Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Natural Sciences
Department of Chemical Engineering

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Optimization of Heat Exchanger Networks using Aspen Energy Analyzer and SeqHENS

Master's thesis in Chemical Engineering
Supervisor: Johannes Jäschke, Truls Gundersen
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Abstract

Heat exchanger network synthesis has been one of the most researched areas within the process industry for the past 40 years. During the seventies, great attention was drawn to the area because of the first world energy crisis. The driving force for this research was its ability to increase energy efficiency in the process industry and thereby reduce the total cost of industrialized products. Heat exchanger network synthesis consists of a three-way trade-off between energy consumption (E), total heat exchanger area (A) and the total number of heat exchangers (U). The main objective of this work was to test different software tools for heat exchanger network synthesis. The main focus has been on SeqHENS, which is an iterative and sequential software, but Aspen Energy Analyzer (AEA) has also been extensively studied. EnergyPinch was tested for suitability, but due to the lack of some important features, it was not further used. The methodology of SeqHENS is comprehensibly outlined, whilst Aspen Energy Analyzer is more briefly discussed.

Several case studies with various sizes and features were conducted in order to reveal strengths and weaknesses in AEA and SeqHENS. The cases were mostly made based on previously examined problems in order to obtain a good basis of comparison. The results from both SeqHENS and AEA are discussed in detail in terms of quantitative aspects such as total annual cost (TAC) and total heat exchanger area, as well as qualitative aspects such as controllability and operability.

The case studies revealed that SeqHENS suggested networks close to the optimal reported in the literature based on TAC, but often with a high degree of complexity. An additional large industrial scale case study (more than 20 streams) was partly conducted where SeqHENS faced a serious problem with the combinatorial explosion in the mixed integer linear programming (MILP) step of the methodology. This case was therefore not reported in this work due to the lack of results. AEA, on the other hand, did not face the same challenges with large scale problems. However, AEA had a tendency to suggest networks with excessive use of utilities. This excess usage of external utilities generally provided networks with low heat transfer area, but far from optimal based on TAC.

Sammendrag

Syntese av nettverk for varmevekslere har vært et av de mest undersøkte områdene innen prosessindustrien de siste 40 årene. I løpet av 70-tallet ble det rettet stor oppmerksomhet mot dette området på grunn av den første energikrisen i verden. Drivkraften for denne forskningen var dens evne til å øke energieffektiviteten i prosessindustrien og dermed redusere den totale kostnaden for industrialiserte produkter. I et varmevekslernettverk må energiforbruk (E), totalt varmevekslerareal (A) og totalt antall varmevekslere (U) avveies for å finne den optimale løsningen. Hensikten i dette arbeidet var å teste forskjellige programvareverktøy for syntese av varmevekslernettverk. Hovedfokuset har vært på SeqHENS, som er en iterativ og sekvensiell programvare, men Aspen Energy Analyzer (AEA) har også blitt studert. EnergyPinch ble testet for egnethet, men på grunn av mangel på noen viktige funksjoner ble den ikke studert ytterligere. Metodikken til SeqHENS er nøye forklart, mens AEA er kortere oppsummert.

Flere forsøk av ulik størrelse og trekk ble gjennomført for å avsløre styrker og svakheter i SeqHENS og AEA. Forsøk som har vært undersøkt mye i litteraturen tidligere har hovedsakelig blitt valgt. Resultatene fra både SeqHENS og AEA har blitt diskutert i detalj med hensyn på kvantitative aspekter som total årlig kostnad og totalt varmevekslerareal, men også kvalitative aspekter som kontrollerbarhet og driftbarhet har blitt diskutert.

Forsøkene viste at SeqHENS ofte ga nettverket i nærheten av den optimale rapporterte i litteraturen basert på total årlig kostnad, men ofte med en høy grad av kompleksitet. I tillegg til de fire forsøkene som ble gjennomført ble et litt større forsøk undersøkt (mer enn 20 strømmer). Dette ga store problemer for SeqHENS på grunn av den kombinatoriske eksplosjonen i MILP-steget av simuleringen. Dette forsøket ble ikke rapportert grunnet store hull og mangler i resultatene. AEA hadde ikke de samme utfordringene med store nettverk med mange strømmer. Felles for nettverkene som AEA foreslo var imidlertid overdreven bruk av ekstern oppvarming og avkjøling. Dette overforbruket medførte generelt et lavere varmeoverføringsareal, men høy total årlig kostnad.

Preface

This report was written in spring 2019 as a part of the course TKP4900 - Master thesis at the Norwegian University of Science and Technology (NTNU).
The main objective of this work was to test different software tools for heat exchanger network synthesis, but with the main emphasis on SeqHENS. Several case studies have been conducted with various features to reveal the strengths and weaknesses in each software. In order to have a large basis for comparison, cases that have gained a lot of attention in the literature were chosen.
I will first thank Professor Johannes Jäsche for giving me the opportunity to work within the field of optimization of heat exchanger network. This topic is more relevant at the Department of Energy and Process Engineering. During the working period, I have received appreciated guidance from my co-supervisor Professor Truls Gundersen which I am really grateful for. In addition, I would also thank Research Scientist Rahul Anantharaman for his time and providing me access to SeqHENS and Ph.D. candidate Avinash Subramanian for sharing the stream data from his ongoing simulation (case two).

Table of Contents

List of Tables

List of Figures

List of Symbols

Latin symbols

Symbol	Unit	Description
A	$[\mathrm{m}^2]$	Heat exchanger area
a	[\$]	Fixed cost
b	$[\frac{\$}{\mathrm{m}^2}]^{\mathrm{n}}$	Fixed cost
Cp	$[\frac{\mathrm{kW}}{\mathrm{kg}^\circ\mathrm{C}}]$, $[\frac{\mathrm{MW}}{\mathrm{kg}^\circ\mathrm{C}}]$	Heat capacity
E	[kW],[MW]	Energy consumption
F_t	[-]	Correction factor
H	[kW], [MW]	Entalpy
h	$[\frac{\mathrm{kW}}{\mathrm{m}^{2\circ}\mathrm{C}}]$	Individual film heat transfer coefficient
k	[-]	Temperature interval
L	[-]	Number of independent loops
m	$[\mathrm{kg}]$	Mass
N	[-]	Number of process stream and utility types
n	[-]	Economy of scale parameter
Q	[kW], [MW]	Heat transfer duty
q	[kW]	Heat content of a stream
S	[-]	Number of subnetworks
T	$[^\circ\mathrm{C}]$	Temperature
U	[-]	Number of units
U	$[\frac{\mathrm{kW}}{\mathrm{m}^{2\circ}\mathrm{C}}]$	Overall heat transfer coefficient
Y	[kW], [MW]	Penalty for process heat transfer across pinch

Greek symbols

Symbol	Unit	Description
α	[-]	Mass flow fraction in a branch
β	[-]	Mass flow fraction in a branch
γ	[-]	Mass flow fraction in a branch
Δ	[-]	Change in property value
δ	[-]	Mass flow fraction in a branch
ϵ	[-]	Mass flow fraction in a branch
ζ	[-]	Mass flow fraction in a branch
η	[-]	Mass flow fraction in a branch
θ	[-]	Mass flow fraction in a branch
κ	[-]	Mass flow fraction in a branch
λ	[-]	Mass flow fraction in a branch

Acronyms

AEA	=	Aspen Energy Analyzer
CW	=	Cooling Water
EMAT	=	Exchanger Minimum Temperature Approach
GAMS	=	General Algebraic Modeling System
GCC	=	Grand Composite Curve
GHG	=	Green Housegas
HEN	=	Heat Exchanger Network
HENS	=	Heat Exchanger Network Synthesis
HLD	=	Heat Load Distribution
HP-Steam	=	High Pressure Steam
HRAT	=	Heat Recovery Approach Temperature
LP	=	Linear Programming
MILP	=	Mixed Integer Linear Programming
MINLP	=	Mixed Integer Non-linear Programming
MIP	=	Mixed Integer Programming
NLP	=	Non-Linear programming
ST	=	Steam
TAC	=	Total Annual Cost

Chapter 1

Introduction

1.1 Background

Heat exchanger network synthesis (HENS) has been an active research area for over 40 years[1]. During the seventies, great attention was drawn to the area because of the first world energy crisis. The driving force for this research was its ability to increase energy efficiency in the process industry and thereby reduce the total cost of industrialized products. From this point, the study of different alternatives to minimizing the energy consumption started. Actually, the heat exchanger network synthesis consists of a three-way trade-off between energy consumption (E), total heat exchanger area (A) and the total number of heat exchangers (U).

Before the 1970s, when Linnhoff and Flowers [2] introduced the pinch point, HENS problems were governed by heuristics and treated as a single problem. The discovery of the pinch point led researchers to separate the problem into three sub-problems and solve them sequentially. This was a major discovery that reduced the problem complexity significantly, but for large scale problems, this method was hard to solve manually and further research was needed. According to Ravagnani et al. [3], several kinds of studies were conducted aiming to develop methodologies to find optimal heat exchanger network (HEN) designs. The research was concentrated in two important areas, namely pinch analysis which is based on thermodynamics and heuristics, and Mathematical Programming which consists of linear programming (LP), mixed integer linear programming (MILP) and non-linear programming (NLP).

The limitations discovered in the late 1980s regarding the pinch decomposition led the focus on simultaneous approaches where the problem is treated as one single problem and solved all in one step. In general, the problem is formulated as a mixed integer non-linear programming (MINLP) problem to find the optimal HEN based on minimizing total annual cost (TAC). After the HENS problem was proven to be NP-hard in the strong sense [4], renewed interest in the sequential methods was experienced. However, for large scale problems, the total number of binary variables leads to a computational explosion in the MILP formulation in the sequential methods. This is still a persisting issue nowadays. In recent years also heuristic methods of optimization have been introduced to solve linear and non-linear models.

1.2 Motivation

The industrial sector uses more delivered energy than any other end-use sector, consuming about 54% of the world's total delivered energy [5]. Energy is used in the industrial sector for a wide range of purposes, such as process and assembly, steam and co-generation and process heating and cooling. The International Energy Outlook 2016 (IEO2016), estimates that the industrial sector energy consumption worldwide will continue to grow by 1.2%/year, from 222 quadrillion British thermal units (Btu) in 2012 to 309 quadrillion Btu in 2040. Since the primary source for energy production is fossil fuel it is evidently a major contributor to the total worldwide greenhouse gas (GHG) emissions. These gases contribute to the greenhouse effect and could in the worst case lead to catastrophic changes in the Earth's climate. Figure (1.1) shows how the total global CO_2 emission has evolved since 1980, and how it most likely will be in 2050 if no particular actions are taken.

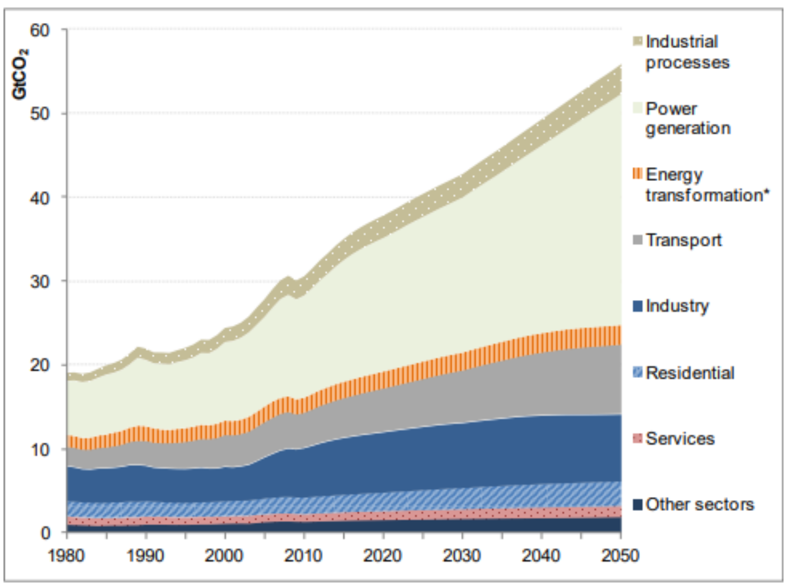

Figure 1.1: Global CO_2 emissions with base case, 1980-2050 [6]

As can be seen in the figure above, the GHG emissions from industry and industrial processes contribute to a large extent to the overall CO_2 emissions. Improving energy efficiency in these sectors will have a great impact on the overall GHG emissions in addition to allowing more profitable businesses. This is where heat integration plays a key role. Heat integration of a process involves minimizing the need for external utilities [1], thus increase the energy efficiency of a process. This can be achieved both in existing processes (retrofit) and in future processes.

[1] Electricity(or mechanical work), heating medium, cooling water, steam and refrigerants are commonly used utilities.

1.3 Objectives

The objective of this work is to use several different software tools for HENS. Several case studies will be conducted to reveal strengths and weaknesses in each software. A comparison of the ”Optimal” heat exchanger network will be done in terms of TAC as well as other features. The focus is mainly on SeqHENS, but also Aspen Energy Analyzer (AEA) will be used and investigated. Energy Pinch will also be mentioned, but due to lack of network generation functions, it will not be included in the comparison.

1.4 Thesis Structure and Guidelines

The content of this thesis is organized into six chapters and one appendix.

Chapter 2 presents a brief description of heat exchangers and heat exchanger networks. Thereafter is the principle of the sequential synthesis of heat exchanger network introduced. Subsequently is optimization methods including mathematical programming approach presented. This approach comprises both sequential and simultaneous methods. At last the different solver algorithm is introduced for LP- problems and MILP-problems.

Chapter 3 presents the different software tools for heat exchanger network synthesis with the main emphasis on the sequential framework. The four subproblems in the sequential framework are briefly described before a procedure of SeqHENS is listed. Thereafter an overview of limitations and challenges in SeqHENS is presented. The last two subsections present Aspen Energy Analyzer and EnergyPinch respectively.

Chapter 4 consists of four case studies with different features to reveal strengths and weaknesses for SeqHENS and AEA. Each case is firstly introduced in terms of stream data and economics and thereafter is the optimization results presented. At last, the optimization results from SeqHENS and AEA (case one and two) are compared with previously reported results from the literature.

Chapter 5 gives a brief discussion on an executive level of the results from the case studies. This in terms of SeqHENS and AEA strengths and weaknesses.

Chapter 6 summarizes first the conclusions based on the previous chapters. Lastly, further work regarding HENS with an emphasis on the further development of SeqHENS is briefly discussed.

Chapter 2

Basic Theory

2.1 Heat Exchanger Principles

Heat exchange is a key unit operation where heat is transferred from a hot region (heat source) to a cold region (heat sink) [7]. The amount of heat transferred, Q can be calculated based on the property of the system. In the process industry, heat exchangers are widely used to heat up or cool down process streams. There are two main principles for how the streams can be connected in a heat exchanger, namely co-current and counter-current. Counter-current is the most effective design because it utilizes the whole contact area to a larger extent because of the temperature driving forces are better utilized as shown in Figure (2.1).

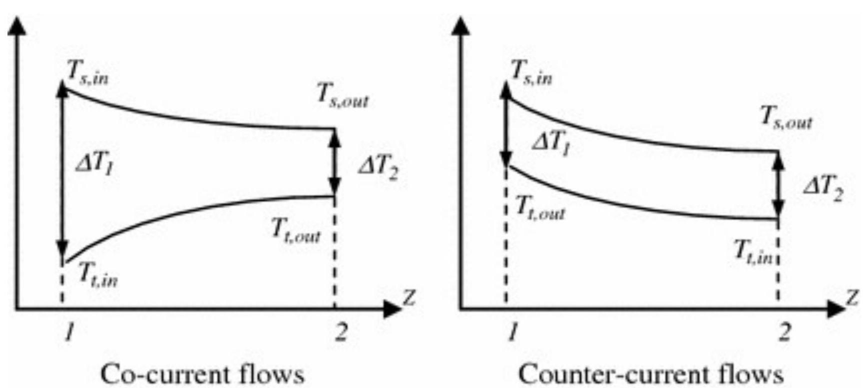

Figure 2.1: Co-current and counter-current heat exchanger design respectively. The temperature profile for both hot and cold streams are given as a function of the contact area in the heat exchanger [8].

Although that ideal counter-current is the most effective configuration, commonly a design in between is used due to mechanical and economical reasons. Shell and tube type of design is often used and a good example of a heat exchanger with a design in between.

Figure (2.2) shows a simple principle drawing of a heat exchanger where a hot stream with temperature $T_{\mathrm{h,in}}$ is cooled down to $T_{\mathrm{h,out}}$, while the cold stream is heated up from $T_{\mathrm{c,in}}$ to $T_{\mathrm{c,out}}$.

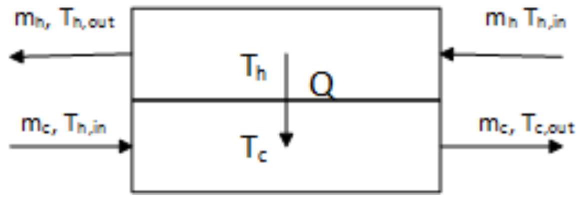

Figure 2.2: A simple illustration of the principle of a pure counter-current heat exchanger.

The heat transfer between the hot and cold stream is defined as Q [$\frac{\mathrm{J}}{\mathrm{s}} = \mathrm{W}$]. A general expression for the heat transferred between the hot and cold side is given in the following equation.

$$Q = UA \cdot \Delta T_{lm} \tag{2.1}$$

Where U is the overall heat transfer coefficient in [$\frac{\mathrm{W}}{\mathrm{m}^{2\circ}\mathrm{C}}$], A is the contact area in the heat exchanger in [m^2] and ΔT_{lm} is the logarithmic mean temperature difference for the heat exchanger. Logarithmic mean temperature difference is defined as follows:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln \frac{\Delta T_1}{\Delta T_2}} \tag{2.2}$$

Here ΔT_1 is the temperature difference in the hot end of the heat exchanger, whilst ΔT_2 is the temperature difference in the cold end.

