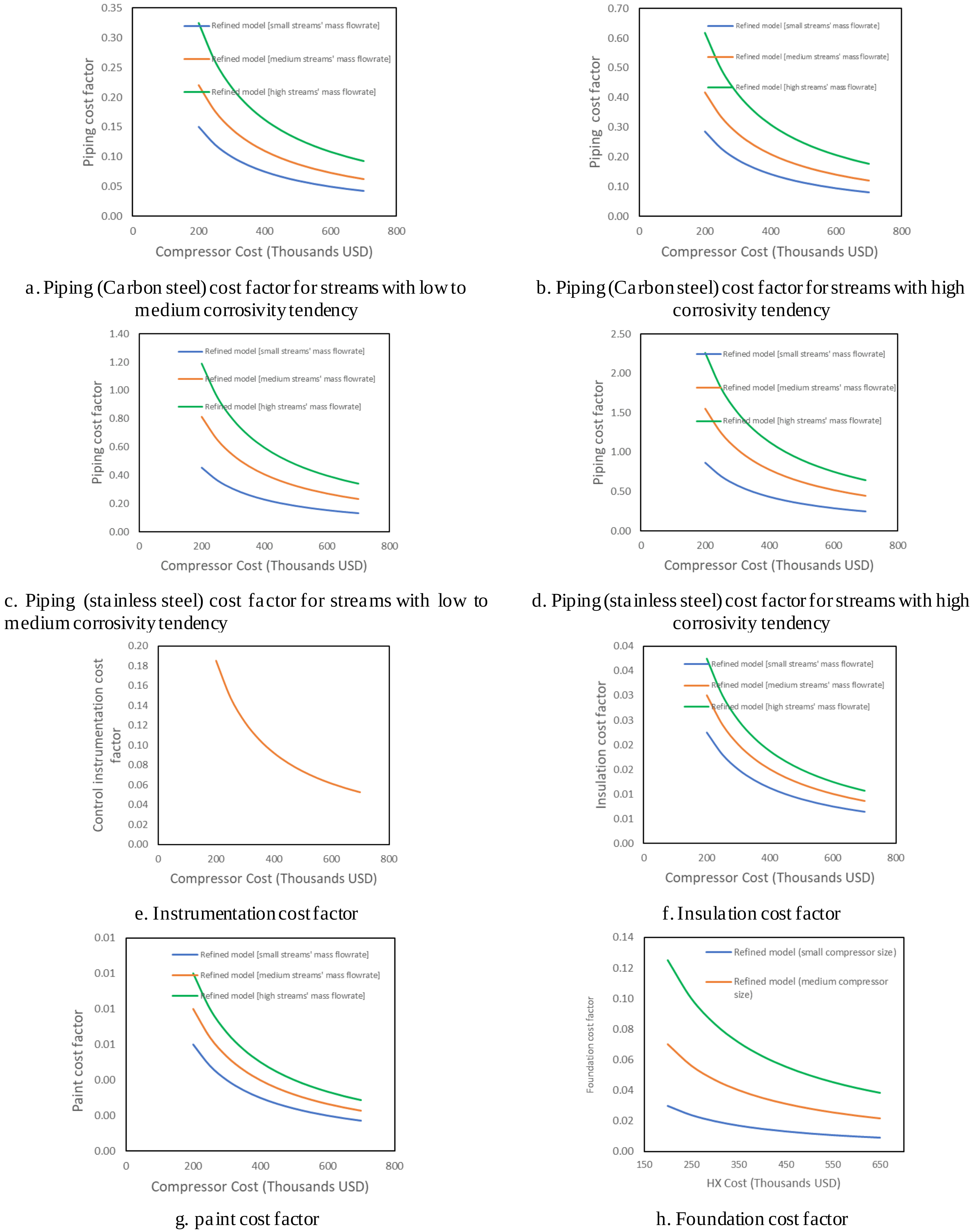


g. paint cost factor



h. Foundation cost factor

Figure 58. Pump auxiliary equipment items cost factors



a. Piping (Carbon steel) cost factor for streams with low to medium corrosivity tendency

b. Piping (Carbon steel) cost factor for streams with high corrosivity tendency

c. Piping (stainless steel) cost factor for streams with low to medium corrosivity tendency

d. Piping (stainless steel) cost factor for streams with high corrosivity tendency

