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Optimization of Heat Exchanger Network using SeqHENS

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Mechanical Engeneering
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Preface

This report was written in the spring 2020 as a part of the cours TEP4905 - Master thesis in Industrial Process Engineering, in Norwegian University of Science and Technology. The main object for this project has to been to reduces the computing time in SeqHENS for complex heat exchangers networks, and develop an indicator for the difficulty for a heat exchanger network for SeqHENS. I will thank my supervisor Truls Gundersen for the opportunity to work with the field of heat exchanger network synthesis. And my co-supervisor Rahul Anantharaman for the opportunity to learn SeqHENS and with all the help with the program through this project.

Abstract

How heat exchanger networks can be set up has been researched since the 1970s. The main goal then has always been to find the most efficient configuration for transferring heat between mass streams. It began in the 1970s with pinch analysis and today there are several programs that can analyze such problems. The main focus of this project is to test one of these programs SeqHENS.

Throughout the report, SeqHENS is tested by reducing the number of temperature intervals. By doing this, the task will be to see if it is possible to reduce the calculation time for SeqHENS. The second part of the task will be to design a "Difficulty Indicator" for SeqHENS. It aims to give an indication of how difficult it is to solve a HENS problem. The results of this study discuss based on three factors, the cost related to the results, calculate the time when the number of temperature intervals is reduced, and any errors that occurs in the results when the number of temperature intervals is reduced.

During this study, four different "Difficulty Indicator" will be tested on the different cases in the study and compared to how good the indication they give for calculation time in SeqHENS.

The results from the case study show that the number of possible matches gives a good indication of how long the time of SeqHENS will be, and the results also show that by reducing the number of temperature intervals this will reduce the quality of the results and in fact increase the time in most circumstances.

Sammendrag

Hvordan varmeveksler nettverk kan settes opp har vært forsket på siden 1970 tallet. Hovedmålet har da alltid vært å finne en mest mulig effektiv konfigurasjon for å overføre varme mellom massestrømmer. Det begynte på 1970 tallet med pinch analyse og i dag finnes det flere programmer som kan analysere slike problemer. Dette prosjektet skal har som hovedfokus å teste et av disse programmene SeqHENS.

Gjennom rapporten blir SeqHENS tested ved å redusere antallet temperatur intervaller. Ved å gjøre dette skal oppgaven se om det er mulig å redusere regnetiden til SeqHENS. Den andre delen av oppgaven vil være å utforme en "Difficulty Indicator" for SeqHENS. Den skal ha som mål å gi en indikasjon på hvor vanskelig det er å løse et "HENS»-problem. Resultatene fra denne studien diskuterer ut fra tre faktorer, kostnaden relaterte til resultatene, regne tiden når antallet temperatur intervaller blir redusert og eventuelle feil som oppstår i resultatene når antallet temperatur intervaller blir redusert.

Under denne studien vil fire forskjellige "Difficulty Indicator" bli testet på de forskjellige casene i studien og sammenlignet etter hvor god indikasjon de gir for regne tiden til SeqHENS.

Resultatene fra case studiet viser at antallet mulige matcher gir en god indikasjon på hvor lang regne tiden til SeqHENS vil være. Resultatene viser også at ved å redusere antallet temperatur intervaller vil dette redusere kvaliteten på resultantene, og faktisk øke regne tiden under de fleste omstendigheter.

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1 Introduction

1.1 Background

Process integration has been around since the 1970s [7]. It started with pinch analyses during the oil crises with the goal of reducing consumption of sources or reduce emissions to the surroundings. From the 1970s to today almost all sectors of industry's has used heat integration technology to improve the efficiency of plants. This can both increase the profit when external sources are reduces, and at the same time it tends to reduce emissions from the process [7].

During the last 40 years interest in heat integration has never been lost by researches, and it has actually flourished. But main objective has changes from the 1970s where the objective was to save energy during the high energy prices to now focusing on that fact that increasing the efficiency can play a key role in helping industry become more climate friendly.

Mathematical programming in process integration started with three different concepts. The concepts were based on heuristics, thermodynamics's and mathematically programming. In later year most of the main focus has been abound thermodynamics's and mathematically programming. When the development of sequential procedure for heat exchanger network synthesis stared mathematically programming got the attention and was the main focus [7]. The sequential procedure has three steps. First find the utility energy consumption, the find the minimum number of heat exchangers and finally find the solution with the lowest area cost for the network. After this the simultaneous NLP, MINLP models was develop. These models do not use pinch temperature and heat recovery approach temperature in the same way as sequential procedure, but a superstructure for each stream.

Heat exchanger network synthesis can be viewed as a tradeoff between investment cost and operation cost. This is because with a high investment cost the process will have a low operation cost and vica versa. This is because it consists of a three-way tradeoff between heat exchanger area, energy consumption and the number of units with the goal to reduce the total cost for the process.

1.2 Motivation

Climate change is one of the biggest challenges facing our generation. The evidence that human activities has affected climate change has only increased the last years [1]. And about half of the cumulative CO_2 emissions from humans between 1750 (pre-industrial era) and 2011 have occurred the last 40 years (1970 to 2010). And in that period CO_2 emissions from industrial processes has contributed about 30% of the increase of the total greenhouse gass (GHG) emission.[1]. And as we can see in Figure 1 industry direct and indirect stand for around 32% of the CO_2 emissions in 2010.

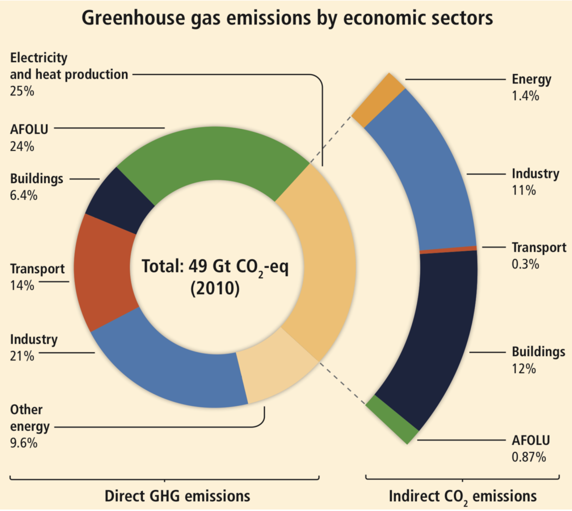


Figure 1: Greenhouse gas emissions by economic sectors in 2010 [1]

In the sustainable development goals from the United Nations which aims to eradicate poverty, fight inequality and stop climate change by 2030 [8]. It is stated that we have to make the production process more efficient to get more out of our sources. If we are going to cut the emissions and use our energy sources in a more efficient way in the industry heat integration can play a key role. Heat integration eliminate unnecessary external heating and cooling in process by using available energy sources, and thus increase the efficiency of the plant. By increasing the efficiency in a plant need for external energy will by reduced and thus reduce the emissions related to the production. This can be done in both existing plant and new plants in the future.

1.3 Objectives

SeqHENS is a software for design and optimization of heat exchanger networks in the conceptual design phase. It is based on a clever combination of Pinch Analysis and Mathematical Programming. SeqHENS is based on the idea of a sequential framework where the original design problem, which is a Mixed Integer Non-Linear Programming (MINLP) problem, is broken down into smaller, more manageable sub-problems that are solved in sequence and in an iterative fashion through loops that focus on the three main cost elements in heat exchanger networks, i.e. energy consumption, number of heat exchangers (units) and total heat transfer area.

The two main challenges when using SeqHENS are (1) the combinatorial explosion caused by the binary variables in the Mixed Integer Linear Programming (MILP) models for finding the fewest number of units and identifying matches between hot and cold streams that would have the prospect of minimizing heat transfer area, and (2) the issue of being trapped in local optima caused by the non-linear and non-convex nature of the model equations for the physical system (heat exchangers) and economy (cost equations for equipment).

While challenge (2) is serious but can be mitigated by using multi-start procedures, challenge (1) will be the focus of this master project. Experience has shown that the difficulty in solving these MILP problems ranges from minutes to days for problems of similar size (i.e. the number of process streams considered). There are two main objectives of this master thesis: (a) to identify a complexity indicator that could give a measure of how complicated it will be to solve the problem at hand, and (b) to test the effect of using a simpler procedure for setting up the temperature intervals for the matching MILP.