As mentioned above, due to economic and mechanical issues industrial heat exchangers have more complex designs than pure counter-current fashion. For a heat exchanger with more than one shell or other deviations from ideal counter-current fashion, the correction factor $F_t \leq 1$ is included and accounts for the deviation from Equation (2.1). The heat transfer in a shell and tube type of heat exchanger is described by the following equation:

$$Q = F_t \cdot UA \cdot \Delta T_{lm} \tag{2.3}$$

2.2 Heat Exchanger Network

The heat exchanger network (HEN) is important for energy savings in the process industry. HEN synthesis is the heat integration between hot and cold process streams to reduce hot and cold utility consumption in industrial processes [9]. The HEN synthesis comprises a three-way trade-off between energy consumption (E), heat transfer area (A) and the total number of units (U). Figure (2.3) illustrate the trade-off.

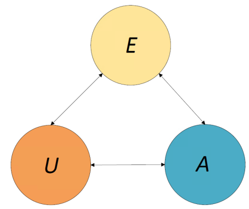

Figure 2.3: The three way trade-off in HENS.

The trade-off includes the quantitative aspect of minimizing TAC, but also qualitative aspects such as network complexity, operability and controllability needs to be accounted for when determining the ”optimal” network.

2.3 Basis of Pinch Analysis

Pinch technology presents a simple methodology for systematically analyzing chemical processes and the surrounding utility systems based on the First and Second Law of Thermodynamics. This method was outlined by Linnhoff and Turner [10] before it was comprehensively described by Linnhoff and Hindmarsh [11]. This is a sequential method for the design of heat exchanger networks where the resulting network reaches the limit for minimum external utilities. The methodology is to divide the system into two separate systems based on an arbitrary/defined minimum temperature approach HRAT (ΔT_{min}). At this point, the system is most constrained due to absolute minimum temperature driving forces. Figure (2.4) shows how the system is divided into two separate systems by the pinch point.

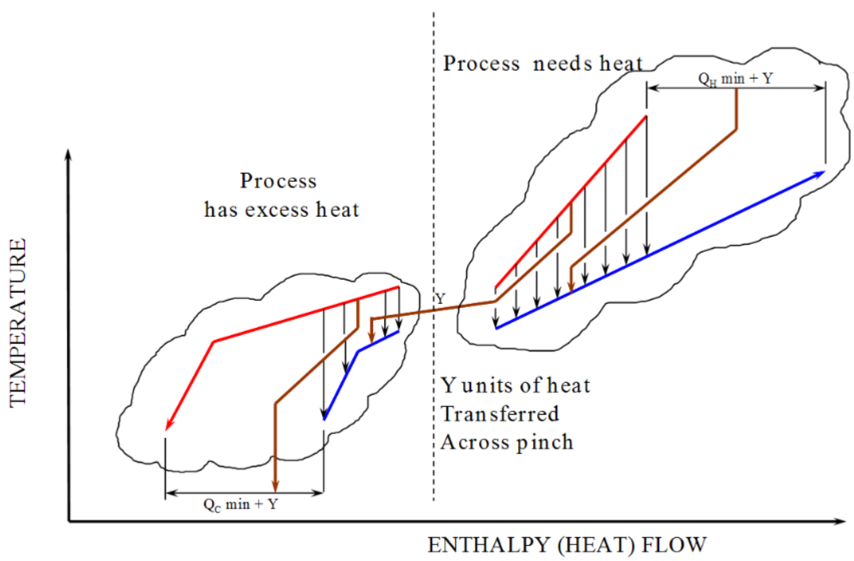

Figure 2.4: Illustration of pinch decomposition for an arbitrary process [12].

The region below pinch is a heat surplus (heat source), whilst above pinch there is a heat deficit (heat sink). Any heat transfer across pinch causes an increase in both hot and cold utility. The

Y term describes the energy penalty if heat is transferred between process streams across pinch, external heating is used below pinch or external cooling is used above pinch.

To summarize, three rules must be obeyed in order to achieve the minimum energy targets for a given process:

- Heat must not be transferred between process streams across the pinch
- There must be no external cooling above the pinch
- There must be no external heating below the pinch

HRAT (ΔT_{min}) is an economic parameter, which is included in three-way trade-off shown in Figure (2.3) as the energy consumption (E).

2.3.1 Composite Curves

Composite curves are a quick and useful tool to estimate the energy target for a heat integration problem without actually having to carry out the network design [13]. The composite curves are constructed by separating the hot and cold process streams and divide the temperature range into intervals. Temperature intervals are established based on the supply and target temperature for the process streams. The temperature change of each interval is drawn as a function of the enthalpy change in the corresponding interval. Since only the enthalpy change is of interest here, the reference enthalpy for the hot and cold streams can be individually determined. The only criterion is that the hot curve must have a higher temperature than the cold in every interval in order to transfer heat. This criterion gives rise to the pinch point which is the point where the hot and cold curve is closest in temperature as illustrated in figure (2.5). The minimum temperature difference referred to as HRAT (ΔT_{min}) will be further discussed in subsequent sections.

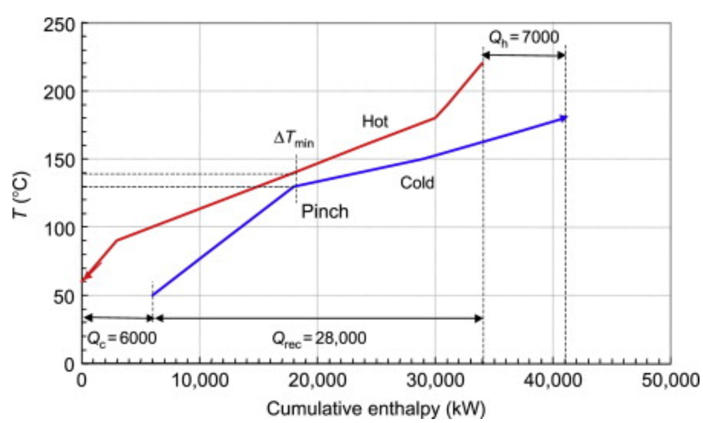

Figure 2.5: The composite curves for an example process [14]. The red line represents the hot process streams, whilst the blue line represents the cold process streams.

In the region where the hot curve is vertically above the cold curve, heat recovery within the process is possible. Targets for both hot and cold utility as well as heat recovery are thereby determined by the composite curve as shown in figure (2.5).

2.3.2 Grand Composite Curve

The heat cascade presented in Figure (2.7) provides all necessary information to construct the Grand Composite Curve (GCC) [15]. A GCC for an example process is shown in figure (2.6). The diagram shows the net accumulated heat surplus and heat deficit in the process. One of the advantages of this representation is that it provides an excellent interface between the process and the utility system. In addition, it can be used to evaluate the integration of special equipment such as distillation columns, heat pumps, etc. As for the composite curves, the GCC is presented in a T-H-diagram, but here only one single curve for the process is drawn. The curve describes the residual heat from the heat cascade. Since the curve includes both hot and cold process streams, a common temperature axis, T^*, is required. Hence, the so-called modified temperature has been introduced. The modified temperatures are established by subtracting half of ΔT_{min} from the hot process stream temperature, likewise, add half of ΔT_{min} to the cold process stream temperature. The modified temperature for a hot stream (i) and cold stream (j) becomes:

$$\begin{aligned} T^*_{h,i} &= T_{h,i} - \frac{1}{2}\Delta T_{min} \\ T^*_{c,j} &= T_{c,j} + \frac{1}{2}\Delta T_{min} \end{aligned} \tag{2.4}$$

Figure (2.6) presents the GCC where the enthalpy change in each interval is a function of the modified temperature.

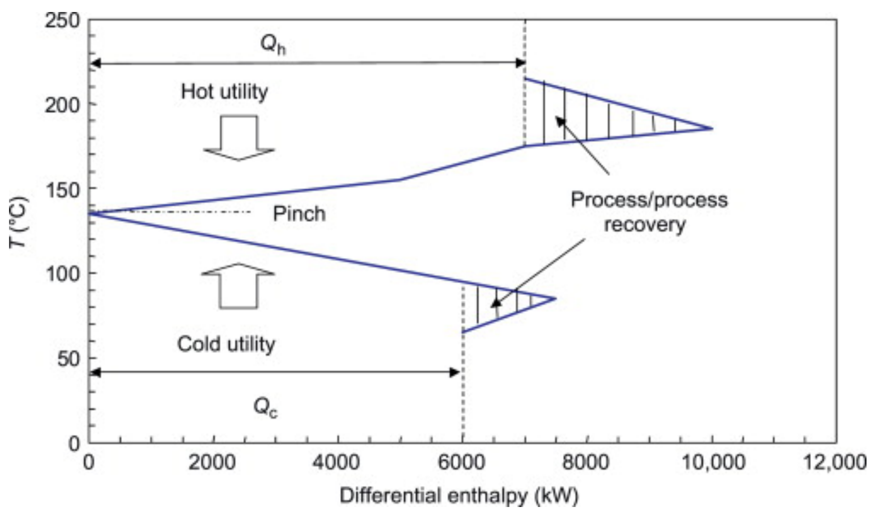

Figure 2.6: The GCC for an example process to illustrate the information hidden in the GCC [14].

The GCC has the same fundamental information as the composite curves (i.e minimum external heating and cooling as well as the location of pinch), but information related to process-to-process heat transfer is hidden. The only information regarding the process-to-process heat exchange that the GCC reveals is heat transfer from a heat surplus interval to a heat deficit interval at a lower temperature. This region is often called ”heat pockets”, but in Figure (2.6) it is referred to as process/process recovery. In addition to give information about minimum external heating and cooling, it also provides information regarding the necessary temperature on utilities. Utility placement is important information when it comes to identifying the near-optimal consumption and possible production of various utility types.

2.3.3 Minimum Number of Heat Exchangers - U_{min}

Establishing the absolute minimum number of heat exchangers in a network, also referred to as U_{min}, is a useful measure when it comes to heat integration. Equation (2.5) shows the rule of thumb for a HEN.

$$U_{\text{min}} = N - 1 \tag{2.5}$$

This rule was first used by Hohmann [16]. Linnhoff et al. [17] explained that the (N - 1) rule is a simplification of Euler's rule from graph theory [18] shown in Equation (2.6)

$$U = N + L - S \tag{2.6}$$

Where U is the number of units in a network, N equals the sum of all process streams and utility types, L is the number of independent loops and S is the number of subnetworks. Since the objective is to establish a lower bond/limit for the number of units ahead of the design step, network-related features, such as loop and subnetworks, are unknown. To overcome this problem L is set to zero (loops can be removed), and the total number of subnetworks is set to one (conservative choice since the presence of subnetwork reduces the total number of units). This reduces equation (2.6) to the $U_{\text{min}} = (N - 1)$.

2.3.4 Minimum Heat Transfer Area

A minimum heat transfer target can be established by considering pure counter-current heat exchange. The area target is a useful measure when evaluating a network [19]. The composite curves can be divided into different enthalpy intervals at the kink points in the hot and cold curve. If heat only is transferred within the intervals, vertical heat transfer takes place along the composite curves. Vertical heat transfer is said to yield the minimum area for a system with equal heat transfer coefficients. Equation (2.7) shows the target for minimum area for a system which includes i intervals and j number of streams.

$$A_{\text{min}} = \sum_{i}^{N_{\text{intervals}}} \frac{1}{\Delta T_{\text{LMTD}_\text{i}}} \left(\sum_{j}^{N_{\text{streams}}} \frac{q_j}{h_j} \right)_i \tag{2.7}$$

Where A_{min} is the total heat transfer area for the network, $\Delta T_{\text{LMTD}_\text{i}}$ is the logarithmic mean temperature difference for interval i, q_j is the heat content of stream j in interval i, and h_j is the film heat transfer coefficient for stream j in enthalpy interval i.

This equation gives a correct target for minimum heat transfer area for any system where the process streams have uniform film heat transfer coefficients. However, the equation above is based on complex networks referred to as a so-called "spaghetti networks" [1]. This means that minimum area

[1] A spaghetti network is a complex network with many stream splits to achieve the target for minimum area. Here the temperature driving forces are optimally distributed.

requires a very large number of units, which is not good from an economic point of view.

For systems with nonuniform heat transfer coefficients Equation (2.7) will still give a good approximation, with errors being typically within 10% of the true target.

2.4 Optimization Methods

There exist two main optimization methods for HENS; sequential synthesis and simultaneous synthesis. The main difference is that the first method divides the overall problem into subproblems, whilst the latter solves the overall problem directly without decomposition.

2.4.1 Sequential Synthesis

Sequential synthesis methods divide a HENS problem into multiple subproblems that are solved sequentially in order to reduce the computational requirement and the overall complexity of the problem [4]. Sequential synthesis via mathematical programming consist typically of solving the following three subproblems successively:

1. Minimum utility consumption ($Q^h_{\min}$ and $Q^c_{\min}$).
2. Minimum number of heat exchangers ($U_{\min}$).
3. Minimum cost with respect to the heat exchanger area (A).

Although the methodology described above uses mathematical programming, it follows the thermodynamic approach where the temperature ranges are partitioned into temperature intervals to ensure that heat exchange follows the laws of thermodynamics.

The minimum utility consumption problem is usually formulated as a linear programming (LP) problem with HRAT as the input parameter. The minimum number of units problem treats utility consumption as a constant in the MILP formulation for determining the target for the absolute minimum number of units. Heat load distributions (HLDs) from the stream matching MILP is thereafter used to generate and optimize final the HEN with a nonlinear programming (NLP) model. The NLP model tries to minimize the heat exchanger area for the given HLD, in order to reduce capital cost related to the network.

2.4.2 Simultaneous Synthesis

In the late 1980s, the research was concentrated towards simultaneous approaches for HENS. For simultaneous optimization the three-way trade-off is solved as one single problem with the objective to minimize TAC. The model is often formulated as an MINLP problem in order to obtain an optimal solution for a given problem.

MINLP refers to mathematical programming with continuous and discrete variables and nonlinearities in the objective function and constraints [20]. MINLP is a natural approach of formulating a problem where it is necessary to optimize the system structure (discrete) and parameters (continuous) simultaneously. This approach is often used for various applications within the fields of the process industry, engineering, management science, and operation research.
MINLP problems are often said to be difficult to solve, because of they combine all the difficulties of their subclasses, namely the combinatorial nature of mixed integer programming (MIP) problem and non-convexity of a NLP problem. It is not surprising that MINLP problems can be challenging to solve since both MIP and NLP are among the class of theoretically difficult problems (NP-complete). Techniques for solving MINLPs include for instance branch and bound and generalized Bender's decomposition. These techniques only guarantee global optimality under (generalized) convexity.

The advantage of applying simultaneous methods for HENS is that they solve the three-way trade-off at the same time, meaning there is no need for specifying HRAT, EMAT or number of units. In addition, pinch decomposition is not pre-specified. Some assumptions are often required in order to reduce the complexity such as in the model by Yee and Grossmann [21]. Isothermal mixing is assumed in order to keep all constraints linear. In theory, the simultaneous methods are preferable, but in practice for large scale problems they often demonstrate severe numerical problems [4].

2.4.3 Transshipment Model for HENS Problems

One of the most widely used models within the field of operation research is the transshipment model [21]. This model is a variation of the well-known transportation model and deals with the optimal allocation of resources. The transportation model seeks to optimize the transportation of a product from a source (e.g plants) to a destination (e.g markets). The transshipment model, on the other hand, investigates the optimal network for shipping the same product from a source to an intermediate node (e.g warehouse) and then to its final destination.

The same analogy can be made for a heat recovery problem. The product can be thought of as heat, which is transferred from a heat source (hot streams) through an intermediate step (temperature intervals) to the destination (cold streams). In order to not violate the second law of thermodynamics, constraints on temperature intervals that ensure that heat only flows from higher to lower temperatures must be included in the model. By partitioning the entire temperature range into intervals according to the rules proposed by Linnhoff and Flowers [22], Grimes [23] and Cerda et al. [24], this can actually be achieved. This procedure guarantee feasible transfer of heat in all temperature intervals, given the minimum temperature approach, ΔT_{min}. Figure (2.7) illustrates the transshipment model for a heat recovery problem.

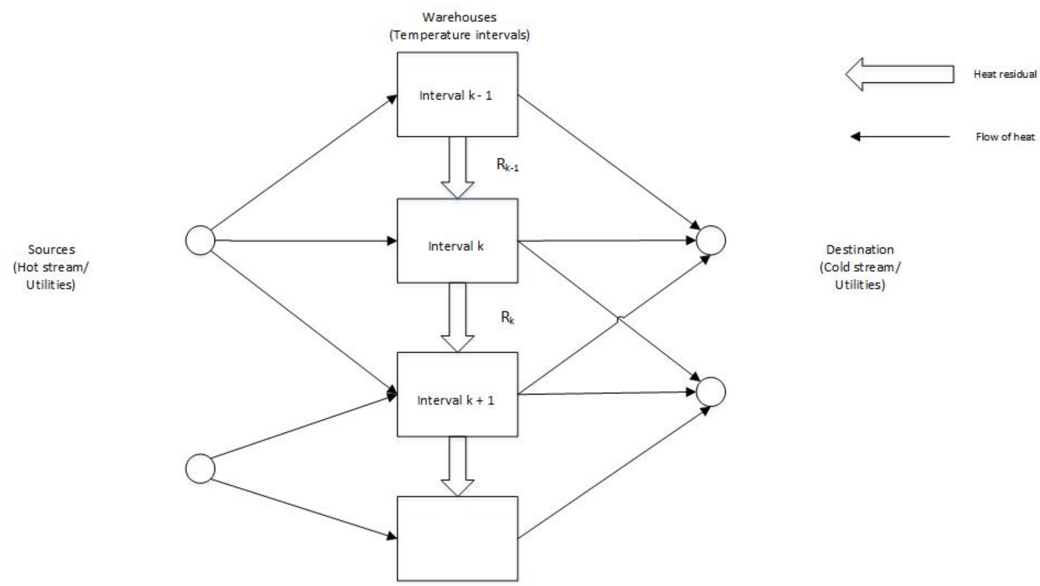

Figure 2.7: Analogy of heat recovery network with transshipment model.