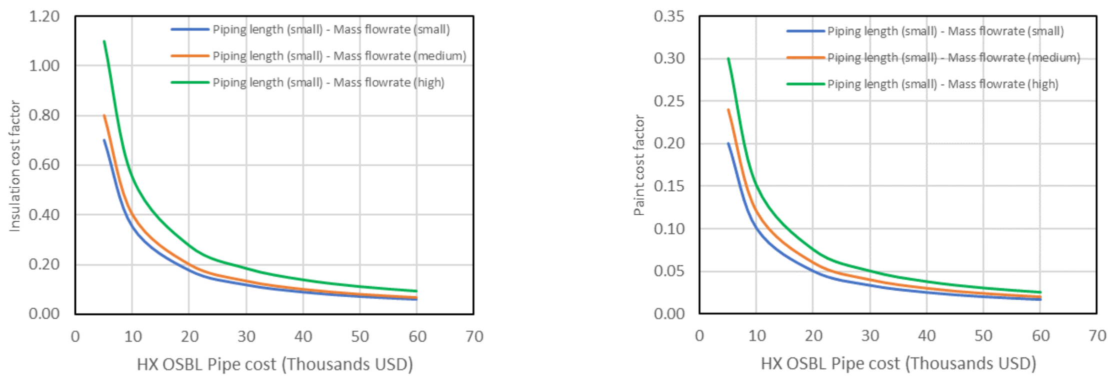
e. Instrumentation cost factor

f. Insulation cost factor

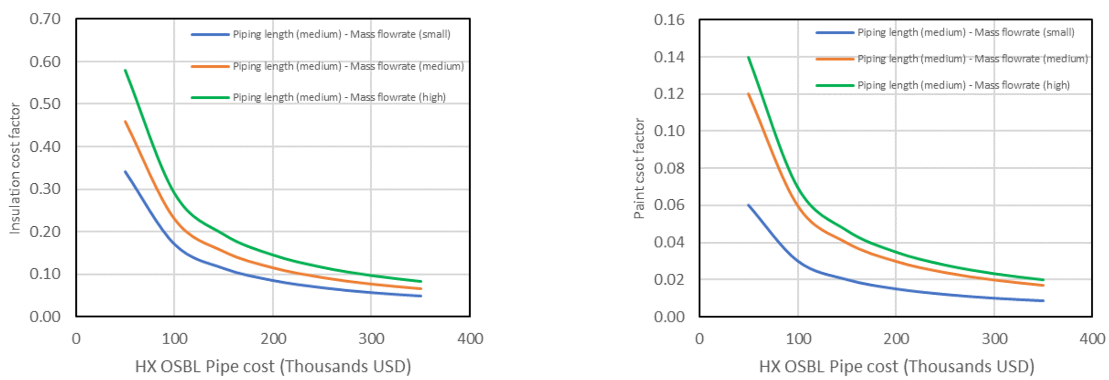
g. paint cost factor

h. Foundation cost factor

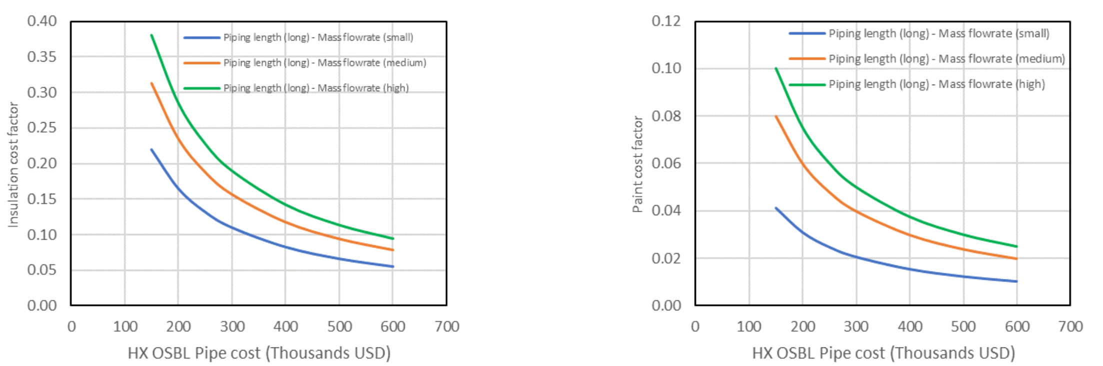
Figure 59. Compressor auxiliary equipment items cost factors



a. Small piping length



b. Medium piping length



c. Long piping length

Figure 60. Auxiliary items cost factors associated with piping system used as connection lines between plant modules.

3.3 Benchmarking enhanced factor-based cost model against conventional factored-based cost model (Gutheri model)

The main goal of this section is to compare the enhanced factor-based cost model performance to that of the conventional factor-based cost model through assessing the profitability assessment of

27 HRPs implied by SWEAMs that summarized in Figure *61*. To account for the influence of the plant topology and hot-cold stream flow rate on the results of the economic assessment, three different scenarios can be considered for the overall piping length implied by new projects, and two different scenarios are considered for the hot-cold stream flowrates, which impacts the diameter of the new piping system.