More specifically, objective (a) should use information available in the stream data, such as number of hot and cold streams to be integrated, feasibility of heat exchange based on temperature information, as well as considerations of heat duty of the potential stream matches. Objective (b) should compare the quality of the Heat Load Distributions (HLDs) that are produced by the matching MILP when using different (and simpler) strategies for setting up the temperature intervals.

1.4 Thesis Structures and Guidelines

This thesis contains of seven chapter's.

Chapter 2 presents the thermodynamic Background and the theory for pinch analyses used in case studies in Chapter 5.

Chapter 3 presents the Background for heat exchangers network synthesis which SeqHENS is built one.

Chapter 4 Four different candidates for a Difficulty Indicator is presented based on the background presented in Chapter 3, which will be tested in the Case Study in 5.

Chapter 5 presents three cases studies. First the stream and cost data is presented with all the assumptions for the case. Then the minimum number of possible matches is presented. The composite curve with heating and cooling demand is presented. Then the Minimum Number of Units sub-problem is presented, with the minimum number of units from SeqHENS. After this the Stream Match Generator sub-problem is presented. In this section the number of temperature intervals and the corresponding solution times are presented. From the results given by the Stream Match Generator sub-problem the Total Annualized Cost, and the difficulty Indicator is presented. Finally this chapter ends with a discussion around the results from SeqHENS.

Chapter 6 presents a overall discussion for the case study that contains, SeqHENS results in general, the results from SeqHENS with regards to the reduction of temperature intervals, and the difficulty indicator is discussed.

Chapter 7 presents the conclusion based on Chapter 6 for the case study. And the presents future work for HENS with an focus on future development on SeqHENS.

2 Thermodynamic Background

2.1 Heat Exchange

In heat exchanger networks the most common way to transport heat is by indirect heat transfer. When using indirect heat transfer, this is typically done by a heat exchanger. The most common heat exchangers used are co-current (Figure 2) and counter-current (Figure 3) heat exchangers or a combination of them. When transferring heat in a heat exchanger we need a heat source and a heat sink. A cold stream is defined as a stream that requires heating (heat sink). Similarly, a hot stream is defined as a stream that needs cooling (heat source) [9].

2.2 Heat Transfer in Heat Exchangers

In a heat exchanger network, the task is to change the energy level of the streams. Energy is exchanged by heat transfer from the hot stream to the cold stream in heat exchangers. The heat transferred in a heat exchanger is calculated by Equation 2.1 and 2.2.

$$\dot{Q} = \dot{m}C_p * \Delta T \tag{2.1}$$

In Equation 2.1, $\dot{Q}$ is the heat transfer in kW, $\dot{m}C_p$ is the heat capacity flowrate in kW/K and ΔT is the temperature change in K for the stream.

$$\dot{Q} = A * U * F_T * \Delta T_{LM} \tag{2.2}$$

In Equation 2.2, A is the area in m^2, U is the heat transfer coefficient in kW/(m^2*K), F_T is the correction factor ($0 < F_T \leq 1$) and ΔT_{LM} is the logarithmic mean temperature difference in K.
In this project we are going to use $F_T = 1$ in the calculations. A simplified formula for the heat transfer coefficient is provided by Equation 2.3. The logarithmic mean temperature difference (LMTD) is calculated by Equation 2.4.

$$\frac{1}{U} = \frac{1}{h_{cold}} + \frac{1}{h_{hot}} \tag{2.3}$$

In Equation 2.3, h_{cold} is the film heat transfer coefficient for the cold stream and h_{hot} is the film heat transfer coefficient for the hot stream, both in kW/(m^2*K).

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{ln(\frac{\Delta T_1}{\Delta T_2})} \tag{2.4}$$

The calculating of ΔT_1 and ΔT_2 for the LMDT it is different for co-current- and counter-current heat exchangers. The expressions for a co-current heat exchanger are provided Equation 2.5 and 2.6. For a counter-current heat exchanger, Equation 2.7 and 2.8 can be used.

$$\Delta T_1 = T_{h,in} - T_{c,in} \tag{2.5}$$

$$\Delta T_2 = T_{h,out} - T_{c,out} \tag{2.6}$$

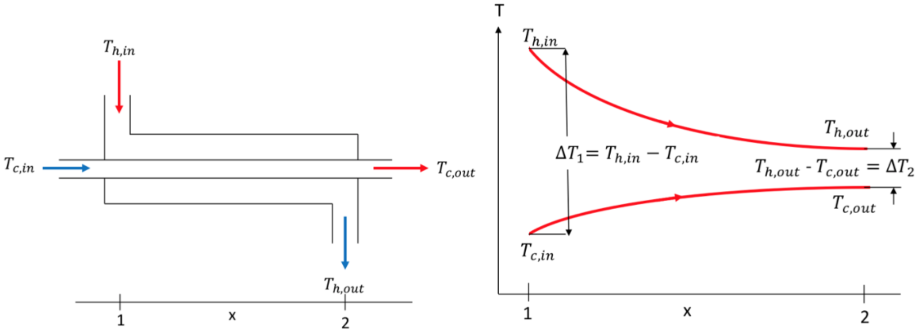


Figure 2: Co-current heat exchanger [2]

$$\Delta T_1 = T_{h,in} - T_{c,out} \tag{2.7}$$

$$\Delta T_2 = T_{h,out} - T_{c,in} \tag{2.8}$$

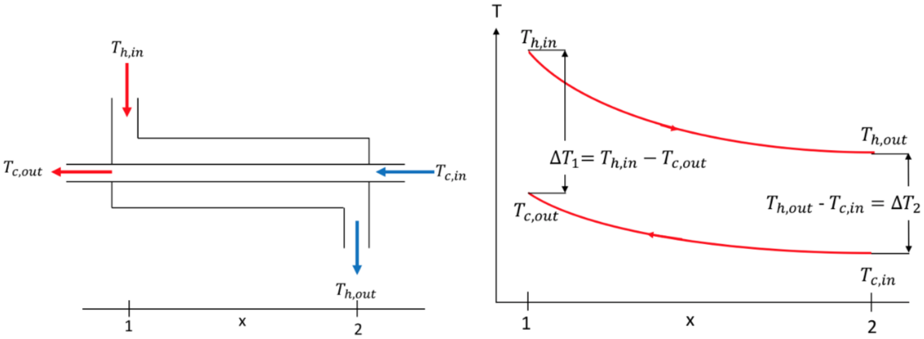


Figure 3: Counter-current heat exchanger [2]

In some cases ΔT_1 equals ΔT_2. This will make ΔT_{LM} impossible to solve by using Equation 2.4. This problem is solved by using Equation 2.9.

$$\Delta T_{LM} = \Delta T_1 = \Delta T_2 \tag{2.9}$$

2.2.1 Heat Transfer Area

When calculating the heat exchanger area, we use Equation 2.10. Equation 2.10 is derived from Equation 2.2, with $F_T = 1$. The heat exchanger area is in m^2.

$$A = \frac{\dot{Q}}{U * \Delta T_{LM}} \tag{2.10}$$

2.3 Pinch Analyses

2.3.1 Composite Curves

When handling multiple stream problems, we add together the heat capacity flowrates over a given temperature interval. In that way we can produce a single Composite Curve (CC) for the hot streams and for the cold streams in a temperature-enthalpy diagram as shown in Figure 4 [9]. For heat to be exchanged, the hot stream always has to be warmer than the cold stream at all points. At the point where temperatures for the hot and cold Composite Curves are closest is called pinch point, and the temperature difference is called the Heat Recovery Approach Temperature (HRAT) or ΔT_{min}. In the region where the two Composite Curves are overlapping on the enthalpy axis, heat can be transferred from the hot streams to the cold streams [3]. This is the heat recovery potential for the heat exchanger network $\dot{Q}_{REC}$. In the region where the cold Composite Curve does not overlap with the hot Composite Curve, it needs to be heated by hot utilities $\dot{Q}_{HU,min}$. In the region where the hot Composite Curve does not overlap with the cold Composite Curve, it needs to be cooled by cold utilities $\dot{Q}_{CU,min}$

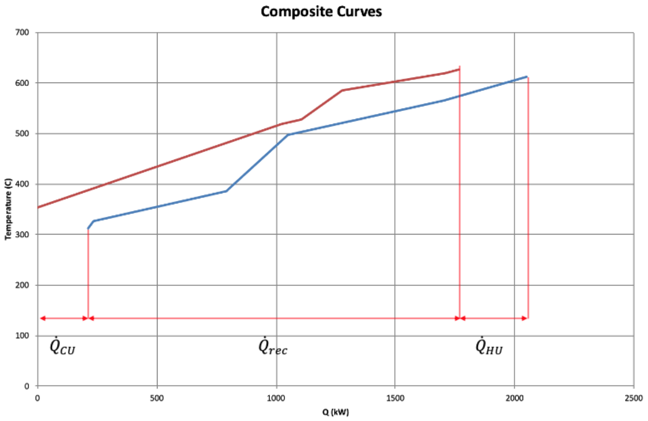


Figure 4: Composite curves for hot and cold streams in an enthalpy-temperature diagram for Case One.