The minimum utility targeting step in the sequential framework is based on this model. For a given HRAT, the minimum hot and cold utility requirements are evaluated.

2.4.4 Branch and Bound Algorithm

The branch and bound algorithm is one of the most commonly used methods for solving NP-hard discrete optimization problems [25].

A branch and bound algorithm searches through the complete space of solutions in order to find the best solution for a given problem. Since the number of possible solutions increases exponentially, explicit enumeration is normally impossible. By use of bounds for a function to be optimized combined with the current optimal solution, the algorithm enables to search only parts of the solution space. At any point during the solution process, the solver has obtained a current best solution, whilst an unexplored pool of possible solutions still exists. At the initial state, the best solution so far is $\pm\infty$ (depending on whether the objective function minimize or maximize) and only one subset exists, namely the complete subset of solutions. Unexplored subspaces are represented as nodes in a search tree as shown in Figure (2.8).

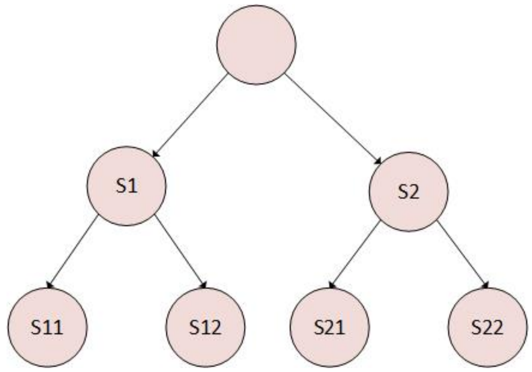

Figure 2.8: Illustration of the branch and bound optimization algorithm.

Initially, the search tree only contains the root, and each iteration in the classical branch and bound algorithm processes one such node. Selection of the node to process, bound calculations and branching are the three main components during iteration. The searching algorithm compares the current solution with the explored branch solution. If the branch solution is better than the previous solution, the solver continues down that route, if not that branch is cut off. In theory, this systematic searching approach guarantees to find the optimal solution. However, for large scale problems, the computational time is very high.

For the minimum number of units problem in SeqHENS, which is formulated as a MILP-problem, the branch and bound algorithm struggle with time consumption. In this formulation, all variables are binary (1 or 0), which tends to introduce degeneracy, meaning that multiple solutions exist with the same value for the objective function. This implies that several branches with solution $U = U_{\min}$, $U = U_{\min} + 1$ and $U = U_{\min} + 2$ are not cut off until the final splits. This leads to an exponential growth in the computational time depending on the number of streams.

Chapter 3

Software Tools for Heat Exchanger Network Synthesis

3.1 The Sequential Framework - SeqHENS

This section presents an overview of the methodology of the sequential framework for heat exchanger network synthesis (HENS) and subsequently the procedure for how to use SeqHENS is outlined. SeqHENS is implemented with several General Algebraic Modeling System (GAMS) solvers with Excel add-in files. The MILP and NLP-problems are solved using CPLEX and CONOPT3 respectively. SeqHENS is implemented in a way that combines mathematical programming with thermodynamic insights to solve HENS problems.

3.1.1 Methodology

Sequential synthesis methods divide the HENS problem into a series of subproblems that are solved sequentially in order to reduce the computational complexity of the problem [4]. The main objective is to find near-optimal heat exchanger networks for industrial size problems.

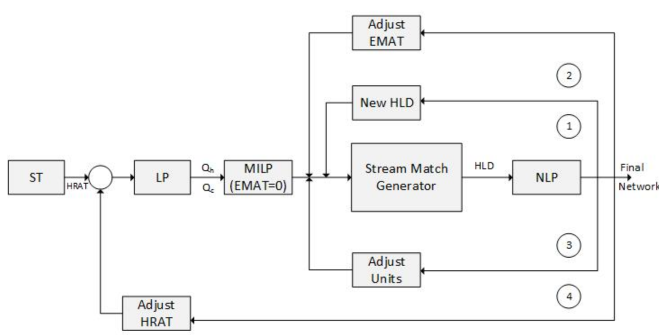

Figure 3.1: The four loops in the sequential framework for HENS.

The subtasks of the sequential framework are displayed in Figure (3.1) and involve: establishing the minimum energy consumption for a given HRAT (LP), determining the minimum number of units

(MILP), finding sets of matches and corresponding Heat Load Distributions (HLDs) for minimum or a given number of units (MILP), and network generation and optimization (NLP). All subtasks will be presented in detail in the subsequent sections.

3.1.2 Minimum Utilities Targeting

The minimum hot and cold utility requirements are determined using a transshipment model based on the model presented by Papoulias and Grossmann [26] which is extended to include multiple utilities. HRAT must be specified prior to obtaining Q_h and Q_c as can be seen in Figure (3.1). The HRAT is held constant in the three inner loops of the framework, while in loop four, it can be adjusted.

3.1.3 Minimum Number of Units

The problem regarding minimum numbers of units is formulated as a MILP transshipment problem once again based on Papoulias and Grossmann model [26]. By using an EMAT of zero, the absolute minimum number of units for a given energy target can be established. The model is modified by Anantharaman [4] to deal with issues related to combinatorial explosion when the problem size increase.

3.1.4 Stream Match Generator

The third step in the sequential framework is the stream match generator. This subproblem generates HLDs for a given energy target and number of units. The subproblem is formulated as a MILP transportation model based on the work of Cerda and Westerberg [27]. The objective function minimizes the ”pseudo-area” of the network. This model is based on the insight that vertical heat transfer is the best option to minimize total heat exchanger area.

3.1.5 Network Generation and Optimization

The final subproblem in the sequential framework is the network generation and optimization part. Here, cost optimum heat exchanger network is generated for a given HLD. This problem is formulated as an NLP problem, which is based on generating a set of superstructures [28]. This is a non-convex model which means that there may be several local optima that do not correspond to the global optimum. However, this issue is partly taken care of in SeqHENS by use of an automated starting value generator based on physical insight, which at least ensures ”good” local optimum.

The input to the NLP is as mentioned a set of stream superstructures. The stream superstructure is dependent on the total number of units one specific process stream has. Figure (3.2) shows the superstructure for a process stream with three units.

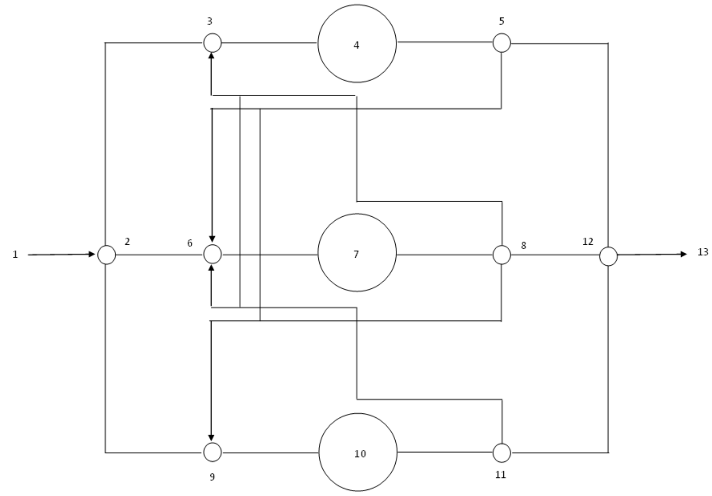

Figure 3.2: Superstructure for a three unit process stream. The superstructure consist of arcs (arrows) and nodes. The nodes represent either a stream split/connection or a heat exchanger, while the arcs represent the amount of flow in each stream.

The HLD from the stream match generator step is used to generate stream superstructures. Each process stream has its own superstructure and by combining all these superstructures, the final network can be visualized. The last part is not automated yet, thus this has to be done by hand. This part can be fairly time-consuming, especially for problems with several process streams.

3.1.6 Loops in the Sequential Framework

The four loops in the sequential framework shown in Figure (3.1) represent the three-way trade-off in the HENS problem. The first and second loop can be thought of as area loops, the third loop as the unit loop and the fourth loop as the energy loop.

This loop division lets the user evaluate multiple networks for different parameters, which helps to locate HLDs close to the optimal solution.

Since SeqHENS is not yet fully automated, it is necessary for the user to run the optimization and generate a new network for each change of parameter values to establish the optimal network with the lowest TAC. A detailed description of the various optimization steps is listed in the subsequent section.

3.1.7 SeqHENS Procedure

SeqHENS is a semi-automatic software tool for generation of HENs. To obtain the final HEN design, several files are required and it is essential to go through the different steps in the correct sequence. The procedure described below lists the important steps when running the software.

1. Open SeqHENS.xls $\rightarrow$ Insert stream and utility data, specify HRAT $\rightarrow$ Push get GAMS Inputs to obtain ${Q_h}^{\min}$ and ${Q_c}^{\min}$ (Min Util sheet) $\rightarrow$ Save and close SeqHENS.xls.

2. Open GAMS $\rightarrow$ File $\rightarrow$ Project $\rightarrow$ New project $\rightarrow$ Save in the same folder as the other files!

3. File $\rightarrow$ Open $\rightarrow$ Umin.gms $\rightarrow$ Run ($U_{\min}$).

4. Open SeqHENS.xls $\rightarrow$ GAMS Input (SMG) sheet $\rightarrow$ Enter $U_{\min}/U$ where No. Hxs is specified (cell C2) $\rightarrow$ Save and close SeqHENS.xls!

5. Open GAMS $\rightarrow$ File $\rightarrow$ EMAT1.gms $\rightarrow$ Run.

6. Open GAMS $\rightarrow$ File $\rightarrow$ EMAT2.gms $\rightarrow$ Run.

7. Open GAMS $\rightarrow$ File $\rightarrow$ EMAT3.gms $\rightarrow$ Run.

8. Open SeqHENS.xls $\rightarrow$ NLP Input sheet $\rightarrow$ Select EMAT1,2 or 3 $\rightarrow$ Push Fill NLP data from.

9. Open HENS.xls $\rightarrow$ Copy row 9-155 column A-AO from SeqHENS.xls to HENS.xls(same cells) $\rightarrow$ Specify a cost law.

10. Push Generate Arcs, Combinatorial, Variable Generator, Generate Arcs in that sequence $\rightarrow$ Save and close both SeqHENS.xls and HENS.xls.

11. Open GAMS $\rightarrow$ File $\rightarrow$ NetworkGEN.gms $\rightarrow$ Run.

12. Compare z for different EMAT's.

13. To generate the grid diagram/HEN design, use mcp,T listed in NetworkGEN.lst and fill in arcs in Superstructure.xls (by hand).

14. To obtain a network with more units than $U_{\min}$, choose $U = U_{\min} + 1, +2...$ in point four and follow the same procedure to point 14.

3.1.8 Limitations and Challenges

One of the main limitations in the sequential framework is that it does not generate networks with cyclic matches between the same pair of streams. This problem arises in the stream match generator subproblem, where HLDs are generated for a given number of units and where only one connection between the same two process streams is allowed. In addition, the maximum number of heat exchangers on one stream is set as four. Despite that this is a problem in the start value generator, the MILP which finds suitable HLDs allows five and more heat exchangers. This becomes a major problem for unbalanced problems, where many hot streams are connected with one cold stream or the opposite.

The sequential framework is said to struggle to solve large industrial size problems (more than 20 streams) due to combinatorial explosion [4]. The four case studies conducted in this work did not face serious challenges with combinatorial explosion since the size of the problems is smaller. However, for a balanced case with 20 streams (ten hot and ten cold), the MILP started to struggle to find HLDs for several optimizations with different number of units. This case was not further studied due to the lack of results.

SeqHENS does not guarantee a global optimum, which makes it difficult to know if there exists a better solution to a given problem. Anyway, experience has shown that the solutions at least are good solutions based on TAC.

During this work, SeqHENS has shown that sometimes the NLP struggles to find a feasible solution for a given HLD. In addition, if a process stream is attached with more than four units, an error in the start value generator occurs. This limits the range of solutions especially for unbalanced problems (many hot streams compared to cold or opposite).

The inner loop in the sequential framework, the HLD loop, was not considered in this work. The lack of supervision from the developer of SeqHENS combined with missing programming skills in GAMS resulted in that this loop was not used. Regardless, experience has shown that the HLD from the stream match generator gives HLDs close to the optimality.

3.2 Aspen Energy Analyzer

Aspen Energy Analyzer (AEA) is an energy management software for performing optimal heat exchanger network design to minimize process energy consumption [29]. This is a well known commercial software developed by AspenTech. Since it is a part of the Aspen Engineering family it can easily be integrated with Aspen HYSYS/Plus. Thus, accurate stream data can be used in the heat exchanger network design phase from a steady-state simulation. AEA is said to generate near-optimal solutions to HEN problems.
This software allows minimizing energy costs both in grassroots design as well as retrofit cases. AEA provides a lot of features that other software lack, for instance, multiple steam levels, stream split constraints, forbidden matches, etc. can be specified by the user. This makes the program very comprehensive when it comes to applications. In addition, the interface is quite user-friendly

and no detailed manual should be necessary. Nevertheless, a detailed description of how to use the program can be found in [30].

AEA generates networks fairly rapidly independent of the problem size. Several designs are suggested based on the input data. Since AEA is a commercial software it is rather difficult to find a detailed description of the optimization algorithm the program relies on. However, while running it is stated that both LP and MILP problems are solved. After AEA has suggested HEN designs, it is possible to optimize these networks within the program. Here, loops and paths are used to minimize TAC or total heat exchanger area, dependent on user decisions. The networks become slightly better, but often the network configuration violates the three important rules given in chapter two regarding the excessive use of utilities. In addition, fairly often the program struggles to optimize the suggested structures for networks consisting of many units.

Although the optimization algorithm fairly often struggles to generate good heat exchanger networks based on TAC, it is more realistic in terms of individual heat exchanger type (shell and tube). In addition, it also accounts for temperature dependencies of heat capacities, heat transfer coefficients and that the heat exchanger might have several shells. This is also included in the built-in cost function for a heat exchanger in AEA as shown below.

$$\text{Cost} = a + b \cdot \left(\frac{\text{Area}}{\#\text{Shells}}\right)^n \cdot \#\text{Shells} \qquad 0 \leq n \leq 1 \tag{3.1}$$

Where a and b are constants and n is the economy of scale parameter. All these extra features give a more realistic industrial-oriented picture of the total cost of a heat exchanger.

3.3 EnergyPinch

EnergyPinch is a software developed for heat exchanger network synthesis at the University of Manchester. This software was tested for suitability for HENS early in this work. It was experienced that EnergyPinch was a good tool for targeting and simple HENS problems. Limitations come into play when the networks become fairly large since the maximum amount of heat exchangers is 15. In addition, the grid diagrams must be generated manually in the program. Due to the lack of an automated network generator, this software was not further considered. However, for targeting and small scale problems it is a useful program.

Chapter 4

Case Studies

4.1 Case One

Case one concerns a rather simple problem consisting of four process streams and two utility streams. This problem has been given much attention in the literature in previous years. The fact that this problem is small and has a good basis for comparison, makes the problem a great starting case for SeqHENS. Stream and cost data are obtained from the literature and the results are thereby easy to compare directly in terms of TAC as well as complexity (no. of splits etc.). Both the result provided by SeqHENS and AEA was compared to the literature.

4.1.1 Case One - Stream Data and Economics

Stream and cost data for case one is presented in Table (4.1).

Table 4.1: Stream and cost data for case one [31].

Description	T_{supply} [°C]	T_{target} [°C]	ΔH [kW]	mCp [$\frac{\text{kW}}{°\text{C}}$]	$U \cdot F_t$ [$\frac{\text{kW}}{\text{m}^2 °\text{C}}$]
H1	175	45	1300	10	0.2
H2	125	65	2400	40	0.2
C1	20	155	2700	20	0.2
C2	40	112	1080	15	0.2
Heating	180	179	-	Var	0.2
Cooling	15	25	-	Var	0.2

Cost data:

Heating cost: 120 [$\frac{\$}{\text{kW,year}}$]
Area cost [\$] $= 30000 + 750 \cdot$ Area$^{0.81}$
Annual area cost [$\frac{\$}{\text{year}}$]$= 9663 + 241.575 \cdot$ Area$^{0.81}$
Interest rate: 10%

Cooling cost: 10 [$\frac{\$}{\text{kW,year}}$]
Annual cost factor $= 0.3221$
Plant lifetime: 5 years

The cooling and heating demands are determined by specifying HRAT. Optimal HRAT was found by plotting TAC as a function of HRAT. The result is presented below in Figure (4.1).

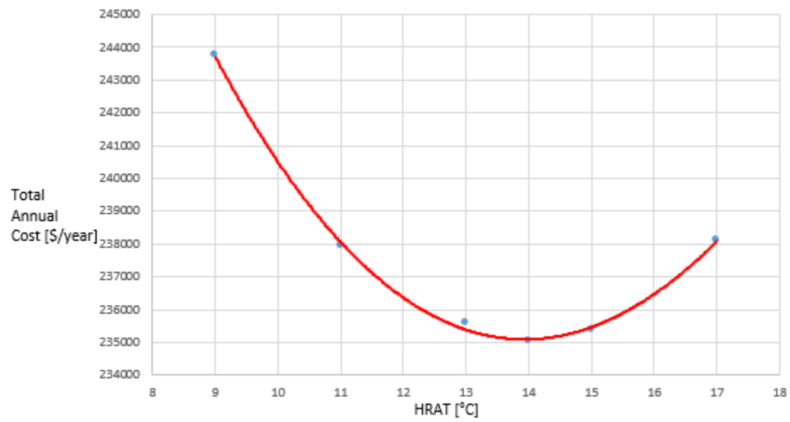

Figure 4.1: TAC as a function of HRAT to find the optimal HRAT for a five unit network by use of SeqHENS.