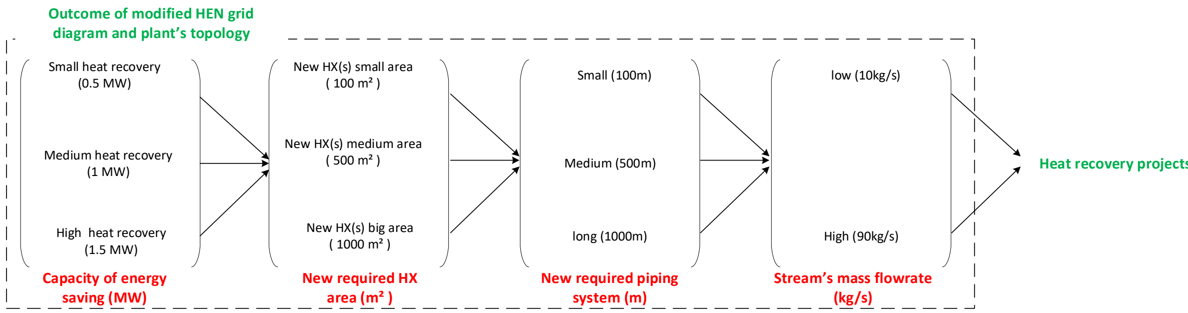
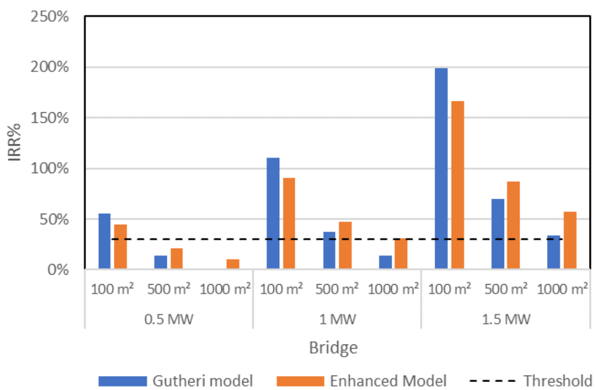


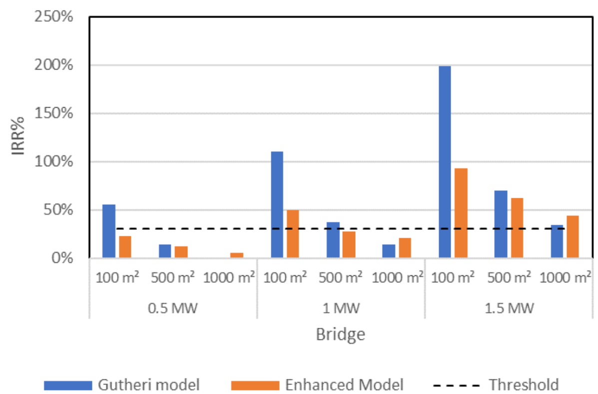
Figure 61. Case study framework

The case study considers the following:

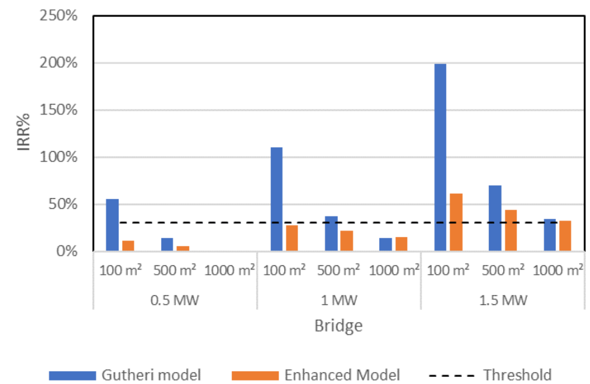
- The existing HXs are flexible enough to meet new operating and thermal conditions resulting from increased thermal integration between HEN process streams.
- The case of "inserting new HX" is considered, using a process-process HX.
- The purchase price of the new HX is estimated based on shell-and-tube (floating head) HX.
- Carbon steel is selected as the construction material for new equipment required to implement topology changes implied by modified HEN.
- Bridge implementation does not require a new pump for the following reasons (i) new HXs are sized based on the allowable pressure drop (1 bar) rather than the heat transfer coefficient of the streams, (ii) there are no elevation differences between the streams, and (iii) friction losses caused by the new piping system increases the plant pressure drops by maximum 1 bar, which is within the range of the allowable pressure drop assumed.
- As phase types for heat exchange between hot and cold process streams, liquid-to-liquid exchange (Figure 13) and gas-to-gas heat exchange (Figure 14) are alternatives.
- HX hot and cold streams have a low to moderate tendency toward corrosivity.