2.3.2 Grand Composite Curve

The Grand Composite Curve (GCC) gives the same information as the Composite Curves and the problem table algorithm, but in the Grand Composite Curve we can more clearly see the hot and cold utilities.

In the construction of the Composite Curve we could see how enthalpy intervals were set up based on the supply and target temperatures. This was done separately for the hot and cold streams in the composite curve. The same can be done for both the cold- and hot streams in the grand composite curves [9]

When constructing a single curve, we need to change the temperatures for the streams. This new temperature is called the shifted temperature. The shifted temperature for the hot streams is calculated with Equation 2.11 and for the cold streams Equation 2.12 [9].

$$T^*_{H,i} = T_{H,i} - \frac{1}{2} * \Delta T_{min} \tag{2.11}$$

$$T^*_{C,j} = T_{C,j} + \frac{1}{2} * \Delta T_{min} \tag{2.12}$$

Where $T^*_{H,i}$ and $T^*_{C,j}$ are the shifted temperature for the hot or cold streams i or j and $T_{H,i}$ and $T_{C,j}$ is the actual temperature for the hot or cold stream i or j.

The change in enthalpy through the temperature intervals is calculated from Equation 2.13 [3].

$$\Delta H_k = \left[\sum_{cold\,streams} (\dot{m}C_{p,c}) - \sum_{hot\,streams} (\dot{m}C_{p,h}) \right] * \Delta T_i \tag{2.13}$$

where ΔH_i is the change in enthalpy for temperature interval k with temperature span ΔT_i.

2.3.3 Pinch Temperature and Heat Recovery

By using pinch analyses, we can divide the composite curve into two separate systems. The composite curve will be dived at the pinch point because this is where the driving forces are at a minimum. The system above the pinch point will function as a heat sink and will absorb heat from the hot utilities. The system below the pinch point will function as a heat source, and have heat removed by the cold utilities. When using this methodology, heat transfer across the pinch point is avioded. Otherwise heat transfer across the pinch will increase Q_{HU} and Q_{CU} by XP as shown in Figure **??** a). Since the system above the pinch point is defined as a heat sink one should not use cold utilities above the pinch point. This will increase Q_{HU} by XP as shown in Figure 5 b). Since the system below the pinch point is defined as a heat source one should not use hot utilities below the pinch point. This will increase Q_{CU} by XP as shown in Figure 5 c).

2.4 Number of Heat Exchangers

When starting a case in SeqHENS we need the minimum number of heat exchangers. When calculating the minimum number of heat exchangers we assume zero loops, and set the number of

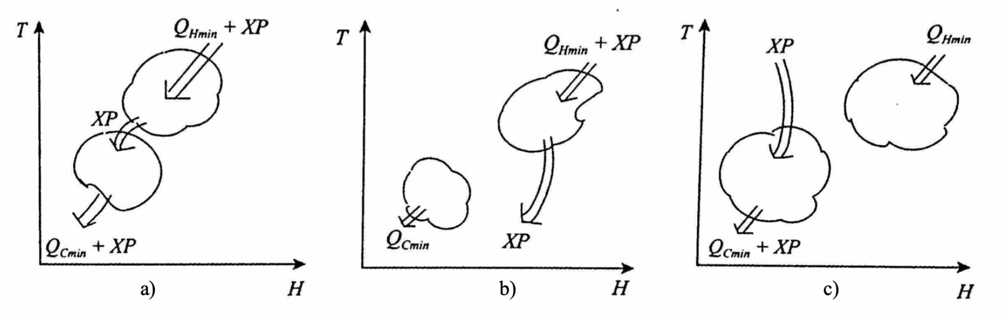


Figure 5: Three forms of cross pinch heat transfer [3].

subgraphs to one in Equation 2.14 (Euler's Rule from graph theory). This gives that the minimum number of heat exchangers is the number of streams including the utilities minus one if we don't know the pinch temperature.

$$E = N + L - S \tag{2.14}$$

Where E is the edges, N is the nodes, L is the loops and S is the subgraphs.

$$U_{min} = N - 1 \tag{2.15}$$

where U_{min} is the minimum number of heat exchangers and N is the number of hot- and cold streams including utilities. In this work we are going to use Equation 2.15 when calculating the minimum number of heat exchangers.

2.5 Heat exchangers Network Economics

In this project we are going to compare different SeqHENS results. The comparison is done with Total Annualized Cost (TAC) for the heat exchanger network. The TAC is obtained from the Capital Cost and Operating Cost.

2.5.1 Operating Cost

The Operating Cost is the cost related to utility cost for the heat exchangers network. In this project we will look at the Operating Cost related to the heating and cooling demand from external utilities.

$$C_O = C_{HU} * \dot{Q}_{HU} + C_{CU} * \dot{Q}_{CU} \tag{2.16}$$

where the C_O is the Operating Cost given in \$/year, C_{HU} is the cost of heating in \$/(kW*year), $\dot{Q}_{HU}$ is heating demand in kW, C_{CU} is the cost of cooling in \$/(kW*year) and $\dot{Q}_{CU}$ is cooling demand in kW.

2.5.2 Capital Cost

The Capital Cost is the investment cost for the heat exchanger network. In this thesis we will look at the investment cost related to the heat exchanger area.

$$C_E = C_C + C_B * A^M \tag{2.17}$$

where C_E is the Equipment cost given in \$/year, C_C is starting cost not dependent on the area given \$, C_B is a cost factor given in \$/(m^2), A is the heat exchanger area in m^2 and M is an exponent representing economy of scale. This Equation has to be calculated for each heat exchanger in the network.

2.5.3 Total Annualized Cost

The Total Annualized Cost is the total cost per year of the heat exchanger network. It is the Operating Cost plus the Capital Cost.

$$TAC = C_E + C_O \tag{2.18}$$

Where the TAC is the Total Annualized Cost in \$/year.

3 Optimization Background and SeqHENS

Solving a Heat Exchanger Network Synthesis (HENS) problem involves a trade-off between energy (E), area (A) and number of units (U) with a goal of achieving the lowest possible total annualized cost. Energy that must be supplied or removed from the system is done with hot or cold utilities. If little energy is recovered from the network, the system will have a low area or few units and vice versa. If the network has many heat exchangers, the area will be reduced by optimizing the driving forces. As we can see from Equation 2.17, the heat exchanger will have a starting cost that does not change with the area. Therefore, costs can increase with a high number of units even if the area is low. Which solution is optimal will vary with the costs associated with hot and cold utilities, costs associated with the area and units.

In heat exchanger network optimization the two main approaches are with Sequential Synthesis and Simultaneous Synthesis. The main difference between the two approaches is that when using Sequential Synthesis, the problem is dived into more manageable sub-problems. This makes the problem easier to solve. In simultaneous synthesis all three trade-offs are taken into account simultaneously. This can give a better solution, but the computing requirements are increased [6].