The result of the optimization in SeqHENS revealed that HRAT = 14 °C was the optimal solution based on TAC. HRAT = 14 °C is thereby used in the consecutive optimizations. By specifying this value, the following composite curves can be obtained:

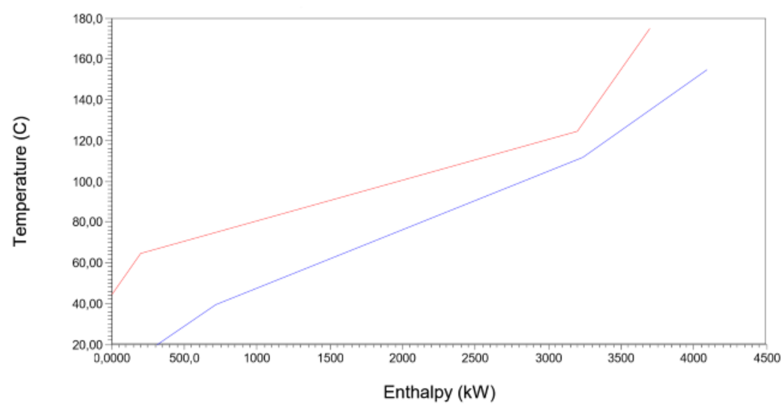

Figure 4.2: Hot and cold composite curves for case one. The red line represents the hot process streams, whilst the blue line represents the cold process streams.

From the composite curves, it can be seen that the pinch point is located at 125 °C and the heating and cooling demands are 395 kW and 315 kW respectively. Heat recovery within the process becomes 3385 kW for this HRAT.

The targets for number of units listed in Table (4.2) show the minimum number of units for some heat recovery $U_{\min}$ and maximum heat recovery $U_{\min}^{\mathrm{MER}}$.

Table 4.2: Target for minimum number of units for some heat recovery and maximum heat recovery.

	Target
$U_{\min}$	5
$U_{\min}^{\mathrm{MER}}$	7

It can be noticed that even though AEA gives five as the minimum number of units, a network with four units was generated in AEA as can be seen in Figure (4.6).

4.1.2 SeqHENS - Case One

To find the optimal HEN design based on TAC, several plots were made. The first plot presents TAC as a function of the number of units in order to find the optimal solution in terms of the number of units. The second plot was made to verify and substantiate that SeqHENS yields near-optimal solutions. The optimal HEN design in terms of TAC is displayed in Figure (4.5).

Figure (4.3) shows TAC as a function of units. This graph was constructed to obtain a quantitative measure on what number of units yields the optimal solution.

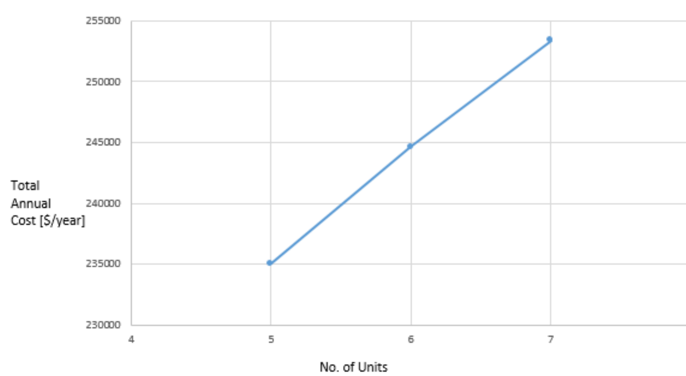

Figure 4.3: TAC as a function of number of units obtained from SeqHENS.

The plot reveals that the best choice of option based on TAC is obtained by five units. Normally this graph should give a global minimum where the TAC decreases initially and then increases with the number of units. The minimum number of unit step in SeqHENS provided $U_{\min} = 5$ as the lowest target, while AEA gave a solution with four units as shown in the subsequent section. The advantage by adding an extra unit in terms of the decreased area does not counteract the additional cost related to the new unit. This is further substantiated by Figure (4.4), which presents the total heat exchanger area as a function of number of units.

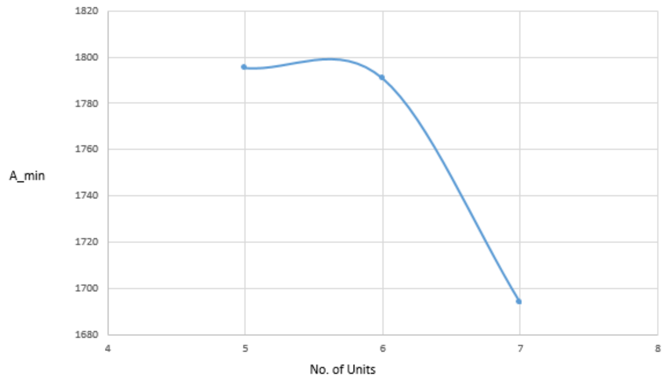

Figure 4.4: Total heat exchanger area as a function of number of units obtained from SeqHENS.

As explained in Section (2.3.4), the total heat exchanger area should decrease when a new unit is introduced. This is because of the possibility of better utilization of temperature driving forces which reduces the total heat exchanger area. The trend is not evident between five and six units, while at seven units, the optimal solution has a lower total area as expected. SeqHENS cannot provide HEN designs with more than seven units, because two streams can not be matched more than once [4]. This makes it impossible to verify that the area curve should eventually stabilize.

The optimal HLD for this case is presented below, and was used as input to the network generation and optimization step in SeqHENS. For the three consecutive cases, the HLDs are shown in Appendix (A.1) due to their size.

Table 4.3: The optimal HLD obtained from the MILP step in the sequential framework. The first row represents cold utility or cold process streams, whilst the first column represents hot utility or hot process streams. The numbers represent a heat exchanger with a given duty in kW.

	CW	C1	C2
ST		395	
H1	315	985	
H2		1320	1080

By use of this HLD, the optimal network presented in Figure (4.5) can be obtained. Table (4.4) describes the heat exchanger data for the optimal solution.

Table 4.4: Heat exchanger data for the cost-optimal network obtained from SeqHENS.

Unit	Duty [kW]	Area $[m^2]$	Type
I	985	442.6	Process-Process
II	315	79.2	Cooler
III	395	90.2	Heater
IV	1320	645.0	Process-Process
V	1080	538.3	Process-Process

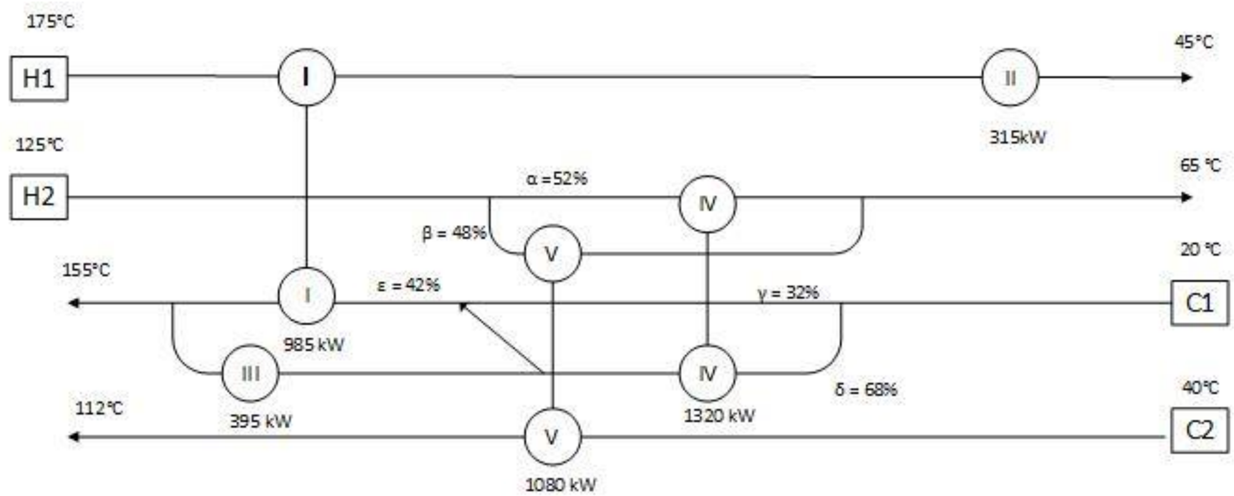

Figure 4.5: The cost-optimal network based on TAC by use of SeqHENS.

From Figure (4.5) it can be observed that the optimal network based on TAC includes two splits and one ”bypass”. This is the cost-optimal solution, but not necessarily the optimal solution when both operability and controllability issues are taken into account. It is quite easy to include a penalty term in the objective function for stream splits. However, it is more difficult to quantify how much penalty in terms of cost a stream split should give. Thus, this issue is often not accounted for in the objective function. The network above has a TAC = 235.017 $[\frac{\$}{\text{year}}]$ by use of five units.

4.1.3 AEA - Case One

In this optimization, HRAT (ΔT_{min}) is set equal to 14 °C as for the SeqHENS optimizations for comparison reasons. The final network cannot be compared directly as AEA uses a different cost function in the optimization algorithm. Regardless, the obtained networks are back-calculated with a similar cost function as SeqHENS to compare. Figure (4.6) shows TAC as a function of the number of units.

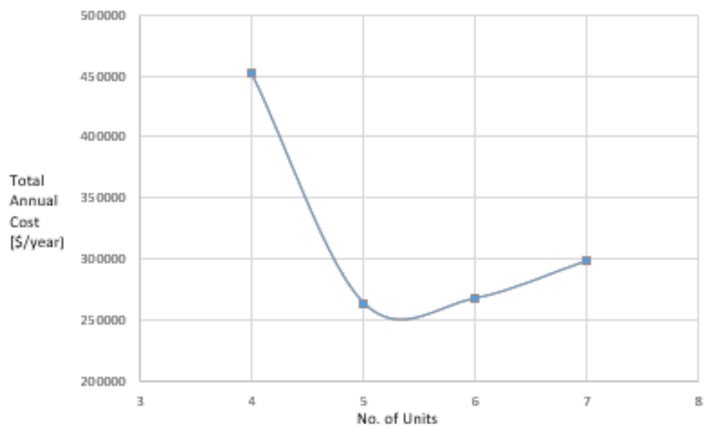

Figure 4.6: TAC as a function of number of units obtained from AEA.

The shape of the TAC curve is as expected for a system with four process streams. TAC decreases by adding units until a certain number of units, before it increases. The optimal network was obtained with five units as in SeqHENS. However, the TAC was much higher due to the excessive use of utilities as will be explained more in detail in the subsequent section. Figure (4.7) presents the total heat exchanger area as a function of the number of units.

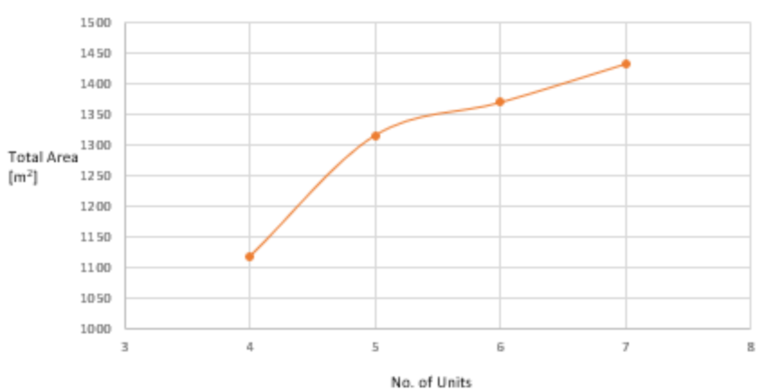

Figure 4.7: Total heat transfer area as a function of number of units for AEA optimizations.

It can be observed that the trend in the area curve is opposite of the expected behavior. This might be an indication on the fact that the HEN design obtained in AEA is not optimal. As explained in the above section, the area should decrease with increasing number of units. An explanation for this behaviour might be that the utility usage decreases as the number of units increases, meaning that the temperature driving forces decrease. This implies higher heat transfer area.

The optimal HEN design based on TAC from AEA optimizations is presented in Figure (4.8), the consecutive heat exchanger data is presented in Table (4.5).

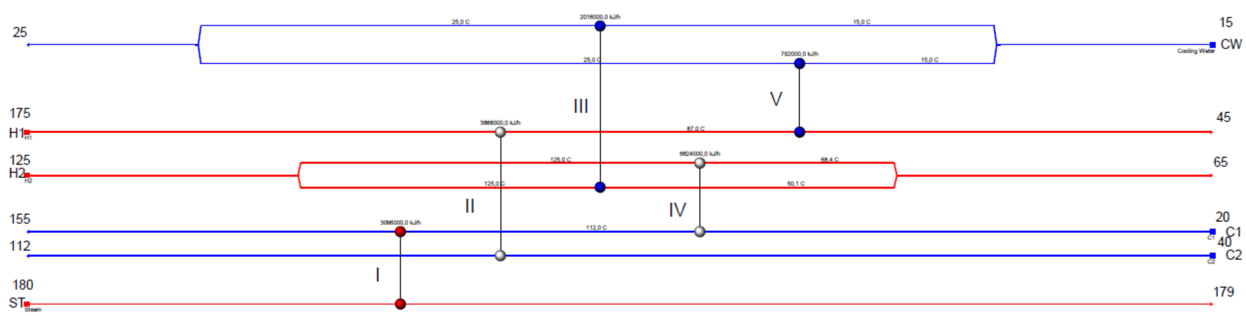

Figure 4.8: The optimal HEN design obtained from AEA optimization. The design consists of two process-process heat exchangers, two coolers and one heater.

Table 4.5: Heat exchanger data for the cost-optimal network obtained from AEA.

Unit	Duty [kW]	Area [m^2]	Type
I	860	202.2	Heater
II	1080	260.4	Process-Process
III	560	91.2	Cooler
IV	1840	699.3	Process-Process
V	220	63.0	Cooler

The network consists of five units in total with only one stream split. AEA generate HEN designs directly where both hot and cold utility streams are included. The cold utility stream is the one at the top, while the bottom stream is the hot utility. Although the TAC is much higher than for SeqHENS, the network complexity is lower, which makes it easier to control and operate the suggested network.

4.1.4 Comparison Between SeqHENS, AEA and Literature

As mentioned in the above sections, this problem has been given a lot of attention previously in the literature. Table (4.6) presents a brief summary of the different networks obtained by SeqHENS, AEA and the literature.

Table 4.6: Key numbers from the optimal solution found by SeqHENS and AEA, compared to values from the literature. TAC marked with a star indicates that the area was not reported in their work, but manually calculated from the given network.

Method	TAC $[\frac{\$}{\text{year}}]$	Units	Splits	Total area $[\text{m}^2]$	Q_H [kW]	Q_C [kW]	Reference
SeqHENS	235.017	5	2	1783	395	315	-
AEA	263.926	5	1	1335	860	780	-
Rezae E. et al.	239.797*	6	1	1479	566	486	[32]
Daniel Declercq	226.721*	5	2	1681	385	305	[33]

As can be seen in Table (4.6), the manually optimized network by Daniel Declercq is the overall optimal solution based on TAC. If the total heat transfer area of the suggested networks are compared, both AEA and Rezae et al. give networks with lower total area. This can be explained by the fact that both networks have excessive utility consumption. The temperature driving forces tend to increase when using utilities instead of utilizing the heat within the process. This affects again the total area in a positive way as can be seen by rearranging Equation (2.3). However, the trade-off between energy and heat exchanger area clearly shows that this is far from the optimal solution. The network obtained by SeqHENS has slightly higher energy consumption and total area, which results in a higher TAC. Moreover, the suggested network from SeqHENS introduces more complexity through the bypass stream in the second split. This indicates that SeqHENS does not generate the absolute optimal solution. Nevertheless, the network is close to optimum in terms of TAC and in general better compared to other automatic software tools.

4.2 Case Two

The background data for case two is of an intermediate scale industrial sized problem. The problem consists of 13 process streams and two utility streams. The stream data, in this case, is based on a process for synthetic natural gas (SNG) production plant simulated in Aspen Plus [34]. This process is a gasification type of process, which typically creates excess heat. Thus, steam generation must be taken into account. In this case, both SeqHENS and AEA are used to obtain HEN designs and thereafter compared. Due to the lack of literature on this particular problem, no validation with literature was possible. In addition, AEA has some features incorporated that SeqHENS lack, which will be further explained in the subsequent sections. This makes it difficult to compare the results directly.

4.2.1 Case Two - Stream Data and Economics

Table (4.7) presents the stream data and economic parameters for case two. All stream data are obtained from the background process simulation in Aspen Plus [34]. It should be mentioned that the heat transfer coefficient, h, is temperature averaged over the temperature domain for each specific stream.

Table 4.7: Stream data from the background process for case two.

Stream	T_s [°C]	T_t [°C]	ΔH [kW]	mCp [$\frac{kW}{°C}$]	h [$\frac{kW}{m^2°C}$]
H1	337.4	200.0	241.4	1.76	0.17
H2	238.1	25.0	233.4	1.10	0.21
H3	71.5	22.0	699.6	14.14	0.36
H4	37.4	22.0	109.66	7.09	0.06
H5	1000.0	200.0	4673.8	5.84	0.03
H6	706.1	200.0	2126.4	4.20	0.17
H7	1050	110.0	4085.9	4.35	0.02
H8	202.0	45.0	3181.9	20.22	1.98
H9	535.5	200.0	646.5	1.93	0.17
H10	200.0	30.0	928.7	5.46	0.10
C1	25.0	900.0	3340.2	3.82	0.01
C2	124.0	200.0	298.5	3.93	0.13
C3	30.0	200.0	159.7	0.94	0.09

Cost data:

Heating cost: 78.9 [$\frac{\$}{kW,year}$]

Cooling cost: 6.7 [$\frac{\$}{kW,year}$]

Area cost [\$] $= 30000 + 750 \cdot \text{Area}^{0.81}$

Annual cost factor $= 0.3221$

Annual area cost [$\frac{\$}{year}$]$= 9663 + 241.575 \cdot \text{Area}^{0.81}$

Plant lifetime: 5 years

Interest rate: 10%

The price of steam and cooling water is obtained directly from AEA default values.

The composite curves presented in Figure (4.9) are based on the stream data listed in Table (4.7). The red line represents the hot streams, while the blue line represents the cold streams.