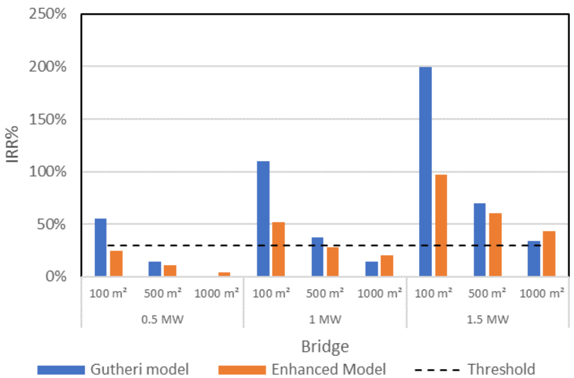
a. low Hot – Cold mass flowrates, small new piping system length



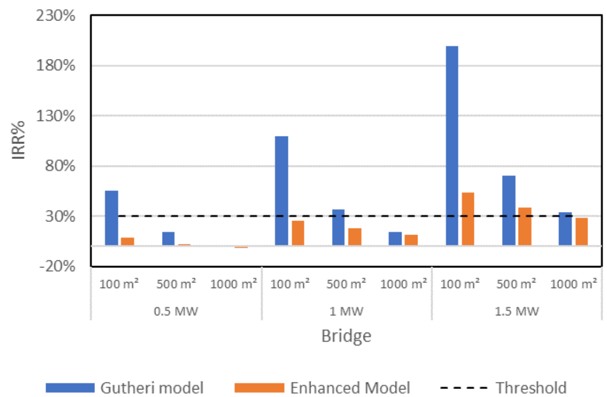
b. low Hot – Cold mass flowrates, medium new piping system length



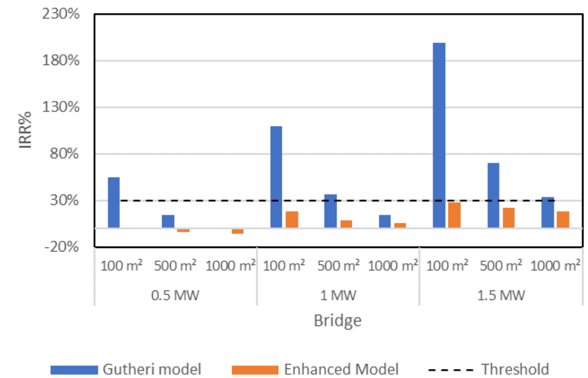
c. low Hot – Cold mass flowrates, long new piping system length



d. high Hot – Cold mass flowrates, small new piping system length

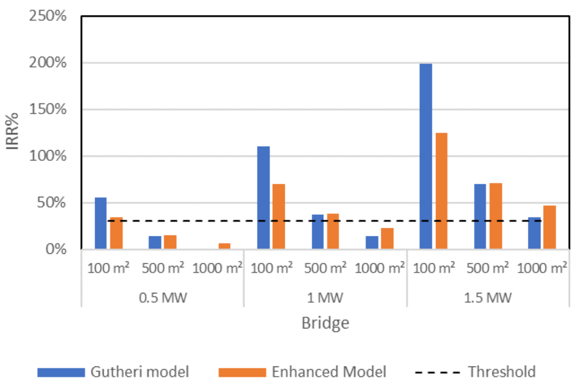


e. high Hot – Cold mass flowrates, medium new piping system length

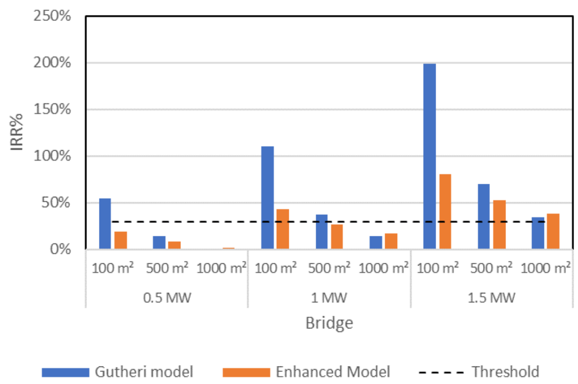


f. high Hot – Cold mass flowrates, long new piping system length

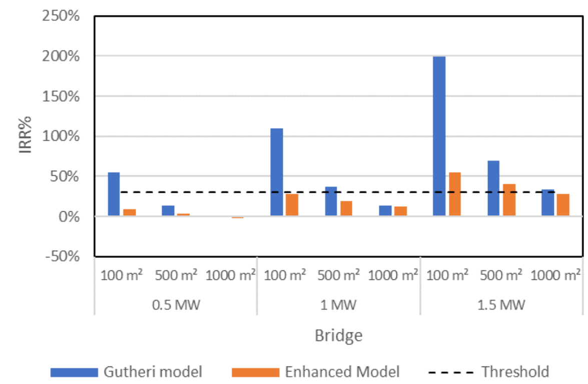
Figure 62. Case study – Economic return for Bridge modifications (conventional costing vs. enhanced costing) – liquid/liquid heat exchange