3.1 Sequential Synthesis

In Sequential Synthesis the problem is divided into sub-problems that are solved in sequence. First we find minimum utility cost, then find the solution with the lowest number of units for the given utility consumption. After this we find lowest area for different networks with the given number of heat exchangers. Then the capital cost for the given area is calculate[6]. Then increase the number of units, and compare the capital cost for different number of units. Then increase the utility cost, this is done by increasing the HRAT. From this compare the total annual cost for different HRAT.

1. Find minimum utility cost (E)
2. Find minimum number of units (U)
3. Find the lowest capital cost (Calculated from A)

The minimum utility cost is solved as a Linear Programming Problem (LP problem) with the HRAT as parameter [6]. When finding the matches between cold and hot streams solve this as Mixed Integer Linear Programming (MILP) transshipment problem is solved [6] with the number of units as the parameter. The cold and hot utilities are treated as cold and hot streams. When solving this problem the total network can be divided into sub-networks and solved independently for each sub-network or it can be solved simultaneously for the network. The solution from the MILP problem will then indicate matches that take place as shown in Equation 3.1 and the heat transfer for each match [6]. When having this information we can make a network from the different possible matches. When solving this, we can have more that one solution from the MILP problem duty.

$$y_{i,j} = \begin{cases} 1 & \text{if match between i and j.} \\ 0 & \text{otherwise.} \end{cases} \tag{3.1}$$

Where i is the hot stream that matches with cold stream j.

When the network is generated from the MILP model, a superstructure for each stream is generated [6]. The superstructure gives information on stream splits and heat duties for each stream and its heat exchanger. From the superstructure, the stream matches can be derived. In Figure 6 some the possible solutions for a three stream problem is shown, and Figure 10 shows the superstructure with the variables. From the temperatures and heat duties given by the superstructure the capital cost can be derived.

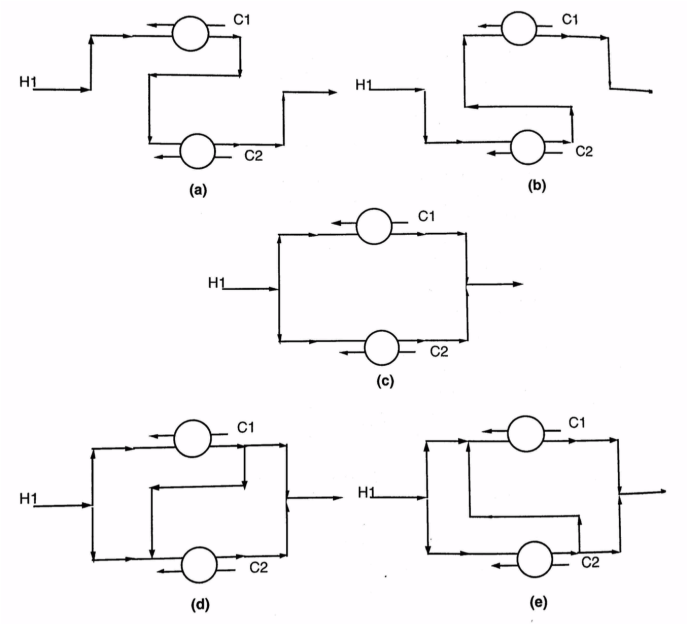


Figure 6: Some possible solutions for a three stream problem (One hot and two cold streams) [4]

3.2 Simultaneous Synthesis

Simultaneous synthesis is preformed as a Mixed Integer Non-Linear programming (MINLP) model on a different superstructure than in sequential synthesis [6]. MINLP model is a used in problems where it is necessary to simultaneously optimize the system structure and the parameters [10]. This makes the MINLP problems difficult to solve because they combine Mixed Integer Programming (MIP) and Non-Linear Programming (NLP) [10]. The superstructure used solving MINLP problems is based on a stage-wise superstructure where matches between any pair of hot and cold streams can occur [6]. In each stage all streams are split into a number of branches that is equal to the number of opposite type streams. It is assumed that the mixing of stream branches is isothermal. In Figure 7 we can see a superstructure for a MINLP problem.

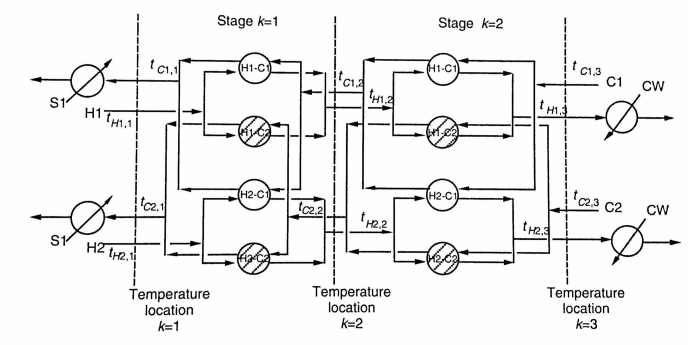


Figure 7: Superstructure for a MINLP problem with two stages [4]

3.3 SeqHENS

This section will discuss SeqHENS, and will manly focus on the background needed for the cases study. Most of the text is from the doctor thesis by Rahul Anantharaman [5]. When using a simultaneous synthesis to solve industrial sized problems the needs of the industry is not met with today's computing power and optimization technology. SeqHENS is a sequential framework for solving these types of problems with the main objective to find a near optimal solution. SeqHENS is a compromise between pinch analyses and simultaneous (MINPL) models. The problem is divided into four sub-problems and solved sequentially as listed below and shown in Figure 8 [4].

1. Establishing minimum Energy consumption (LP)
2. Determining minimum number of units (MILP)
3. Finding sets of matches and corresponding Heat Load Distribution (HLD) from a MILP
4. Network generation and optimization (NLP)

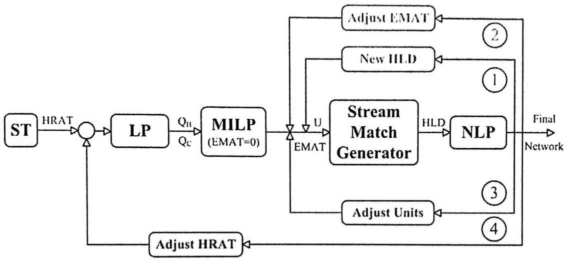


Figure 8: The sequential framework for SeqHENS [5]

3.3.1 Minimum Energy Consumption

The minimum energy consumption is the energy consumption from the utilities. The utility targeting is done by using a transshipment model based on model presented by Papoulias and Grossmann [11] and extended to include multiple utilities [5]. Using HRAT as an variable we can find the minimum hot and cold utilities.

3.3.2 Minimum Number of Units

The Minimum Number Units is an important step in finding the optimal solution for a network in HENS. It was identified that the number of units was the was the most important contributors to the networks total annualized cost, because the total heat exchanger area for different solutions is often similar.

When finding the Minimum Number of heat exchangers SeqHENS needs:

1. a set H of hot process streams and hot utilities
2. a set C of cold process streams and cold utilities
3. supply and target temperature, heat capacities and flow rate
4. temperatures or temperature ranges and fixed heat load of the utilities
5. Exchanger Minimum Approach Temperature (EMAT) set to zero

The first step, and the focus in this section is to calculate the minimum number of matches between the hot process streams and utilities with the cold process streams and utilities. Heating and cooling requirements for each stream from section 3.3.1 are the parameters for this calculation.

EMAT is set to zero in the Sequential Framework to determine the absolute minimum number of units for a given level of heat recovery.

The minimum number of unit's sub-problem is formulated as an MILP transshipment problem based on the model presented by Papoulias and Grossmann [11], but the model used in SeqHENS differs from Papoulias and Grossmann since no it has no pinch decomposition in the network.