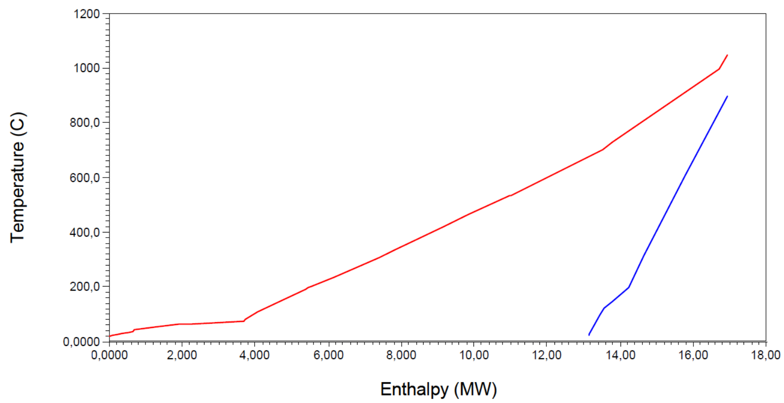

Figure 4.9: The hot and cold composite curve for case two. The red line represents the hot streams, while the blue line represents the cold streams

It can be observed from the composite curves that the cold streams can be totally integrated with the hot streams with no use of external heating. In fact, the large heat surplus in the process allows steam generation, which will be a source of revenue. Due to the large heat surplus, there is no pinch point that makes this a so-called threshold problem. However, by the introduction of steam generation, a utility pinch point will occur as shown below in the balanced composite curves. The difference between composite curves and balanced composite curves is that in the latter also utility streams are included. Figure (4.10) presents the balanced composite curves for a HRAT $(\Delta T_{min}) = 20\,°C$.

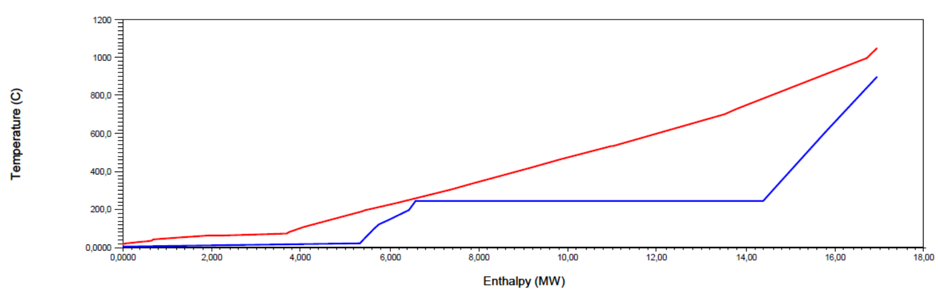

Figure 4.10: Balanced composite curves for the background process. The hot and cold utilities are also included in addition to the hot and cold process streams. This diagram reveals how much steam that can be produced for a given HRAT (ΔT_{min}).

At this level of HRAT (ΔT_{min}), approximately 7.7 MW of HP-steam can be produced. This is set as a basis for optimization in both SeqHENS and AEA. It can be observed that steam at lower temperatures can be produced, but due to limitations in SeqHENS regarding steam production this is not included. Moreover, by introducing multiple steam levels, more units are required which increases the number of units in the network. The grand composite curve presented in Figure (4.11) was made to visualize that 7.7 MW of HP-steam can be produced at 250 °C.

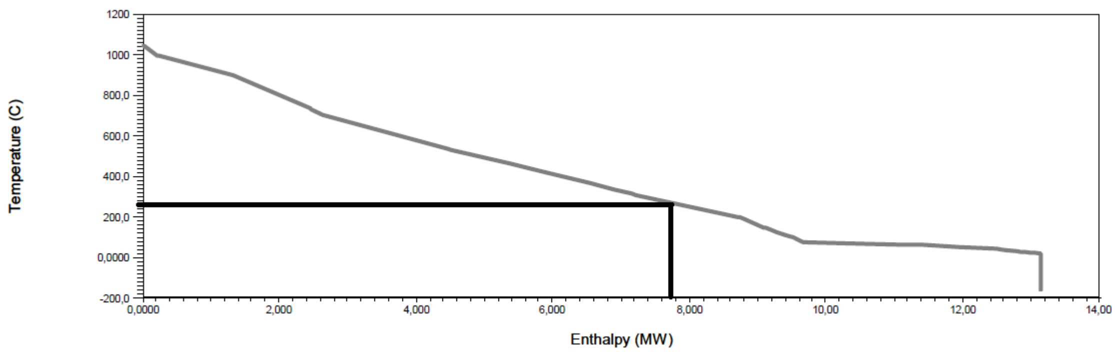

Figure 4.11: The grand composite curve of the process. The gray line represents the process streams, while the black line is included to show how much HP-steam that can be generated at 250 °C.

The gray line represents the process streams, while the black line shows that approximately 7.7 MW of HP-steam can be produced by the heat surplus within the process. Data regarding utilities is shown in Table (4.8).

Table 4.8: Utility data for case two.

Utility type	T_s [°C]	T_t [°C]	Pressure [Bar]
HP Steam	249	250	40.2
CW	10	25	1.0

It was assumed that boiler feed water at 249 °C is available in sufficient amount at the site and is introduced at the shell side of the heat exchangers to generate steam. This is done to simplify the system.

The target for number of units can be calculated based on Equation (2.5) or found in AEA. Table (4.9) shows the unit target for some heat recovery (U_{min}) as well as maximum energy recovery ($U_{\text{min}}^{\text{MER}}$).

Table 4.9: Target for number of units for some heat recovery and maximum heat recovery.

	Target
U_{min}	14
$U_{\text{min}}^{\text{MER}}$	19

4.2.2 SeqHENS - Case Two

This case was quite difficult to conduct with SeqHENS due to the way it is implemented. The start value generator gave an error since no hot utility was necessary. In addition, steam generation is not a feature implemented in SeqHENS. These problems were handled by adding an imaginary cold stream that needed some hot duty and treats the steam production stream as a cold process stream. With these adjustments, it is plausible that the solutions obtained are not the true optimal at each point. Regardless, the optimization results are showed below.

Figure (4.12) shows TAC in $[\frac{\mathrm{M\$}}{\mathrm{year}}]$ as a function of number of units with a HRAT = 20 °C.

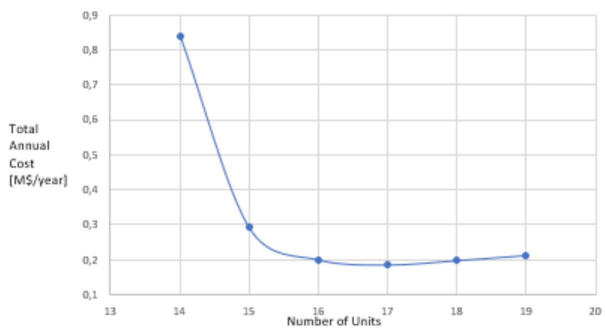

Figure 4.12: TAC as a function of number of units for case two obtained from SeqHENS optimization.

As can be observed from the figure above, the cost related to the network decreases when the number of units increases from U_{min} up to its optimum at 17 units. At optimum, the cost related to the network is 185.700 $[\frac{\$}{\mathrm{year}}]$. After the optimum point, U_{Opt}, the TAC increases slightly. It is reasonable to believe that this is the true optimum for the given HRAT since both the TAC and the total heat exchanger area presented in Figure (4.12) and Figure (4.13) follow the expected trends. However, optimization with lower HRAT showed issues with convergence for SeqHENS and thereby it might be plausible that better solutions exist.

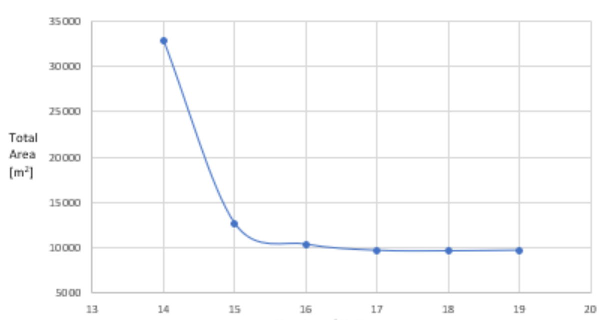

Figure 4.13: Total heat exchanger area as a function of number of units obtained from SeqHENS optimization.

The total area plot shows asymptotic behavior when the number of units in the network increases. The so-called ”$U_{\max}$” can be determined where the area does not decrease with increasing units. This arises when the temperature driving forces are optimally distributed.

The individual heat exchanger features as well as the cost-optimal network are presented in Table (4.10) and Figure (4.14) respectively.

Table 4.10: Heat exchanger data for the cost-optimal network obtained from SeqHENS optimization.

Unit	Duty [kW]	Area $[\mathrm{m}^2]$	Type
I	159.1	21.1	Process-Process
II	81.7	10.4	Steam Production
III	233.4	22.8	Cooler
IV	699.6	160.8	Cooler
V	109.5	211.9	Cooler
VI	2982.6	767.5	Steam Production
VII	1691.0	3922.8	Process-Process
VIII	1909.6	156.3	Steam Production
IX	198.9	35.0	Process-Process
X	18.0	0.8	Cooler
XI	935.8	187.5	Cooler
XII	1979.5	611.4	Steam Production
XIII	1649.1	3182.2	Process-Process
XIV	3181.9	95.8	Cooler
XV	547.0	66.4	Steam Production
XVI	99.5	39.1	Process-Process
XVII	928.7	169.3	Cooler

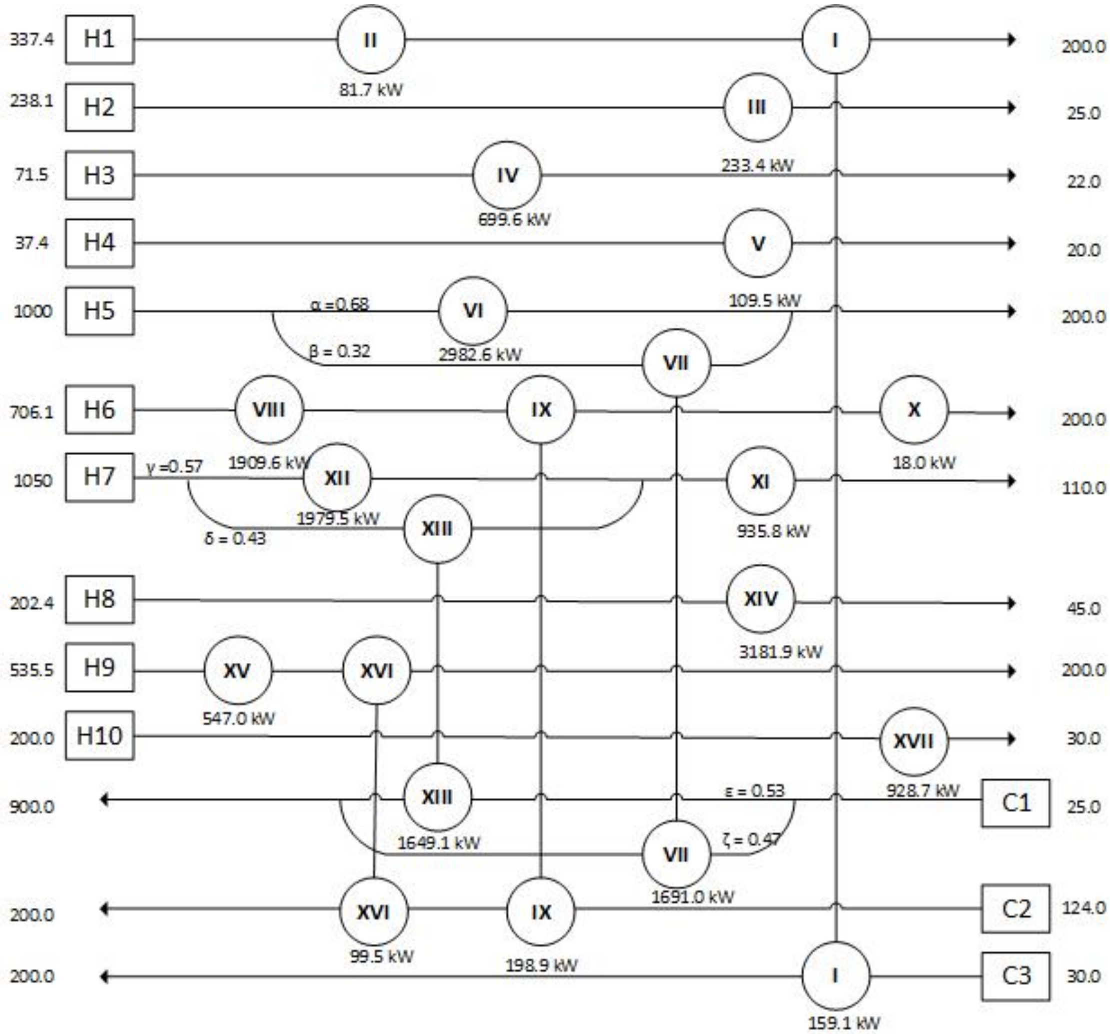

Figure 4.14: The cost-optimal HEN design obtained from SeqHENS. The network consist of 17 units in total. The units can be divided into five process-process units, seven coolers and five steam production units.

This network consists of three stream splits that increase the network complexity. In addition, the heat exchanger size varies significantly from 0.8 m^2 up to 3923 m^2, which is not favorable from a controllability point of view.

4.2.3 AEA - Case Two

In this particular case, the built-in cost function in AEA was used to calculate the cost related to the generated networks. Thus, directly comparing the total cost is not relevant. However, the network features are highly interesting to discuss and compare. The optimization algorithm for a generated network that includes loops and paths did not work at all for this problem. The number of streams might be too high for the loop and path optimization routine in AEA.

Figure (4.15) shows the total cost as a function of number of units.

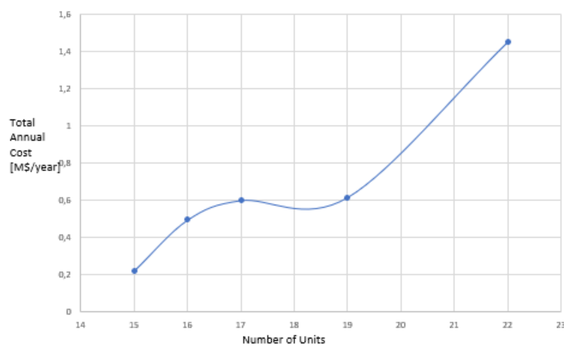

Figure 4.15: TAC as a function of number of units obtained from AEA optimization.

It can be noticed that networks consisting of $U = U_{\text{min}} = 14$, $U = 18$, $U = 20$, and $U = 21$ were not obtainable here. It is not possible to specify the number of units prior to optimization in AEA, which leads to inconsistencies in this graphical representation. Regardless, the network consisting of 15 units was the cost-optimal one, whereas the cost increases for networks with more units. To get a deeper understanding of this behavior, a plot showing the total area as a function of the number of units was made.

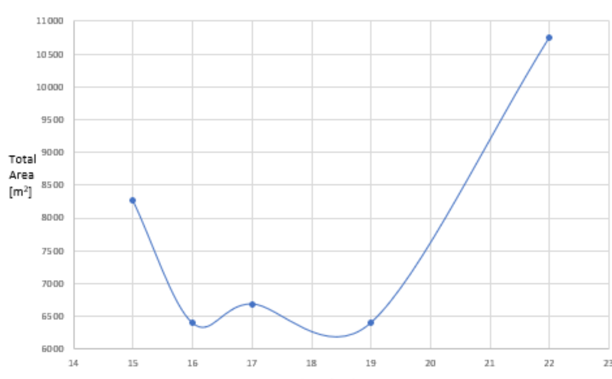

Figure 4.16: Total heat exchanger area as a function of number of units obtained from AEA.

From Figure (4.16) it can be seen that the total heat transfer area decreases when the number of units increases. The network obtained with 22 units is an outlier and deviates significantly from the overall trend. This is a clear indication that a network with lower total area and thus lower cost should exist for 22 units. It is difficult to draw a conclusion from these results as several points are missing.

The cost-optimal network can be seen in Figure (4.17) and the corresponding heat exchanger data in Table (4.11). The grid representation in AEA includes the cooling water and stream generation streams as cold streams at the top. The order of the hot and cold streams are different to the grid representation in SeqHENS. The diagram is showed in a larger version in Appendix (A.2) for better visualization.

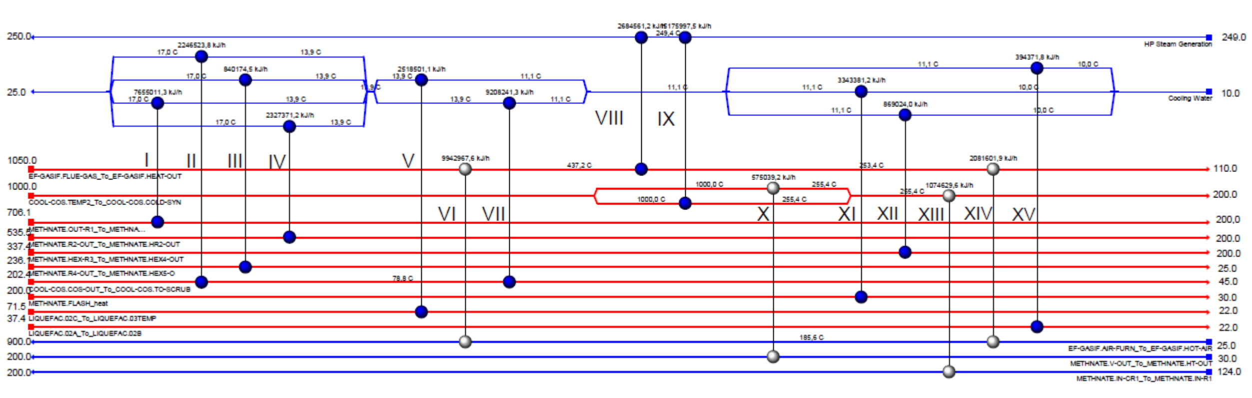

Figure 4.17: The cost-optimal network from case two optimization in AEA.

Table 4.11: Heat exchanger data for the cost-optimal network obtained in AEA.