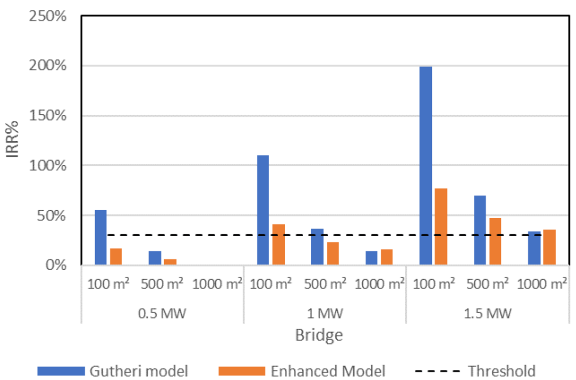
a. low Hot – Cold mass flowrates, small new piping system length



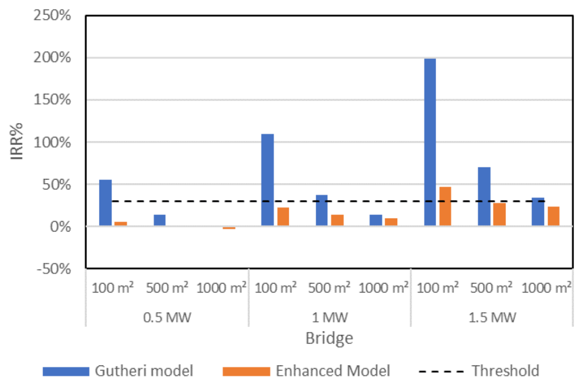
b. low Hot – Cold mass flowrates, medium new piping system length



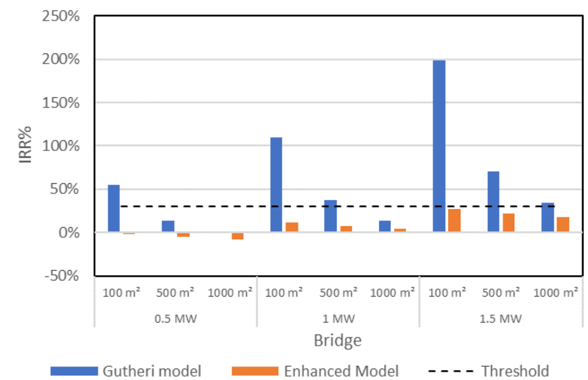
c. low Hot – Cold mass flowrates, long new piping system length



d. high Hot – Cold mass flowrates, small new piping system length



e. high Hot – Cold mass flowrates, medium new piping system length



f. high Hot – Cold mass flowrates, long new piping system length

Figure 63. Case study – Economic return for Bridge modifications (conventional costing vs. enhanced costing) – gas/gas heat exchanging

Figure *62* shows the economic viability resulting from energy saving projects when there is heat exchange between liquids. The global costing method is compared to that of Gutheri [54], which is chosen because it (1) provided cost factors for all HX's ISBL auxillary equipment items and (2) deviates less from refined cost factor values than other conventional factor-based cost models.
It was found that:

- Although the IRR values differ, the number of heat recovery projects with higher IRR than the threshold is the same for both costing methods when the flowrate of the hot and cold streams is small and the length of the new piping system is short (*Figure 62*a).
- Increasing the value of each of the design variables (stream mass flowrates and distance between streams) reduces the IRR of projects analyzed using the enhanced costing approach, as well as the portions of profitable projects with an IRR greater than the threshold (30%).
- Figure *62*f shows that there is no profitable project when using the global costing approach; however, Gutheri proposes that six Bridges are still profitable when stream flowrates are high and the required piping system is long since Gutheri's costing approach uses cost factors that remain constant in different situations.
- In contrast with Gutheri’s costing results, comparing Figure *62* and Figure *63* reveals that the IRR of projects with respect to the new enhanced model decreases when there is phase change of the hot and/or cold streams. Changing the stream phase from liquid to gas necessitates more control to be installed around the HX.

Conclusions

Rapid and accurate cost estimation of heat exchanger network (HEN) retrofit projects is essential during the early design phase for decision-making, as cost over-estimation can result in attractive projects being eliminated, whereas cost under-estimation can result in projects being retained at the early design stage – only to be discarded at later stages of engineering.

The global direct cost of heat recovery projects can be considered as having two main cost elements (i) **Inside Battery Limits or *ISBL***, including the HX purchase cost, installation materials, auxiliary equipment items required for making it operational (piping, control instrumentation, insulation, etc.), and installation labor cost, and (ii) **Outside Battery Limits *OSBL***, including the piping system required for connecting the HX unit into other modules of the plant, and as necessary for this, pump/compressor purchase cost required for eliminating new pressure drop caused as a result of the HEN topology modifications, and installation labour cost.