When finding the number of possible matches is a network. And to find the possible number of matches the following procedure is done. H is all sets of all hot streams and utilities, and C is all sets cold streams and utilities. HP and CP are the sets of hot and cold process streams. HU and CU are the hot and cold utilities. The temperature range for the network is dived into K temperature intervals based on the inlet temperature. The interval with the highest temperature level is set to be $k = 1$, and goes down to the lowest temperature level with $k = K$. The heat load from hot streams or utilities i in temperature interval k is $\dot{Q}^H_{ik}$, and for cold streams or utilities j in temperature interval k is $\dot{Q}^C_{jk}$. The binary variable $y_{i,j}$ is the denotes if it is a possible match between hot stream or utility i with cold stream or utility j. If it is a possible match between the two streams or utilities $y_{i,j} = 1$, and if not $y_{i,j} = 0$.

$$minz = \sum_{i \epsilon H} \sum_{j \epsilon C} y_{i,j} \tag{3.2}$$

where $minz$ is the number of possible matches between hot process stream or utility i and cold

process stream or utility j.
When the number of streams increases, the MILP formulation for this sub-problem becomes hard and can be impossible to solve due to the combinatorial explosion. As the number of streams increases the binary tree increases exponentially and the time required to solve the problem will also increases exponentially. It was found that this problem usually happens in more than 20 streams. It was found that the number of streams does not necessarily results in prohibitive solution time. This is due to the fact that a set of hot and cold process streams can have process streams where matches between them is not possible due to thermodynamic limitations. This is illustrated in Figure 9 where it is not possible to transfer heat between H2 and C2, and thus the number of possible matches is reduced compare with cases where all streams can exchanges heat between them. This effect will be even bigger if the number of streams increases, and the number of streams where heat transfer cannot happen increases.

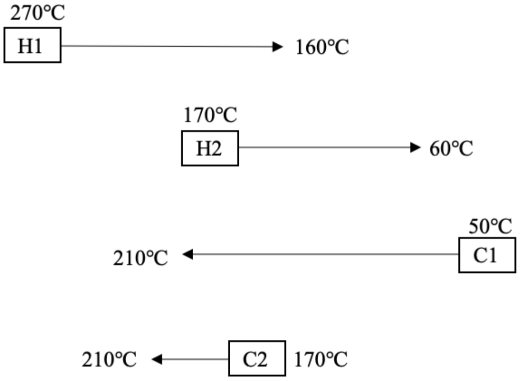


Figure 9: Stream data where heat transfer is not possible between all streams

The number of streams, and the possible number of matches between then are important characteristics in an optimization problem. The number of streams will not directly increase the solution time, but the number of possible matches usually increase and thus increases the solution time. This is an important characteristic when the solution time increases exponentially, even the best algorithms can end op useless.

3.3.3 Stream Match Generator

In this sub-problem the stream match generator makes the heat load distribution for the given energy target and the number of units. The objective here is to minimize the total annualized cost for the network. This is done by minimize the heat transfer area for the network within the specified level of heat recovery and the number of units [5]. One of the most important steps in the Stream Match Generator is the creation of temperature intervals. The smaller the size of the temperature intervals, the better “pseudo-area” represent the actual area. When the size of the temperature intervals becomes small the number of temperature intervals will increase, and thus increase the calculation time. This can be a problem for bigger cases. For this reasons SeqHENS uses four levels of temperature intervals and they are constructed the following way:

1. Establish the balanced composite curve, using HRAT, stream and utility data.
2. Supply and target temperatures of all streams, including utility streams, are set to be the Primary Hot/Cold Temperatures.
3. For all cold supply and target temperature, find adjacent hot temperature placed vertically above the kinks of the cold composite curve. These are the Secondary Hot Temperature. similarly, for all the hot supply and target temperature, find adjacent cold temperatures placed vertically bellow the kinks of the composite curve. These are the Secondary Cold Temperatures.
4. For all cold supply temperatures, find the corresponding Tertiary Temperatures by adding EMAT. Disregard any hot temperatures that is colder than the coldest target temperature. Similarly, for all hot supply temperatures, find the corresponding Tertiary Cold Temperatures by subtracting EMAT. Disregard any cold temperatures that is warmer than the coldest target temperature.
5. Quaternary Hot/cold temperatures are calculated by adding/subtracting EMAT to/from the Secondary Cold/hot Temperatures.
6. The Hot/Cold temperatures from Steps 2 to 5 are merged. They are then sorted and duplicated temperatures removed to give the corresponding hot and cold temperature intervals.

The problem with this procedure is that it can give a lot of temperature intervals when the number of streams increase, as shown in Table 1. This will make the MILP formulation for the Streams Match Generator hard and eventually impossible to solve due to "combinatorial explosion". This will eventually make the solution time in SeqHENS to large. This project will try to reduce the number of temperature intervals by removing the quaternary and tertiary temperature intervals.

TI Generation method	Number of hot TI's	Number of cold TI's
Secondary	39	39
Tertiary	59	61
Quaternary	75	77

Table 1: Temperature intervals for case 21TP1

In the Stream Match Generator the procedure has to try all different solution with the possible matches within the network. This will increase the solution time, the same way as in section 3.3.2. With the procedure in this transcript it is possible to get matches with very little heat transfer. This will give to problems within the program. The first one is that it can have a high number of possible matches thus resulting in a long solution time. The second problem with this is not always realistic for industry sized plants with heat exchangers with a very little heat transfer. That's why this study are going to test if it is possible to reduce the number of possible matches between streams. This are going to be done by adding a constraint to Equation 3.3, where the possible amount of heat has a minimum requirement. If this the possible heat transfer between the streams is smaller than the requirements this step will change U_{ij} to zero as seen in Equations 3.4 and 3.5. The minimum requirement value for heat exchanges between streams is set separately for each case.

$$U_{ij} = min\{\sum_{k\epsilon TI} \dot{Q}_{ik}^{H}, \sum_{k\epsilon TI} Q_{jk}^{C}, max[min(\dot{m}Cp_{i}^{H}, \dot{m}Cp_{j}^{\dot{C}}) * (T_{s,i}^{H} - T_{s,j}^{C} \breve{} EMAT), 0]\} \tag{3.3}$$

$$U_{ij} = U_{ij,old} \quad \text{if} \quad U_{ij,old} \geq \dot{Q}_{ij,min} \tag{3.4}$$

$$U_{ij} = 0 \quad \text{if} \quad U_{ij,old} < \dot{Q}_{ij,min} \tag{3.5}$$

3.3.4 Network generation and optimization

This sub-problem generates a cost optimum for the heat exchanger network from the given set of heat load distributions. It is formulated as an NLP problem and does not include EMAT or HRAT [**?**]. The results from this sub-problem is a superstructure for each stream. These superstructure needs to be combined by hand to construct the heat exchanger network. Figure 10 shows the superstructure for a stream with two heat exchangers.

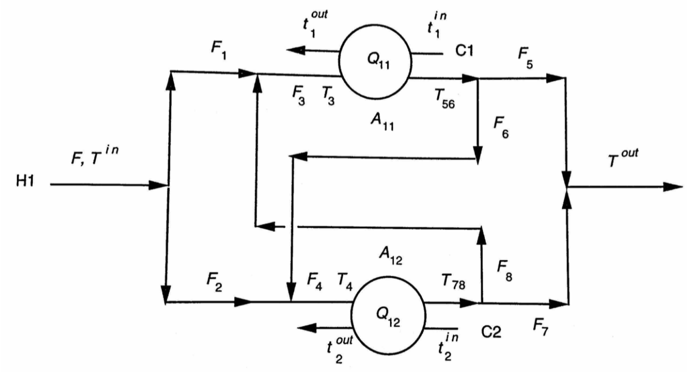


Figure 10: Superstructure with all variables for a stream with two heat exchangers [6]

4 Difficulty Indicator

4.1 Difficulty Indicator Background

In this project we are going to look at how difficult it is to find a solution in SeqHENS and we are going to use solution time as parameters to compare the cases. From Chapter 3 the number of temperature intervals and the number of possible matches is presented as the main factors for the increase in calculation time. The first one is the time SeqHENS uses to solve the cases, and the other one is the number of possible matches. And it is these two parameters that the difficulty indicator will include. The objective for the difficulty indicator will be to give a indication for how difficult a set of streams is to solve for SeqHENS. To obtain an accurate measurement of this, four different difficulty indicators will be tested with different weighting between the number of possible matches, the number of stream and the number of temperature intervals in the case study and be compared in the discussion. The number of streams is related to the number of temperature intervals, but this can be calculated without entering the stream data into SeqHENS. The four different Difficulty Indicators is presented in the next section.