Unit	Duty [kW]	Area [m^2]	Type
I	2126.4	43.4	Cooler
II	624.0	178.3	Cooler
III	233.4	22.6	Cooler
IV	646.5	15.5	Cooler
V	699.6	167.4	Cooler
VI	2761.9	3953.0	Process-Process
VII	2557.8	117.7	Cooler
VIII	745.7	845.7	Steam generation
IX	4215.6	915.8	Steam generation
X	159.7	16.2	Process-Process
XI	928.7	148.2	Cooler
XII	241.4	7.5	Cooler
XIII	298.5	192.1	Process-Process
XIV	578.2	1540.0	Process-Process
XV	109.5	110.4	Cooler

The network presented in Figure (4.17) consists of four process-process heat exchangers, nine coolers and two steam generation units with a TAC = 221.591 $[\frac{\$}{\text{year}}]$. The heat exchanger area varies from 7.5 m^2 to 3953 m^2. Even though the network complexity seems high in Figure (4.17), the multiple stream split of cooling water is the largest contributor. This configuration would not be implemented in a real HEN design due to the high complexity. Apart from the cooling water, only one split is necessary for this network.

4.2.4 Comparison Between SeqHENS and AEA

As mentioned previously, this case has no basis in the literature for comparison as the stream data is obtained from an ongoing simulation [34]. In addition, the results from SeqHENS and AEA cannot be compared directly since they are based on different assumptions. Regardless, some network features like utility consumption/generation and complexity can be compared.

Table (4.12) presents the network features for the cost-optimal networks from both AEA and SeqHENS.

Table 4.12: Network features for both SeqHENS and AEA. The number of splits in the AEA network is marked with a star since the process streams only need one split, whilst the cooling water stream is split several times.

Method	Units	Splits	Total area $[\mathrm{m}^2]$	Q_H^{prod} [kW]	Q_C[kW]	TAC $[\frac{\$}{\text{year}}]$
AEA	15	1*	8274	4961	8167	221.591
SeqHENS	17	3	9661	7500	5629	185.700

It can be noticed that the AEA network has excessive cooling water consumption, while at the same time it generates much less steam than the target. The network obtained in SeqHENS has a higher complexity with three stream splits. Both the total area and the cost are difficult to compare since they are based on different assumptions.

4.3 Case Three

Case three is an intermediate scale industrial sized problem with balanced amounts of hot and cold streams. In total there are nine process streams, four hot and five cold. The process streams require both heating and cooling to reach their target temperature. The background process listed in Table (4.13) is from an aromatic plant and has been extensively studied since it was presented by Linnhoff and Ahmad (1990) [35]. Since this problem has been given so much attention, only SeqHENS studies was conducted.

4.3.1 Case Three - Stream Data and Economics

Table (4.13) presents the stream data and economics used in case three. All data are obtained from [36].

Table 4.13: Stream and utility data for case three [36].

Stream	T_s [°C]	T_t [°C]	mCp [$\frac{\text{kW}}{°\text{C}}$]	ΔH [MW]	h [$\frac{\text{kW}}{\text{m}^2°\text{C}}$]
H1	327	40	100	28.70	0.50
H2	220	160	160	9.60	0.40
H3	220	60	60	9.60	0.14
H4	160	45	400	46.00	0.30
C1	100	300	100	20.00	0.35
C2	35	164	70	9.03	0.70
C3	85	138	350	18.55	0.50
C4	60	170	60	6.60	0.14
C5	140	300	200	32.00	0.60
Hot Oil	330	250	-	-	0.50
CW	15	30	-	-	0.50

Cost data:
Hot oil cost: 60.0 [$\frac{\$}{\text{kW,year}}$]   Cooling cost: 6.0 [$\frac{\$}{\text{kW,year}}$]
Area cost [\$] $= 10000 + 350 \cdot$ Area
Annual area cost [$\frac{\$}{\text{year}}$] $= (10000 + 350 \cdot$ Area)/5
Plant lifetime: 5 years
Interest rate: 0%

From the stream data, the composite curves shown in Figure (4.18) can be obtained.

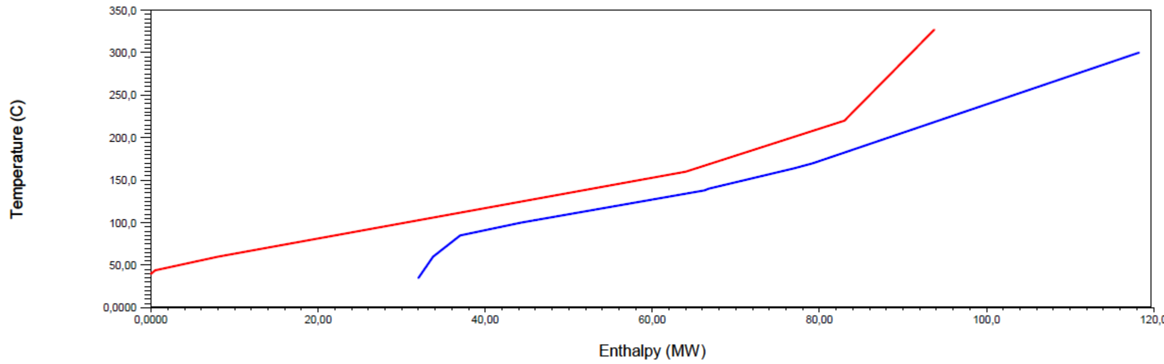

Figure 4.18: The composite curves for case three with a HRAT = 25 °C.

In the work of Linnhoff and Ahmad the optimal HRAT is proven to be 26 °C. HRAT is chosen to be 25 °C in this case in order to obtain networks with fewer units than in literature. At this level, the heating and cooling demands are 24.48 MW and 32.20 MW respectively and a total process heat recovery at 68.05 MW.

The GCC is made from the stream data presented in Table (4.13). It can be observed from Figure (4.18) that the slope of the hot and cold composite curve are almost parallel in the middle region. This means that the temperature driving forces are small, which results in a large total heat exchanger area. This makes the pinch point sensitive to changes in HRAT as can be seen in the GCC.

Figure (4.19) shows the GCC for three different HRATs.

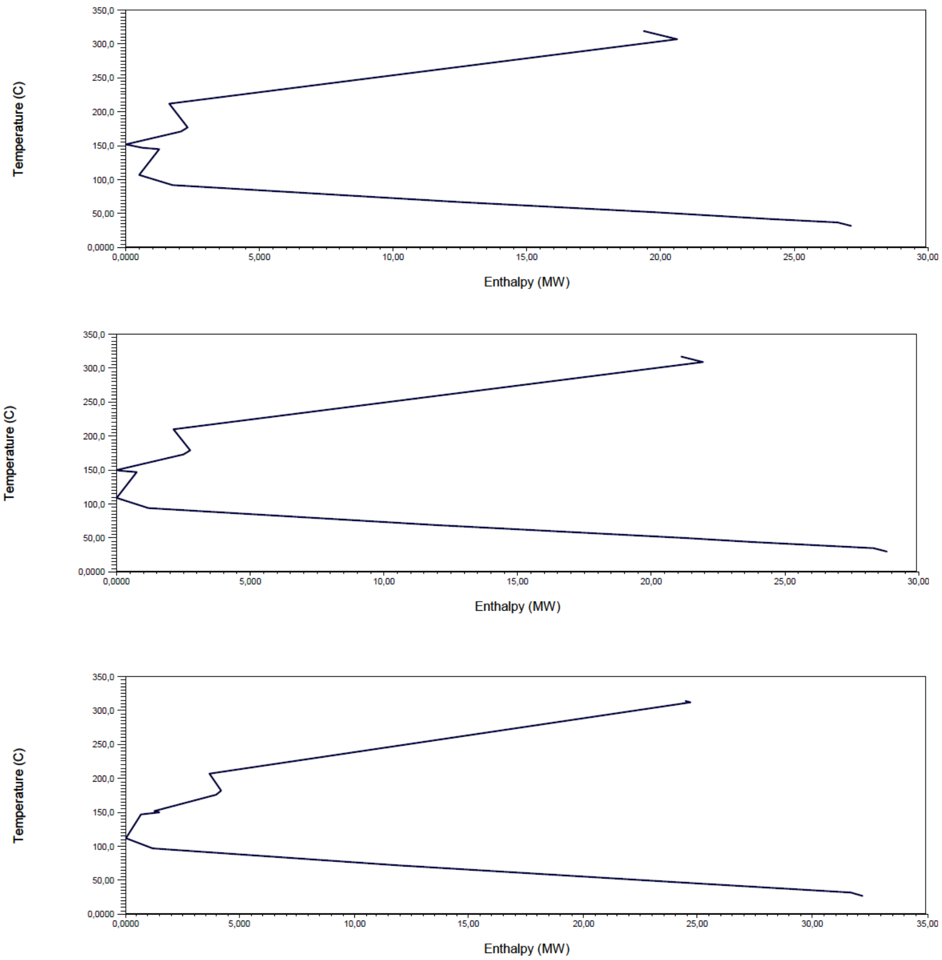

Figure 4.19: The GCC for case three; (a) HRAT = 15 °C (b) HRAT = 19 °C (c) HRAT = 25 °C

It can be observed that at HRAT = 19 °C, a new pinch point occurs. The pinch temperature move from 160 °C (hot pinch temperature) down to 100 °C (cold pinch temperature) by crossing this limit as shown in the above figure. This stream data feature makes the problem even more interesting to investigate. Thereby, optimizations at all three levels of HRAT are conducted in SeqHENS.

Targets for the number of units are calculated in AEA and shown in Table (4.14).

Table 4.14: Targets for number of heat exchangers in case three calculated by AEA.

	Target
U_{min}	10
$U_{\text{min}}^{\text{MER}}$	15

It can be noticed that the minimum number of units is equal to the $(N-1)$ rule given in Equation (2.5).

4.3.2 SeqHENS - Case Three

Figure (4.20) was made to investigate and verify the optimal HRAT for this particular problem.

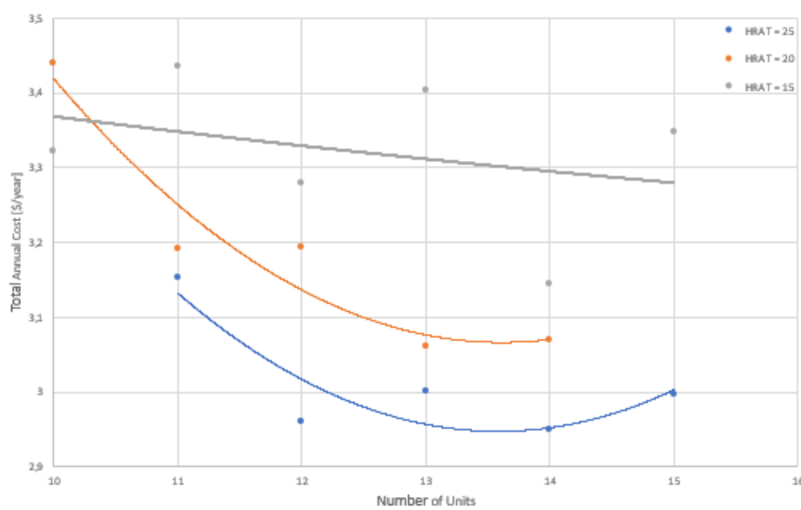

Figure 4.20: TAC in $[\frac{\text{M\$}}{\text{year}}]$ as function of number of units for three different HRATs.

It can be noticed that for an HRAT = 15 $^\circ$C the points fluctuate significantly, and no particular trend can be observed. For HRAT = 20 $^\circ$C and 25 $^\circ$C they seem to fit the line more or less as expected. Although some deviations can be observed for all choices of HRAT, the trend is clearly that HRAT = 25 $^\circ$C gives the lowest TAC. This result was expected as the literature reports the same behaviour.

Figure (4.21) shows TAC as a function of the number of units for a HRAT = 25 °C.

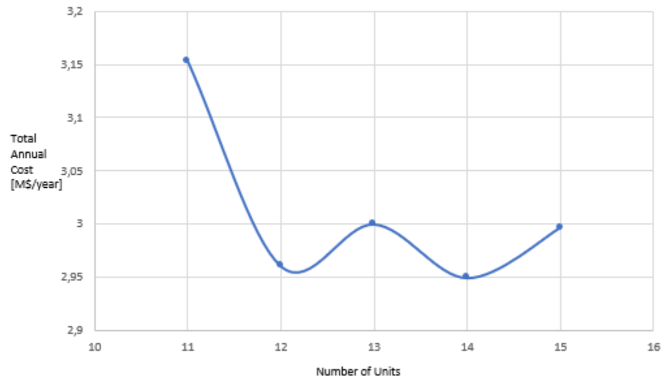

Figure 4.21: TAC as a function of numbers of units obtained from SeqHENS optimization.

Networks with minimum number of units were not possible to obtain in SeqHENS for this case. The start value generator gave an error indicating that in some point of the calculations a denominator became zero. One possible reason for this might be that it is impossible to cool down the hot stream without external cooling due to the large temperature difference required. However, from 11 to 15 units it worked properly, and networks were generated. Once again, it is difficult to conclude that the optimal point from the optimization is the true optimum. The suggested cost-optimal network with 13 units deviates from the trend and thereby it could be that there exists networks with 13 units that have lower TAC. Regardless, the optimal network based on the optimization consists of 14 units and has approximately TAC = 2.95 $[\frac{\text{M\$}}{\text{year}}]$.

The total heat exchanger area as a function of the number of units is presented in Figure (4.22). The total area plot gives a qualitative measure of how good the solutions are.

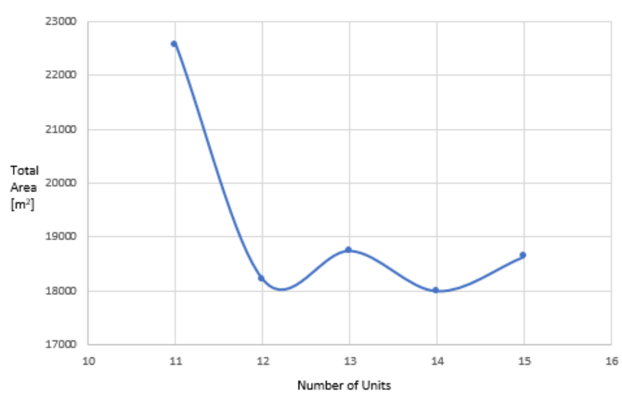

Figure 4.22: Total heat exchanger area as a function of number of units obtained from SeqHENS.

The total heat transfer area plot indicates that at least the networks consisting of 13 and 15 units, might not be the optimal networks. The area should decrease with increasing number of units until it stabilizes.

Table (4.15) and Figure (4.23) show the heat exchanger features and cost-optimal network obtained in this case respectively.

Table 4.15: Heat exchanger data for the cost-optimal network obtained from SeqHENS optimizations.

Unit	Duty [kW]	Area $[\mathrm{m}^2]$	Type
I	7072	749.6	Process-Process
II	11687	1977.9	Process-Process
III	5130	937.8	Process-Process
IV	4812	462.3	Cooler
V	8757	1374.9	Process-Process
VI	832	145.8	Process-Process
VII	3126	463.4	Cooler
VIII	6474	1822.9	Process-Process
IX	24240	2620.8	Cooler
X	139	29.3	Process-Process
XI	17710	3970.8	Process-Process
XII	3896	731.7	Process-Process
XIII	8313	1280.3	Heater
XIV	16166	1431.7	Heater

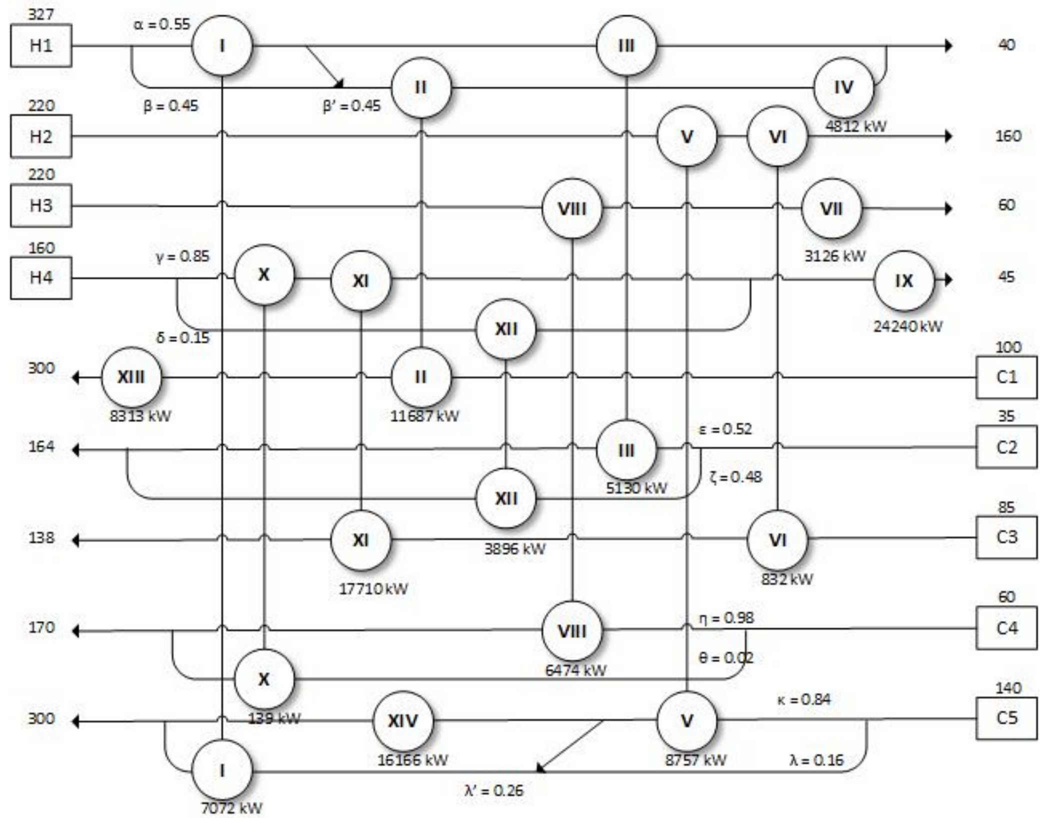

Figure 4.23: The cost-optimal solution obtained from SeqHENS optimizations. The network consists of 14 units including nine process-process heat exchangers, three coolers, and two heaters.