In the early design stage when there is insufficient information to carry out the global costing approach necessary for the rigorous economic assessment of HRPs, factor-based cost models can be used to estimate the capital costs of the heat exchanger and auxiliary equipment. However, (1) cost factors are typically proposed for the heat exchanger unit/modifications only, whereas HEN topology modifications imply the main equipment (heat exchanger, pump/compressor, piping system, controls…), and (2) HX cost factors are unreliable due to their insensitivity to equipment design alternatives and overall plant topology. These drawbacks motivated this work, whose goal was to develop enhanced factored-based cost models for recommendations from sire-wide energy analysis methods, including for the cases of (i) adding new HXs, (ii) modifying existing HXs, (iii) stream splitting-mixing, and (iv) resequencing of existing HXs. In addition, cost factors associated with installing a new HX, pump/compressor, and piping system have been estimated considering operating conditions and expected plant topology. To use the global costing factors, the user must have information associated with (1) phase and corrosivity tendency of the HEN process streams, (2) process stream mass flowrates, and (3) qualitative information associated with distance and elevation difference between various plant process areas.

The case study illustrates how the adoption of the costing model may affect the decision regarding heat recovery projects, by comparing the global factored-based cost model with conventional costing approaches. It was discovered that, despite the energy-saving capacity of the project and the new HX size implied, by increasing the mass flowrate of the process streams (which specifies the diameter of the piping system) and the distance between the plant's process zones (which specifies the length of the piping system), the number of profitable projects with an IRR greater than the threshold is zero when projects are evaluated using a global factored-based cost model.