4.2 Difficulty Indicators

$$DI1 = N_{matches} + N_{streams} \tag{4.1}$$

$$DI2 = N_{matches} + N_{TI,hot} + N_{TI,cold} \tag{4.2}$$

$$DI3 = N_{matches} * N_{streams} \tag{4.3}$$

$$DI4 = N_{matches}^2 + N_{TI,hot} + N_{TI,cold} \tag{4.4}$$

Where $N_{matches}$ is the number of possible matches, $N_{TI,hot}$ is the number of hot temperature intervals, $N_{TI,cold}$ is the number of cold temperature intervals and $N_{streams}$ is the number of streams.

5 Case Studies

5.1 Case One - 7TP1

5.1.1 Stream Data

Stream	$T_{supply}[K]$	$T_{target}[K]$	$\dot{m}C_p[kW/K]$	h [kW/(m^2*K)]	$\Delta H[kW]$
H1	626.0	586.0	9.802	1.25	392.080
H2	620.0	519.0	2.931	0.05	296.031
H3	528.0	353.0	6.161	3.20	1078.175
C1	497.0	613.0	7.179	0.65	834.852
C2	389.0	576.0	0.641	0.25	119.867
C3	326.0	386.0	7.627	0.33	457.62
C4	313.0	566.0	1.690	3.20	427.57
HU	650	650	—	3.50	—
CU	293	308	—	3.50	—

Table 2: Stream data case one

Cost of Heat Exchangers ($): $8,600.0 + 670(Area)^{0,83}$
Cost of Cooling Utility ($): $20 * \dot{Q}_{CU}$
Cost of Heating Utility ($): $200 * \dot{Q}_{HU}$

5.1.2 Possible Number of Matches

In this case, the number of possible matches is the same for EMAT1, 2 and 3 (2,5K, 5K and 10K). From Table 3 $min\ Z$ equals 19.

	C1	C2	C3	C4	CU
H1	1	1	1	1	1
H2	1	1	1	1	1
H3	1	1	1	1	1
HU	1	1	1	1	0

Table 3: Possible Matches between streams

5.1.3 Minimum Energy Consumption Sub-problem

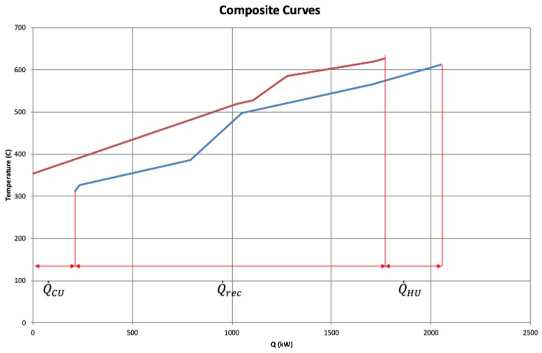


Figure 11: Composite Curve for 7TP1

Figure 11 shows the Composite Curve for 7TP1 with Heat Recovery Approach Temperature (HRAT) at 25K. The result from Minimum Energy Consumption in SeqHENS gives $\dot{Q}_{HU}$ at 287.73 kW, $\dot{Q}_{HU}$ at 212.19 kW and $\dot{Q}_{rec}$ at 2050.02 kW.

5.1.4 Minimum Number of Units Sub-problem

In this case the first loop for the Stream Match Generator Sub-problem will be with the minimum number of units, and for each loop the number of units will increase by one. From Equation 2.15 the minimum number of units is 8. The results from the Minimum Number of Units sub-problems also give us 8 heat exchangers, for the minimum number of units.

5.1.5 Stream Match Generator Sub-problem

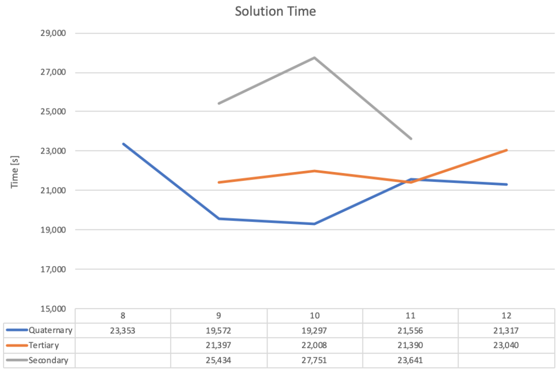
When testing the Stream Match Generator Sub-problem, this study will try to decrease the number of temperature intervals (TI) as discussed in Section 3.3.3. This will be done by first running the case through SeqHENS with four levels of temperature intervals, then with three levels of temperature intervals, and two levels of temperature intervals. The results from this test will be compared by using solution time, total annualized cost and errors in the results due to the removal of temperature intervals.

TI Generation method	Number of hot TI's	Number of cold TI's
Secondary	14	15
Tertiary	20	19
Quaternary	24	23

Table 4: Temperature intervals for case 7TP1

The number of temperature intervals in each case is shown in Table 10. The number of hot and cold temperature intervals is reduced from 24/23 with Quaternary temperature intervals to 14/15 with Secondary temperature intervals. Solution time for the Stream Match Generator sub-problem

is calculated from the average of EMAT 1,2 and 3 for each number of heat exchangers, starting with the minimum number of units. In some cases, SeqHENS did not find any solution, in these cases the time is removed from the calculation, thus the average time from EMAT 1,2 and 3 with solutions. The solution time for the Stream Match Generator sub-problem is plotted in Figure 12.

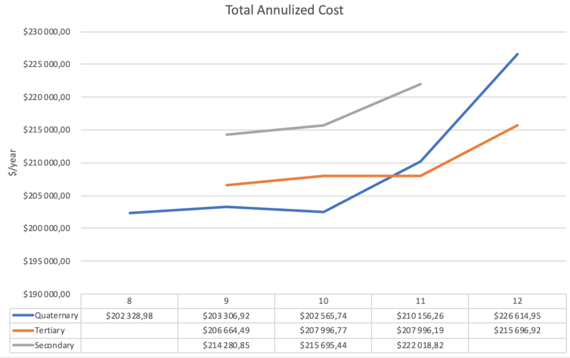


	8	9	10	11	12
Quaternary	23,353	19,572	19,297	21,556	21,317
Tertiary		21,397	22,008	21,390	23,040
Secondary		25,434	27,751	23,641	

Figure 12: Stream Match Generator Solution time for Case 7TP1

From Table 12 we can see that SeqHENS didn't find any results for 8 heat exchangers with Secondary and Tertiary temperature intervals. This is discussed further in Section 5.1.6. From this case we can see that the case with Quaternary temperature intervals has the overall fastest solution time with the exception with 12 heat exchangers.

5.1.6 SeqHENS results and Difficulty Indicator



	8	9	10	11	12
Quaternary	$202 328,98	$203 306,92	$202 565,74	$210 156,26	$226 614,95
Tertiary		$206 664,49	$207 996,77	$207 996,19	$215 696,92
Secondary		$214 280,85	$215 695,44	$222 018,82	

Figure 13: Total Annualized Cost for 7TP1

From Figure 13 we can see that the result from 8 heat exchangers with four levels of temperature intervals has the best Total Annualized Cost at 202,308.98 $/year. With two and three levels of temperature intervals, the best total annualized cost is 206,665.49 and 214,280.85 $/year with 9 heat exchangers. The result from SeqHENS gives the following network. In the table Hot and Cold is the streams on hot and cold side of the heat exchanger. T is temperature in Kelvin, $\dot{Q}$ is heat transfer in the heat exchanger in Kilowatt and A is the heat transfer area in m^2.