The network consists of 14 heat exchangers, nine process-process heat exchangers, three coolers and two heaters. As can be observed, the network is rather complex with five stream splits and two ”bypasses”. From a controllability point of view, this is surely not the optimal network.

The second best choice in terms of TAC is the 12 unit network presented in Figure (4.24). The TAC is slightly higher, but the network structure is significantly less complicated. In addition, the units are more uniformly distributed in terms of their size. This is an advantage from a controllability point of view. Table (4.16) shows an overview of features related to each unit in the network. The resulting network can be seen in Figure (4.24).

Table 4.16: Heat exchanger data for the alternative network consisting of 12 units obtained from SeqHENS optimizations.

Unit	Duty [kW]	Area $[\mathrm{m}^2]$	Type
I	7180	905.2	Process-Process
II	9040	1322.3	Process-Process
III	9150	1224.5	Process-Process
IV	3350	349.0	Cooler
V	9600	1686.6	Process-Process
VI	3000	450.9	Cooler
VII	6600	1885.5	Process-Process
VIII	1600	360.7	Process-Process
IX	18560	4679.9	Process-Process
X	25850	2711.0	Cooler
XI	9250	1251.9	Heater
XII	15230	1388.6	Heater

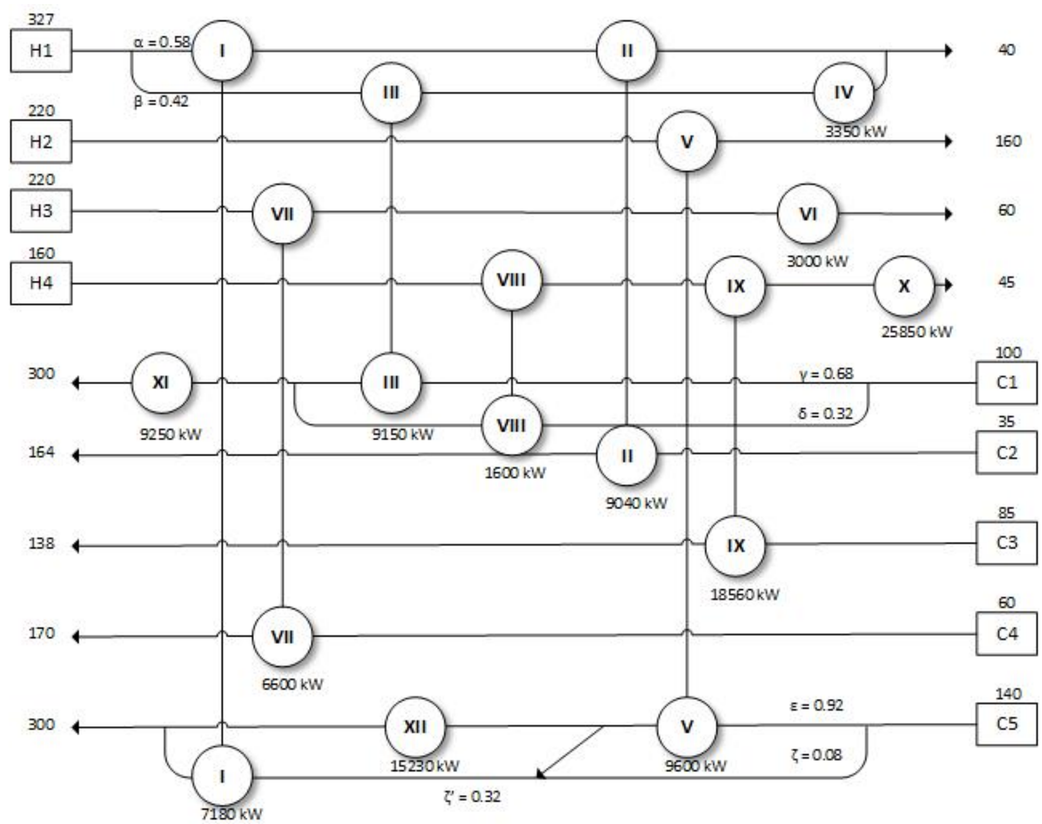

Figure 4.24: Alternative network obtained from SeqHENS, which consists of 12 units with slightly higher TAC, but less complex structure.

4.3.3 Comparison Between SeqHENS and Literature

As previously mentioned, this problem has been extensively studied since it was presented by Linnhoff and Ahmad [35]. Table (4.17) lists the important features of networks from previous work as well as for this work.

Table 4.17: Comparison of networks obtained from SeqHENS with previous work on this case.

Method	Splits	Total area $[\mathrm{m}^2]$	Units	Q_h [MW]	Q_c [MW]	TAC $[\frac{\mathrm{M\$}}{\mathrm{year}}]$	Reference
Linnhoff and Ahmed (1990)	0	17400	13	25.31	33.03	2.960	[35]
Zhu et al. (1995)	2	16630	14	26.22	33.94	2.970	[37]
Lewin (1998)	2	17050	12	25.09	32.81	2.936	[38]
Pettersson (2004)	7	17437	17	24.27	31.99	2.905	[36]
This work	5(7)	17999	14	24.48	32.20	2.949	-
This work	3(4)	18213	12	24.48	32.20	2.961	-

As can be seen from Table (4.17), the optimal network obtained in this work is close to the optimal found in the literature. The total heat transfer area is slightly higher, while the utility consumption is lower than for most of the cases. This indicates that they have used an HRAT slightly higher than in this work. The network suggested by Pettersson (2004) seems to be the overall cost-optimal network. As for the SeqHENS solution, the complexity is rather high with many stream splits. The alternative network suggested in this work has slightly higher TAC, but an advantage is that the complexity is significantly reduced.

4.4 Case Four

This problem is an intermediate industrial sized problem consisting of eight hot and seven cold streams. The problem was originally introduced by Björk and Pettersson (2003) [39] and has been extensively studied in recent years. For comparison reasons, an HRAT = 18 °C is chosen.

4.4.1 Case Four - Stream Data and Economics

Table (4.18) presents the stream data and economics of this problem.

Table 4.18: Stream data and economics for case four.

Stream	T_s[°C]	T_t[°C]	mCp [$\frac{\text{kW}}{\text{°C}}$]	h [$\frac{\text{kW}}{\text{m}^2\text{°C}}$]
H1	180	75	30	2.0
H2	280	120	60	1.0
H3	180	75	30	2.0
H4	140	40	30	1.0
H5	220	120	50	1.0
H6	180	55	35	2.0
H7	200	60	30	0.4
H8	120	40	100	0.5
C1	40	230	20	1.0
C2	100	220	60	1.0
C3	40	190	35	2.0
C4	50	190	30	2.0
C5	50	250	60	2.0
C6	90	190	50	1.0
C7	160	250	60	3.0
Hot utility	325	325	-	1.0
Cold utility	25	40	-	2.0

Cost data:
Hot utility cost: 80 [$\frac{\$}{\text{kW,year}}$]
Cold utility cost: 10 [$\frac{\$}{\text{kW,year}}$]
Annual area cost [$\frac{\$}{\text{year}}$] $= 8000 + 500 \cdot \text{Area}^{0.75}$

The composite curves for the process are obtained from AEA and can be seen in Figure (4.25).

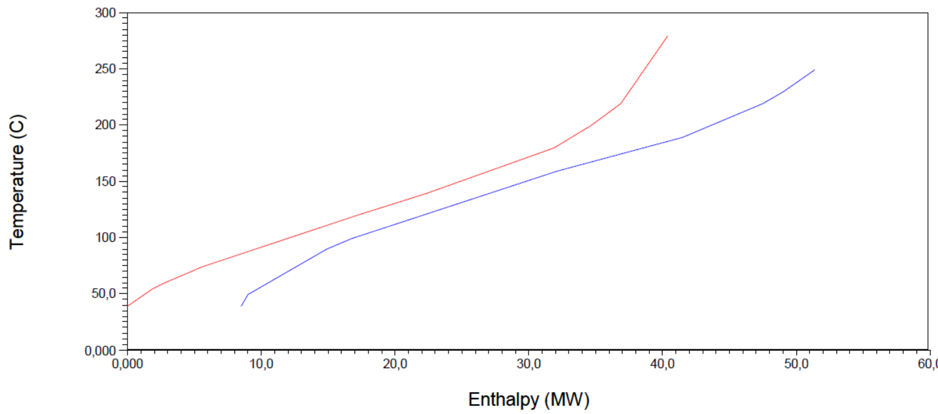

Figure 4.25: The hot and cold composite curves obtained from stream data in case four. The red line represents the hot process streams, whilst the blue line represents the cold process streams.

From Figure (4.25) it can be observed that the utility consumption for the given HRAT is approximately 10950 kW and 8550 kW for hot and cold utility respectively. At this choice of HRAT, the pinch point is located at 140/122 °C and the heat recovery in the process is thereby approximately 31900 kW.

The unit target for some heat recovery and maximum heat recovery in this case is again calculated in AEA and are listed in Table (4.19)

Table 4.19: Unit targets for maximum heat recovery ($U_{\mathrm{min}}^{\mathrm{MER}}$) and some heat recovery (U_{min}).

	Target
U_{min}	16
$U_{\mathrm{min}}^{\mathrm{MER}}$	27

The minimum number of units is equal to the $(N-1)$ rule, however as can be seen in subsequent sections, networks with fewer units can be achieved.

4.4.2 SeqHENS - Case Four

The SeqHENS optimizations revealed that networks with fewer units than the calculated $U_{\min}$ from Equation (2.5) were possible to obtain. The minimum number of unit loop (MILP) resulted in $U_{\min} = 14$ for an HRAT = 18 $^{\circ}$C as the absolute minimum. This result can be explained by Equation (2.6), where more than one subnetwork exists. In fact, for larger systems often more than one subnetwork can appear, which results in networks with lower $U_{\min}$ than the $(N-1)$ rule. Subnetworks typically occur if there is a perfect match between a set of streams [1]. Figure (4.26) presents the resulting network consisting of only 14 units.

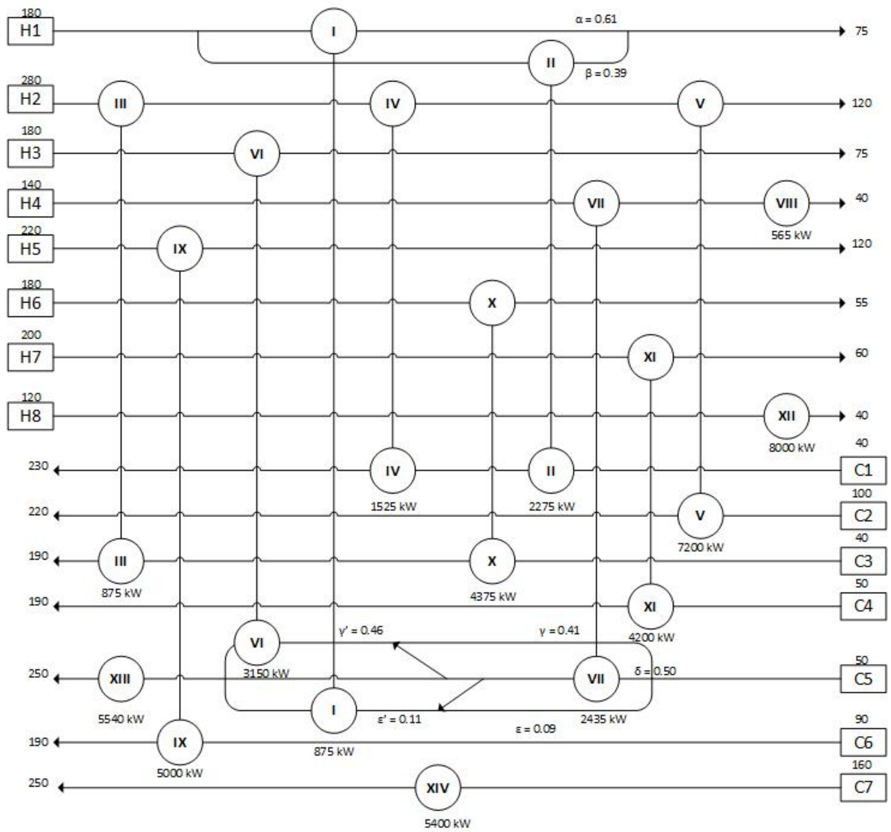

Figure 4.26: A network consisting of only 14 units obtained by SeqHENS optimizations.

As can be observed in the network above, three such subnetworks occur. A perfect match between H7-C4 through unit XI, a perfect match between H5-C6 through unit IX, and the rest of the heat exchangers are the three subnetworks in this system. The occurrence of these subnetworks results in the network with a total of 14 units.

[1]Perfect match means that only one heat exchanger is necessary to fulfill the targets for a set of streams.

The cost-optimal network for this case was found by plotting TAC as a function of the number of units for the given HRAT, as presented in Figure (4.27).

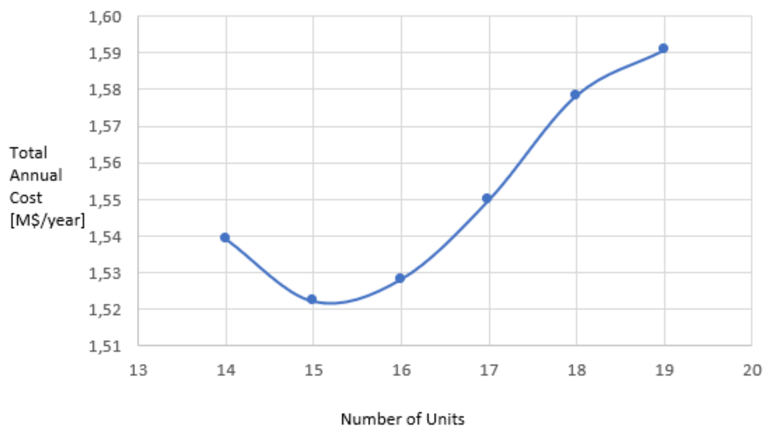

Figure 4.27: TAC as a function of number of units obtained from SeqHENS.

It can be seen that the network consisting of 15 units is the global minimum and thereby the cost-optimal network with TAC = 1.522.297 $[\frac{\$}{\text{year}}]$. A notable trend is that the TAC was lowest for $U = 15$ and increased when the number of units were changed in both directions. An additional plot showing the heat transfer area as function of number of units, was made to substantiate that these solutions are close to optimum. The corresponding total heat transfer areas are presented in Figure (4.28).

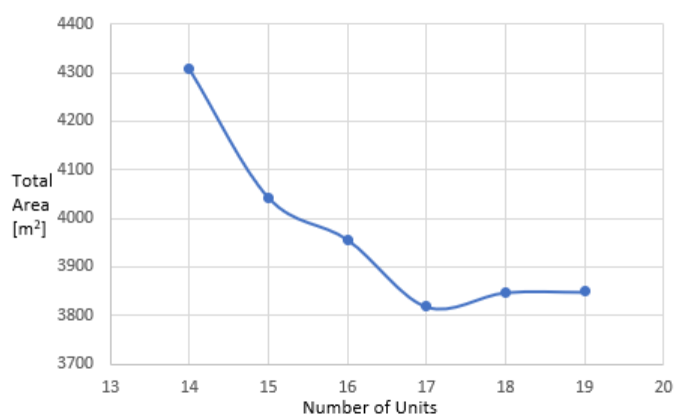

Figure 4.28: The heat transfer area as a function of number of units.

It can be observed from the figure above that the total heat transfer area decreases when adding units, until it stabilizes around 3800 m^2. This result can again be explained by the fact that increasing the number of units allows for better distribution of temperature driving forces, which leads to a decrease in the total area. This result indicates that the obtained network might be the optimal one for the given stream data.

Heat exchanger data and the corresponding cost-optimal HEN design are presented in Table (4.20) and Figure (4.29) respectively.

Table 4.20: Heat exchanger data for the cost-optimal network consisting of 15 units obtained from SeqHENS optimizations.