Appendix A. HX and pump/compressor P&ID used for quantifying cost factors

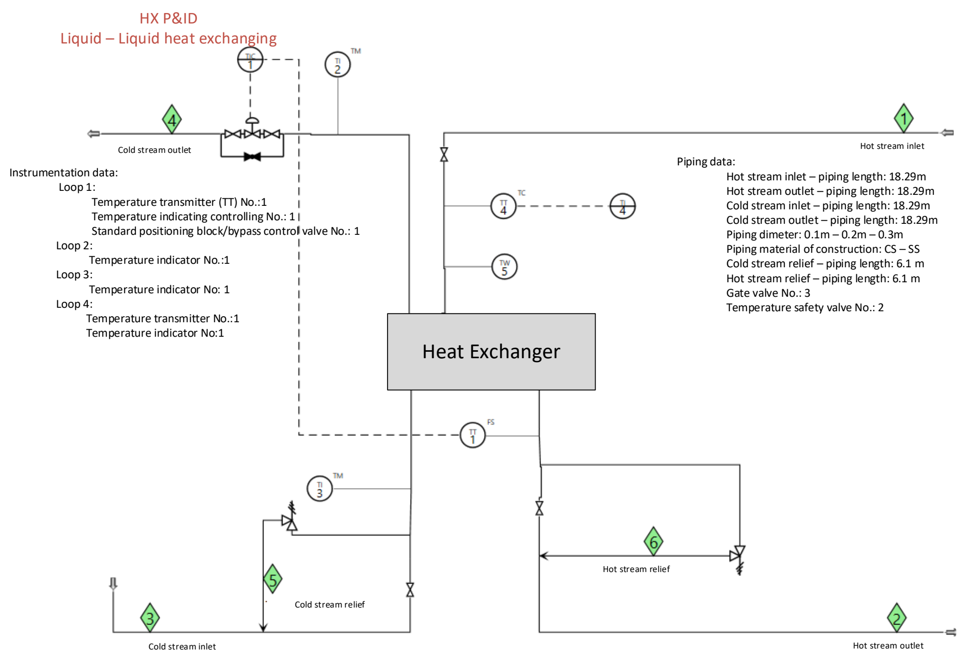


Figure A.1. Heat Exchanger P&ID suitable for liquid-liquid heat exchange

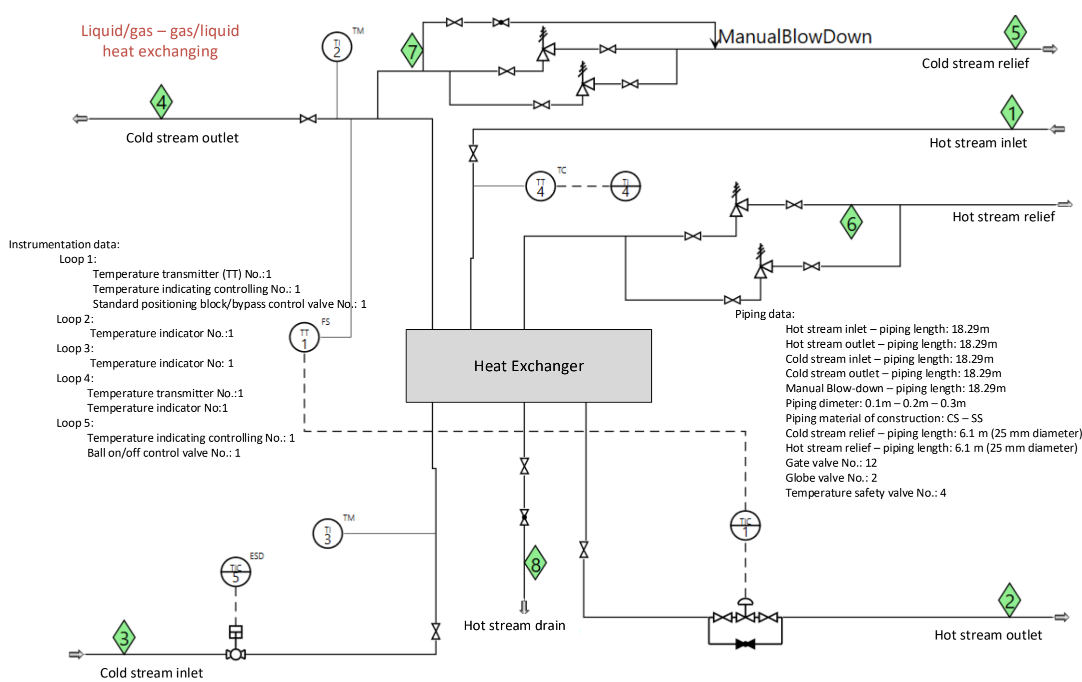


Figure A.2. Heat Exchanger P&ID suitable for Gas-Gas heat exchange

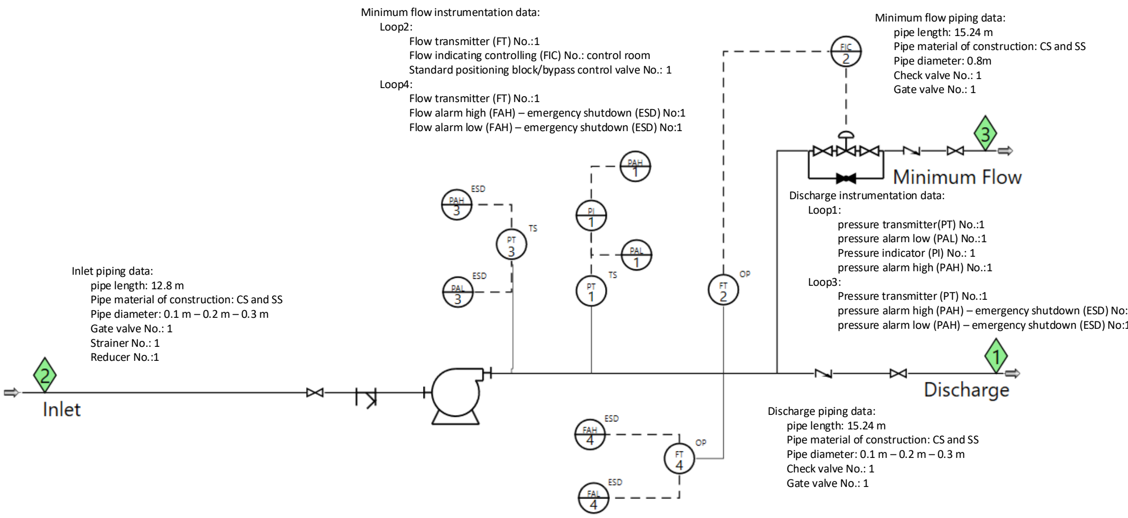


Figure A.3. Pump P&ID

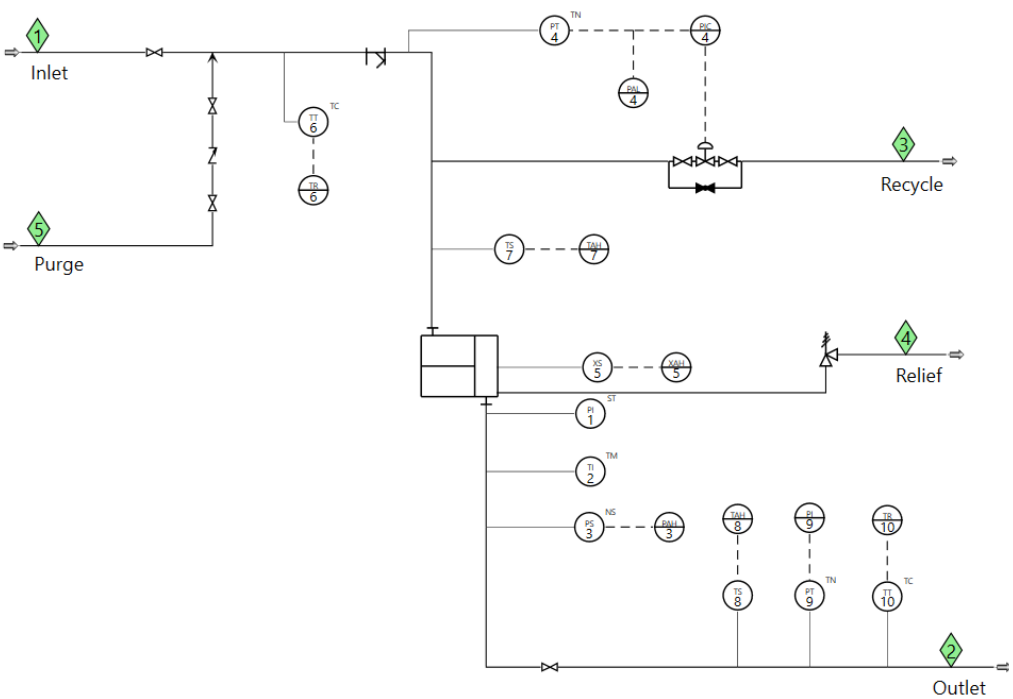


Figure A.4. Compressor P&ID

Appendix B. Case studies economic assessment results broken down by key cost components influencing total investment and operating costs of HRPs implied by SWEAMs.

Table B. 1. Cost components impacting total investment costs of HRPs implied by SWEAMs – **Liquid/Liquid heat exchanging when streams' mass flowrates are small (10kg/s)**

Distance between streams	Heat recovery projects implied by SWEAMs		Cost components (USD) impacting total investment costs of HRPs implied by SWEAMs – Enhanced factor-based cost model							Cost components (USD) impacting total investment costs of HRPs implied by SWEAMs – Conventional factor-based cost model						
			HX	foundation	piping	control	insulation	paint	OSBL piping	HX	foundation	piping	control	insulation	paint	OSBL piping
100 m	500 kW	100 m²	39000	4000	40000	20000	20000	2000	17000	39000	3000	23000	4000	2000	400	-
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
500 m	500 kW	100 m²	39000	4000					110000	39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
1000 m	500 kW	100 m²	39000	4000					220000	39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	

Table B. 2. Cost components impacting total investment costs of HRPs implied by SWEAMs – **Liquid/Liquid heat exchanging when streams' mass flowrates are high (90kg/s)**

Distance between streams	Heat recovery projects implied by SWEAMs		Cost components (USD) impacting total investment costs of HRPs implied by SWEAMs – Enhanced factor-based cost model							Cost components (USD) impacting total investment costs of HRPs implied by SWEAMs – Conventional factor-based cost model						
			HX	foundation	piping	control	insulation	paint	OSBL piping	HX	foundation	piping	control	insulation	paint	OSBL piping
100 m	500 kW	100 m²	39000	4000	108000	20000	55000	6000	37000	39000	3000	23000	4000	2000	400	-
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