Hot	Cold	$T_{hot,in}$	$T_{hot,out}$	$T_{cold,in}$	$T_{cold,out}$	$\dot{Q}$	A
H3	CU	387.44	353.00	293.00	308.00	212.19	1.83
H1	C1	626.00	586.00	518.66	604.03	392.09	22.67
HU	C1	650.00	650.00	518.66	629.04	283.71	8.61
H3	C1	528.00	502.53	497.00	518.86	156.94	40.45
H2	C2	620.00	505.23	389.00	576.00	119.91	38.70
H3	C3	461.72	387.44	326.00	386.00	457.62	22.39
H3	C4	502.53	461.72	313.00	461.77	251.42	1.88
H2	C4	526.63	526.63	461.77	566.00	176.13	60.37

Table 5: Heat exchanger network from SeqHENS with four levels of temperature intervals

Hot	Cold	$T_{hot,in}$	$T_{hot,out}$	$T_{cold,in}$	$T_{cold,out}$	$\dot{Q}$	A
H3	CU	387.44	353.00	293.00	208.00	212.19	1.83
HU	C1	650.00	650.00	573.48	613.00	283.74	9.15
H1	C1	626.00	586.00	518.86	573.48	392.08	15.40
H2	C1	578.60	534.74	506.25	518.86	90.53	46.22
H3	C1	528.00	510.99	497.00	506.25	66.42	7.01
H2	C2	620.00	481.99	389.00	576.00	119.88	44.10
H3	C3	510.90	393.80	326.00	386.00	457.00	16.45
H2	C4	620.00	578.60	515.34	566.00	85.62	29.73
H3	C4	528.00	377.83	313.00	515.34	341.95	6.70

Table 6: Heat exchanger network from SeqHENS with three levels of temperature intervals

Hot	Cold	$T_{hot,in}$	$T_{hot,out}$	$T_{cold,in}$	$T_{cold,out}$	$\dot{Q}$	A
H3	CU	387.44	353.00	293.00	308.00	212.18	1.84
HU	C1	650.00	650.00	573.48	613.00	283.74	9.52
H1	C1	626.00	586.00	518.86	573.48	392.08	15.40
H2	C1	581.76	516.08	497.00	518.86	156.93	92.02
H2	C2	620.00	531.76	501.57	576.00	47.73	31.18
H3	C2	528.00	509.41	389.00	501.58	72.17	5.02
H3	C3	509.41	391.57	326.00	386.00	457.61	16.73
H2	C4	620.00	581.76	511.94	566.00	91.36	30.14
H3	C4	528.00	380.40	313.00	511.94	336.21	5.87

Table 7: Heat exchanger network from SeqHENS with two levels of temperature intervals

When comparing the results and the solution time for this case the number can be put into the difficulty indicator.
For DI1: $N_{matches} + N_{streams} = 26$
For DI2: $N_{matches} + N_{TI,hot} + N_{TI,cold} = 66$
For DI3: $N_{matches} * N_{streams} = 133$
For DI4: $N^2_{matches} + N_{TI,hot} + N_{TI,cold} = 408$
The numbers put into the difficulty indicator are from the case with four levels of temperature intervals, and will be compared with the other cases.

5.1.7 Discussion and Results

As we can see from the results in this case when reducing the number of temperatures intervals, the average solution time for the Stream Match Generator increases. When using two and three temperature intervals SeqHENS could not produce any networks for 8 heat exchangers. The best Total Annualized Cost was also higher when the number of temperature intervals was reduced. This also applies if the comparison is between all the results with 9 heat exchangers, so it not just that the results with four levels of temperature intervals had fewer heat exchangers in the solution. The only exception from this is shown in Table 13 where the Total Annualized Cost is lower for three levels temperature intervals with 11 and 12 heat exchangers.

5.2 Case Two - 15TP1

5.2.1 Stream Data

Stream	$T_{supply}[K]$	$T_{target}[°C]$	$\dot{m}C_p[kW/K]$	h [kW/(m^2*K)]	$\Delta H[kW]$
H1	180.00	75.00	30.00	2	3150.00
H2	280.00	120.00	60.00	1	9600.00
H3	180.00	75.00	30.00	2	3150.00
H4	140.00	40.00	30.00	1	3000.00
H5	220.00	120.00	55.00	1	5000.00
H6	180.00	60.00	35.00	2	4375.00
H7	200.00	60.00	30.00	0.4	4200.00
H8	120.00	40.00	100.00	0.5	8000.00
C1	40.00	230.00	20.00	1	3800.00
C2	128.00	120.00	60.00	1	7200.00
C3	40.00	290.00	35.00	2	8750.00
C4	50.00	290.00	30.00	2	7200.00
C5	50.00	250.00	60.00	2	12000.00
C6	90.00	190.00	50.00	1	5000.00
C7	160.00	250.00	60.00	3	5400.00
HU	325.00	325.00	—	1	—
CU	25	40	—	2	—

Table 8: Stream data case two

Cost of Heat Exchangers ($): $8,000.0 + 500(Area)^{0,75}$
Cost of Cooling Utility ($): $20 * \dot{Q}_{CU}$
Cost of Heating Utility ($): $200 * \dot{Q}_{HU}$

5.2.2 Possible Number of Matches

In this case, the number of possible matches is the same for EMAT1, 2 and 3 (2,544K, 5.088K and 10.175K). From Table 9 $min\ Z$ equals 69.

	C1	C2	C3	C4	C5	C6	C7	CU
H1	1	1	1	1	1	1	1	1
H2	1	1	1	1	1	1	1	1
H3	1	1	1	1	1	1	1	1
H4	1	1	1	1	1	1	0	1
H5	1	1	1	1	1	1	1	1
H6	1	1	1	1	1	1	0	1
H7	1	1	1	1	1	1	1	1
H8	1	1	1	1	1	1	0	1
HU	1	1	1	1	1	1	1	0

Table 9: Possible Matches between streams

5.2.3 Minimum Energy Consumption Sub-problem

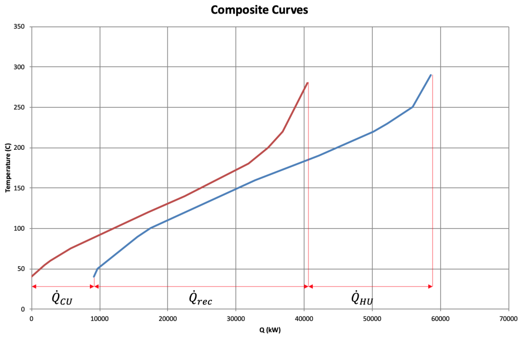


Figure 14: Composite Curve for 15TP1

Figure 14 shows the Composite Curve for 15TP1 with Heat Recovery Approach Temperature (HRAT) at 20.35K. The result from Minimum Energy Consumption in SeqHENS gives $\dot{Q}_{HU}$ at 18.039,25 kW, $\dot{Q}_{HU}$ at 9,164.25 kW and $\dot{Q}_{rec}$ at 31,310.75 kW.

5.2.4 Minimum Number of Units Sub-problem

In this case the first loop for the Stream Match Generator Sub-problem will be with the minimum number of units, and for each loop the number of units will increase by one. From Equation 2.15 the minimum number of units is 16. The results from the Minimum Number of Units sub-problems also give us 16 heat exchangers, for the minimum number of units.

5.2.5 Stream Match Generator Sub-problem

When testing the Stream Match Generator Sub-problem, this study will try to decrease the number of temperature intervals (TI) as discussed in Section 3.3.3. This will be done by first running the case through SeqHENS with four levels of temperature intervals, then with three levels of temperature intervals, and two levels of temperature intervals. The results from this test will be compared by using solution time, total annualized cost and errors in the results due to the removal of temperature intervals.

TI Generation method	Number of hot TI's	Number of cold TI's
Secondary	16	17
Tertiary	26	27
Quaternary	31	31

Table 10: Temperature intervals for case 15TP1 with EMAT1

The number of temperature intervals in each case is shown in Table 10. The number of hot and cold temperature intervals is reduced from 31/31 with Quaternary temperature intervals to 16/17 with Secondary temperature intervals. Solution time for the Stream Match Generator sub-problem

is calculated from the average of EMAT 1,2 and 3 for each number of heat exchangers, starting with the minimum number of units. In some cases, SeqHENS did not find any solution, in these cases the time is removed from the calculation, thus the average time from EMAT 1,2 and 3 with solutions. The solution time for the Stream Match Generator sub-problem is plotted in Figure 12.