Unit	Duty [kW]	Area $[\mathrm{m}^2]$	Type
I	3150	268.1	Process-Process
II	1525	31.3	Process-Process
III	875	15.6	Process-Process
IV	7200	720.0	Process-Process
V	3150	268.1	Process-Process
VI	1640	110.8	Process-Process
VII	1360	74.3	Cooler
VIII	5000	333.3	Process-Process
IX	4375	291.7	Process-Process
X	4200	1260.0	Process-Process
XI	795	33.5	Process-Process
XII	7205	494.5	Cooler
XIII	635	11.5	Heater
XIV	4905	66.3	Heater
XV	5400	63.1	Heater

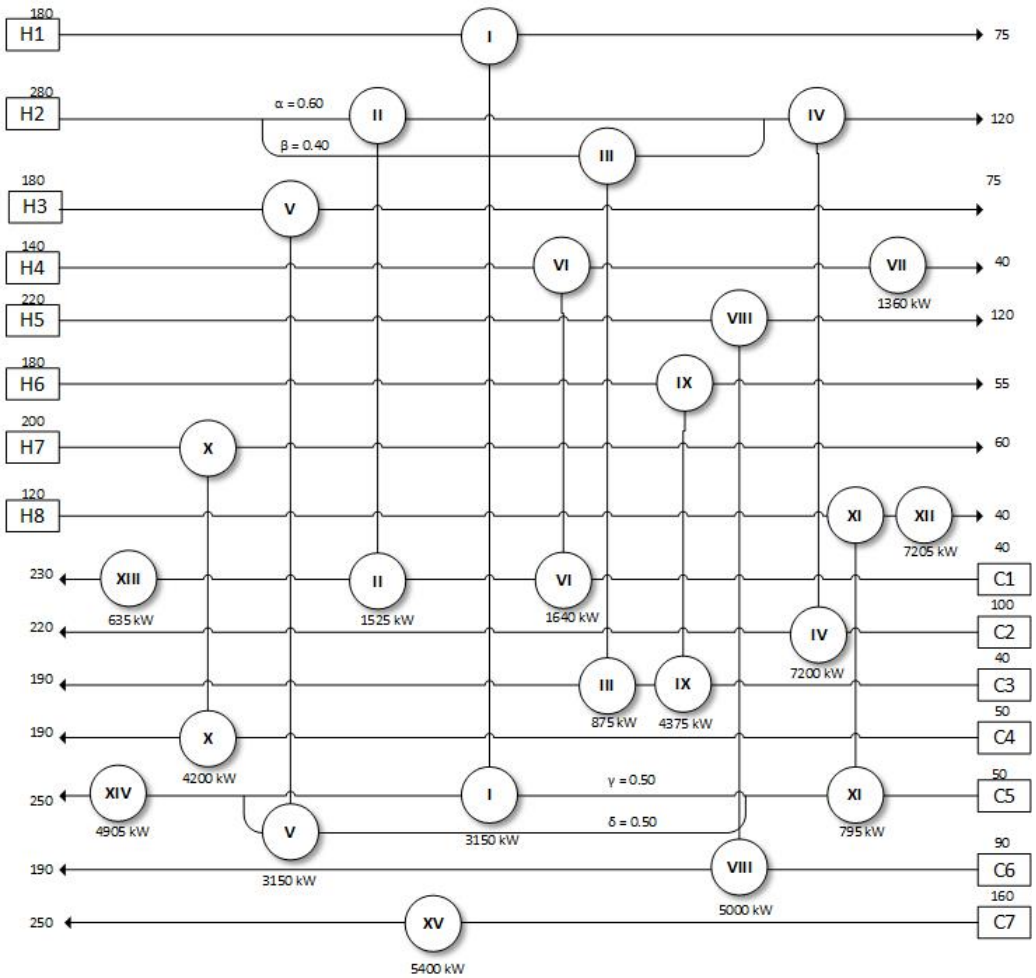

Figure 4.29: The cost-optimal network for case four.

The cost-optimal network consisted of 15 units in total, ten process-process heat exchangers, two coolers and three heaters. The network is significantly less complicated than the suggested network with 14 units showed in Figure (4.26) with only two stream splits.

4.4.3 Comparison Between SeqHENS and Literature

Table (4.21) summarizes the important features of the networks found in literature as well as obtained in this work.

Table 4.21: Comparison of the cost-optimal network obtained from SeqHENS optimization and literature.

Method	Units	Splits	Total area $[\mathrm{m}^2]$	Q_h [kW]	Q_c [kW]	TAC $[\frac{\$}{\mathrm{year}}]$	Reference
Björk & Pettersson	-	-	-	-	-	1.513.854	[39]
Björk & Nordman	-	-	-	-	-	1.530.063	[40]
Fieg et al.	15	-	-	10.617	8241	1.510.891	[41]
Peng & Cui	19	0	4227	10.109	7734	1.527.240	[42]
Peng & Cui	17	0	3691	10.974	8599	1.537.252	[42]
This work	15	2	4043	10.940	8565	1.522.297	-

Due to the lack of network structure, several of the important features were not rendered. Although there are small deviations between the optimal network obtained from all work related to this case, the optimal network from this work is within 0.75 percentage of the optimal network reported. The complexity of the network obtained from SeqHENS, with only two splits, did not differ significantly from the others. The overall cost-optimal network has not reported the network structure, which makes it impossible to compare the complexity.

Chapter 5

Discussion

This section comprises of a discussion regarding both SeqHENS and AEA on a higher level than in the previous chapter. The emphasis was on the overall performance and on what types of problems the software is suitable for.

As explained previously, it is not fair to compare the results obtained in SeqHENS and AEA directly, since they are based on different assumptions. SeqHENS is more suitable at an academical level since it is the optimization routine that is most emphasized, while AEA provides more realistic results from a process industry point of view. For instance, AEA allows for heat exchangers with several shells (i.e shell and tube) and varying heat capacities and heat transfer coefficients (temperature dependencies). In addition, AEA suggests structures for fairly large problems, which SeqHENS cannot handle due to combinatorial explosion. Furthermore, it is an advantage that AEA is very compatible with Aspen Plus/HYSYS, which facilitates the use of this software. In fact, AEA is very user-friendly compared to SeqHENS in the way that it is fully automated with many user specification possibilities. On the other hand, the stepwise procedure in SeqHENS makes the user (design engineer) the top level optimizer making judgments based on both qualitative and quantitative aspects such as HRAT and number of units in the system. This allows for more user interaction during the design process.

Although AEA gives a more realistic view of the heat exchanger cost and heat transfer area, the case studies have revealed that AEA has severe problems with suggesting networks with low energy consumption. From case one, the suggested cost-optimal network (after use of the internal optimizer) has more than twice as much utility consumption than the minimum target for this particular HRAT. Also in case two, the steam generation is much lower than the maximum target at 7.7 MW, and thus excessive use of CW is necessary. This shows that the optimization routine is rather poor compared with SeqHENS and other HENS software tools developed for HEN design. In addition, as experienced from both SeqHENS and similar models reported in the literature, most of the models face severe challenges for large scale industrial-sized problems (more than 20 streams). These problems do not occur in AEA. This is also a clear indication that the optimization routine is not very reliable. Another result that supports this statement is the fact that AEA sometimes suggests infeasible HEN designs, where the temperature difference in either the hot or cold end of a heat exchanger becomes negative. As mentioned in Section (3.2), Aspen Tech claims that AEA generates near-optimal solutions to HEN problems, whereas this work has revealed that the suggested structures are far from optimal, especially based on minimizing the energy consumption.

Both the case studies conducted in this work and previous work with SeqHENS have shown that SeqHENS suggests HEN designs close to the optimal solution reported and most likely the global optimum. The results are more or less consistent when it comes to how the TAC curve and total area curve behave with increasing number of units. Although the networks are close to optimal based on TAC, several other aspects such as controllability and operability are not accounted for. For instance, the cost-optimal network in case four consisting of 14 units may not be feasible from an operability/controllability point of view since cold stream five (C5) is first split in three branches, and thereafter the mass flows in each branch optimized by introduction of two ”bypasses”. So, to realize this design configuration, five control valves are required. To avoid this problem, it is necessary to implement some kind of penalty in the objective function when it comes to stream splits. The main problem is that the NLP routine might find very complex solutions with a small decrease in total cost compared to another structure with a much lower degree of complexity. In fact, Peng and Cui [42] have developed a simultaneous model that uses the simulated annealing algorithm with a constraint that stream splitting is not allowed. The resulting network is still close to the best reported for this case, but much simpler in terms of network structure.

Chapter 6

Conclusions and Further Work

The main objective of this work was to test different software tools for heat exchanger network synthesis. Aspen Energy Analyzer, EnergyPinch, and SeqHENS have all been tested, but the main emphasis has been on SeqHENS. Several case studies have been conducted with various features to reveal the strengths and weaknesses of each software. In order to have a good basis for comparison, cases that have gained a lot of attention in the literature were chosen.
The results from the case studies have been discussed in detail in chapter four, whilst a more executive discussion with an emphasis on overall performance for SeqHENS and AEA were given in chapter five.

The case studies revealed that AEA tends to give networks with excessive utility consumption and thereby being far from the optimal solution. SeqHENS, on the other hand, provided networks close to the optimal reported in the literature in terms of TAC, but often with a high degree of complexity. Anyway, for large scale problems (more than 20 streams), it seemed that the occurrence of combinatorial explosion in the MILP step became visible. This was surely not an issue in AEA where very complicated network structures (large number of units) were obtainable.

There are several improvement areas for SeqHENS in the future. The user-friendliness should definitely be the main focus for further development. At the moment, SeqHENS is difficult to run due to the step-wise procedure and the excessive data transfer between the different Excel files. For an experienced user, this implementation is only time-consuming, whilst for others, it might be too difficult in the sense that other software becomes preferable. In addition, there might be some implementation errors that lead to the issue that the NLP solver does not find suitable networks for some HLDs. Since SeqHENS often generates networks with a high degree of complexity, it should be possible to include a stream split penalty in the objective function, which takes care of this issue.

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Appendix A

A.1 Heat Load Distribution for Optimal Networks

This section comprises of all the HLDs for networks that have been obtained in SeqHENS. Given the HLD's makes it possible to recreate the exact same results as in this work. The numbers in all matrices correspond to a duty between the two streams(row-column connection) given in kW.

A.1.1 Case One

Table A.1: Optimal HLD for case one obtained from SeqHENS. The numbers are given in kW and indicates that two streams are integrated with a heat exchanger.

	CW	C1	C2
ST		395	
H1	315	985	
H2		1320	1080

A.1.2 Case Two

Cold stream four and five are marked with a star since they are not process or utility streams. C4* is made to make the system suitable with both hot and cold utility consumption. C5* is the HP-steam generation stream.

Table A.2: Optimal HLD for case two obtained from SeqHENS. The numbers are given in kW and indicates that two streams are integrated with each other in terms of a heat exchanger. C4* and C5* are not process streams, but included to overcome some issues related to SeqHENS.

	CW	C1	C2	C3	C4*	C5*
ST					0.5	
H1				159.7		81.7
H2	233.4					
H3	699.6					
H4	109.5					
H5		1691.0				2982.7
H6	18.0		199.0			1909.4
H7	457.6	1649.1				1979.2
H8	3181.9					
H9			99.5			547.0
H10	928.7					

A.1.3 Case Three

The first HLD is the cost-optimal 14 units network, whilst the second is the alternative network with 12 units.

Table A.3: The optimal HLD in case three obtained from SeqHENS. The numbers are given in kW and indicates that streams are integrated with each other in terms of a heat exchanger.

	CW	C1	C2	C3	C4	C5
Hot Oil		8312,5				16167,5
H1	4812,5	11687,5	5132,5			7067,5
H2				835,0		8765,0
H3	3128,6				6471,4	
H4	24258,9		3897,5	17715,0	128,6	

Table A.4: HLD for the alternative network in case three obtained from SeqHENS. The numbers are given in kW and indicates that streams are integrated with each other in terms of a heat exchanger.

	CW	C1	C2	C3	C4	C5
Hot Oil		9250,0				15230,0
H1	3350,0	9150,0	9030,0			7170,0
H2						9600,0
H3	3000,0				6600,0	
H4	25850,0	1600,0		18550,0		

A.1.4 Case Four

The first HLD is the network consisting of 14 units, while the latter is the cost-optimal network obtained in this case.

Table A.5: The HLD for the network consisting of 14 units in case four obtained from SeqHENS. The numbers are given in kW and indicates that streams are integrated with each other in terms of a heat exchanger.

	CU	C1	C2	C3	C4	C5	C6	C7
HU						5540,0		5400,0
H1		2275,0				875,0		
H2		1525,0	7200,0	875,0				
H3						3150,0		
H4	565,0					2435,0		
H5							5000,0	
H6				4375,0				
H7					4200,0			
H8	8000,0							

Table A.6: The optimal HLD for case four obtained from SeqHENS. The numbers are given in kW and indicates that streams are integrated with each other in terms of a heat exchanger.

	CU	C1	C2	C3	C4	C5	C6	C7
HU		635,0				4905,0		5400,0
H1						3150,0		
H2		1525,0	7200,0	875,0				
H3						3150,0		
H4	1360,0	1640,0						
H5							5000,0	
H6				4375,0				
H7					4200,0			
H8	7205,0					795,0		

A.2 Grid Diagram Obtained from Aspen Energy Analyzer

The grid diagram obtained from AEA optimization for the optimal solutions for case one and case two are shown in Figure (A.1) and Figure (A.2) respectively.

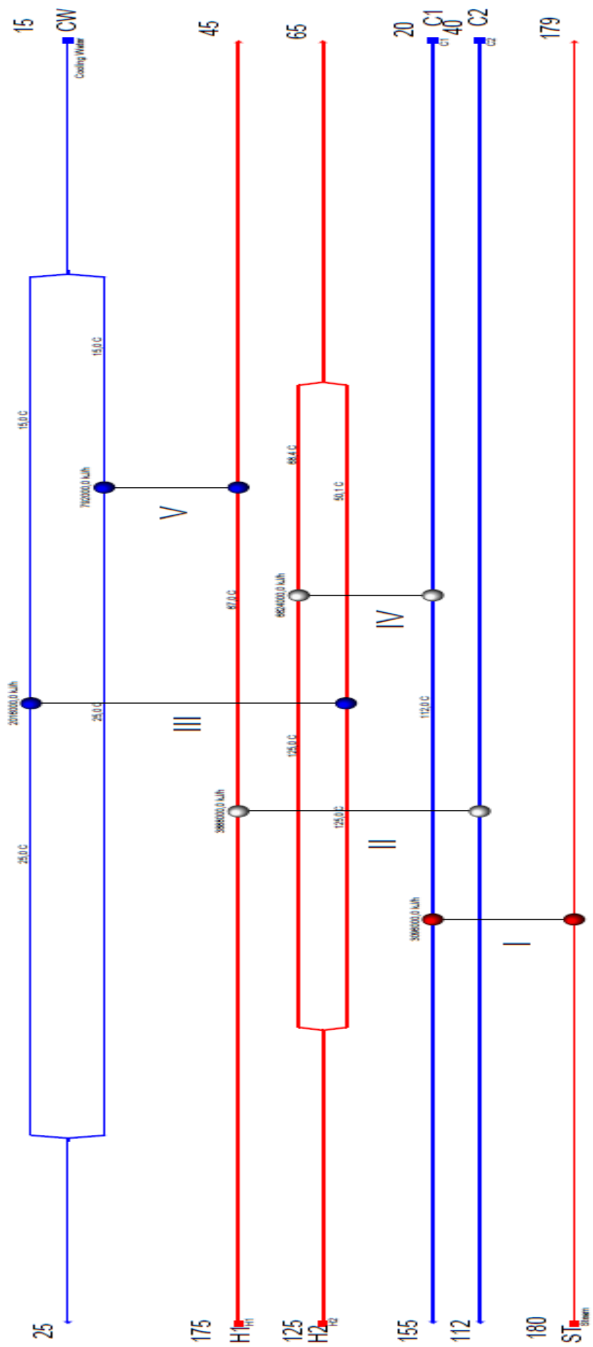

Figure A.1: Grid representation of the cost-optimal network obtained in AEA for case one.

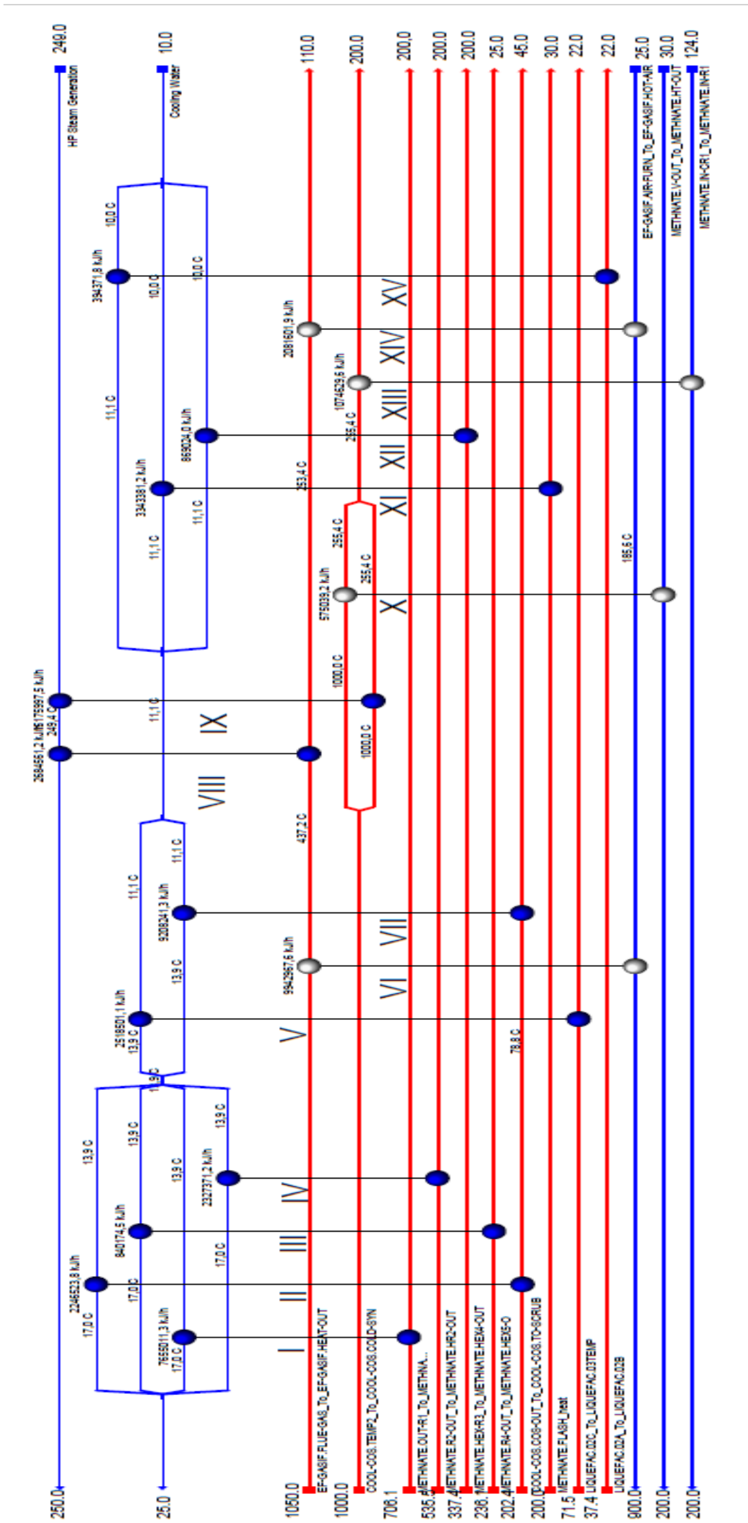

Figure A.2: Grid representation of the cost-optimal network obtained from AEA for case two.

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