500 m	500 kW	100 m²	39000	4000					180000	39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
1000 m	500 kW	100 m²	39000	4000					360000	39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	

Table B. 3. Cost components impacting total investment costs of HRPs implied by SWEAMs – **Gas/Gas heat exchanging when streams' mass flowrates are low (10 kg/s)**

Distance between streams	Heat recovery projects implied by SWEAMs		Cost components (USD) impacting total investment costs of HRPs implied by SWEAMs – Enhanced factor-based cost model							Cost components (USD) impacting total investment costs of HRPs implied by SWEAMs – Conventional factor-based cost model						
			HX	foundation	piping	control	insulation	paint	OSBL piping	HX	foundation	piping	control	insulation	paint	OSBL piping
100 m	500 kW	100 m²	39000	4000	88000	32000	28000	4000	17000	39000	3000	23000	4000	2000	400	-
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
500 m	500 kW	100 m²	39000	4000					110000	39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
1000 m	500 kW	100 m²	39000	4000					220000	39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	

Table B. 4. Cost components impacting total investment costs of HRPs implied by SWEAMs – **Gas/Gas heat exchanging when streams' mass flowrates are low (90 kg/s)**

Distance between streams	Heat recovery projects implied by SWEAMs		Cost components (USD) impacting total investment costs of HRPs implied by SWEAMs – Enhanced factor-based cost model							Cost components (USD) impacting total investment costs of HRPs implied by SWEAMs – Conventional factor-based cost model						
			HX	foundation	piping	control	insulation	paint	OSBL piping	HX	foundation	piping	control	insulation	paint	OSBL piping
100 m	500 kW	100 m²	39000	4000	180000	20000	40000	7000	37000	39000	3000	23000	4000	2000	400	-
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
500 m	500 kW	100 m²	39000	4000					180000	39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
1000 m	500 kW	100 m²	39000	4000					360000	39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1000 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	
	1500 kW	100 m²	39000	4000						39000	3000	23000	4000	2000	400	
		500 m²	110000	10000						110000	9000	66000	11000	6000	1100	
		1000 m²	215000	21000						215000	17000	129000	21500	10000	2150	

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