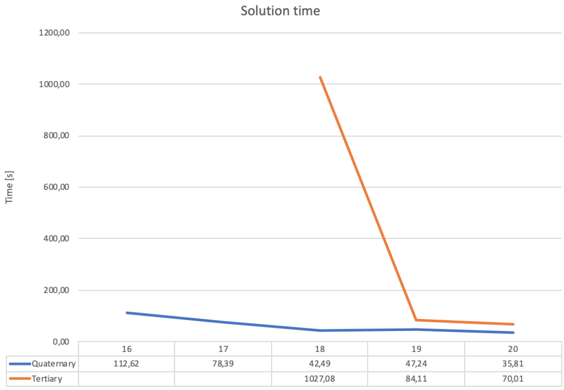


Figure 15: Stream Match Generator Solution time for Case 15TP1

From Table 15 we can see that SeqHENS did not find any results with just secondary temperature intervals. It was also no results from 16 and 17 heat exchangers with tertiary temperature intervals. In this case the solution time was shortest with Quaternary temperature intervals, especially for 18 heat exchangers.

5.2.6 SeqHENS results and Difficulty Indicator

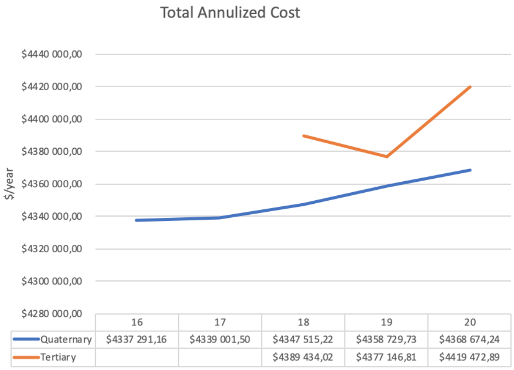


Figure 16: Total Annualized Cost for 15TP1

From Figure 16 we can see that the result from 16 heat exchangers with four levels of temperature intervals has the best Total Annualized Cost at 4,337,291.16 $/year. With three levels of temperature intervals, the best total annualized cost is 4,377,146.81 \$/year with 19 heat exchangers. The result from SeqHENS gives the following network. In the table Hot and Cold is the streams on hot and cold side of the heat exchanger. T is temperature in Kelvin, $\dot{Q}$ is heat transfer in the heat exchanger in Kilowatt and A is the heat transfer area in m^2.

Hot	Cold	$T_{hot,in}$	$T_{hot,out}$	$T_{cold,in}$	$T_{cold,out}$	$\dot{Q}$	A
H4	CU	78.81	40.00	25.00	40.00	1164.25	69.73
H8	CU	120.00	40.00	25.00	40.00	8000.00	515.07
HU	C1	325.00	325.00	173.05	230.00	1139.00	18.79
H7	C1	200.00	56.56	40.00	173.05	2661.03	436.52
H2	C2	240.00	120.00	100.00	220.00	7200.00	720.00
HU	C3	325.00	325.00	165.00	290.00	4375.00	79.79
H6	C3	180.00	55.00	40.00	165.00	4275.00	291.67
HU	C4	325.00	325.00	155.00	290.00	4050.00	71.12
H3	C4	180.00	75.00	50.00	155.00	3150.00	126.00
HU	C5	325.00	325.00	198.75	250.00	3075.24	126.00
H1	C5	180.00	75.00	50.00	171.75	3149.99	208.47
H2	C5	280.00	240.00	158.75	198.75	2400.00	44.31
H4	C5	140.00	78.81	50.00	134.27	1835.76	192.70
H7	C5	200.00	65.57	50.00	174.69	1538.97	230.27
H5	C6	220.00	120.00	90.00	190.00	5000.00	333.33
HU	C7	325.00	325.00	160.00	250.00	5400.00	63.08

Table 11: Heat exchanger network from SeqHENS with four levels of temperature intervals

Hot	Cold	$T_{hot,in}$	$T_{hot,out}$	$T_{cold,in}$	$T_{cold,out}$	$\dot{Q}$	A
H4	CU	99.54	40.00	25.00	400.00	1786.26	82.93
H8	CU	113.78	40.00	25.00	40.00	7378.00	499.89
H2	C1	280.00	247.34	140.20	230.00	1796.00	47.91
H7	C1	200.00	52.61	40.00	140.20	2004.02	231.35
H2	C2	247.34	116.40	100.00	220.00	7199.96	672.82
HU	C3	325.00	325.00	171.19	290.00	4158.25	77.72
H2	C3	280.00	159.53	153.94	171.19	604.03	26.06
H3	C3	180.00	75.00	63.94	153.94	3150.00	179.94
H6	C3	78.94	55.00	40.00	63.94	837.76	52.36
HU	C4	235.00	325.00	175.73	290.00	3428.01	65.27
H1	C4	180.00	75.00	50.00	171.47	3149.98	205.65
H5	C4	220.00	96.67	50.00	202.92	622.02	31.69
HU	C5	325.00	325.00	165.78	250.00	5053.02	67.75
H4	C5	140.00	99.45	50.00	135.41	1215.08	96.60
H6	C5	180.00	78.94	53.81	172.39	3537.26	241.24
H7	C5	200.00	66.13	50.00	177.00	2195.99	340.33
H5	C6	220.00	122.62	102.44	190.00	4377.98	353.55
H8	C6	120.00	113.78	90.00	102.44	622.00	90.97
HU	C7	325.00	325.00	160.00	250.00	5400.00	63.08

Table 12: Heat exchanger network from SeqHENS with three levels of temperature intervals

When comparing the results and the solution time for this case the number can be put into the difficulty indicator.
For DI1: $N_{matches} + N_{streams} = 84$
For DI2: $N_{matches} + N_{TI,hot} + N_{TI,cold} = 131$
For DI3: $N_{matches} * N_{streams} = 1035$
For DI4: $N^2_{matches} + N_{TI,hot} + N_{TI,cold} = 4823$
When comparing the DI with case one all the four different suggestions all four of them gets higher, something that fits the increasing solution time compared with case one.

5.2.7 Discussion and Results

In this case we can see from Table 15 that the solution time increased with the reduction of the number of temperature intervals the same way as in case one. In this case the reason for this was clearer than in case one. As the number of temperature intervals decreases the numbers of results was reduced. If we compare the same number of heat exchangers when decreasing the number of temperature intervals. If one of EMAT1, 2 or 3 don't have any result with four levels of temperature intervals, the problem always gets bigger for three levels of temperature intervals. From Table 16 and 15 it is no results for three levels of temperature intervals with 16 and 17 heat exchangers. In these cases, one of EMAT 1,2 or 3 did not work with four temperature intervals. And the results from 18, 19 and 20 heat exchangers with three levels of temperature intervals did not have results

from all three EMAT's. This can be an indication for that when the number of temperature intervals is reduced the solution time increases because it's more difficult for SeqHENS to find the best solutions.
When comparing the Total Annualized Cost for the network the Total Annualized Cost for the network with four levels of temperature intervals was 39,855 $/year lower than the Total Annualized Cost with three levels of temperature intervals. This is 0.9% higher than the results from four levels of temperature intervals. The increase in Total Annualized Cost can be related to the fact that the results from three levels of temperature intervals have three more heat exchangers with a staring annualized cost of 8,000$/year for each heat exchanger before the area is taken into account.

5.3 Case Three - 21TP1

5.3.1 Stream Data

Stream	$T_{supply}[K]$	$T_{target}[°C]$	$\dot{m}C_p[kW/K]$	h [kW/(m^2*K)]	$\Delta H[MW]$
H1	240.50	131.80	25.80	1	2804.00
H2	136.00	24.00	213.70	1	23924.00
H3	310.00	207.00	30.20	1	3111.00
H4	201.00	165.00	239.00	1	8604.00
H5	233.00	17.00	42.40	1	9158.00
H6	281.00	34.90	128.90	1	31722.00
H7	181.00	160.00	91.20	1	1915.00
H8	237.80	245.00	185.30	1	7931.00
H9	340.00	192.00	19.30	1	2856.00
H10	151.00	35.00	15.20	1	1763.00
H11	465.00	29.00	100.10	1	43644.00
C1	15.00	335.00	171.00	1	54720.00
C2	26.90	282.20	124.30	1	31734.00
C3	106.50	486.00	98.00	1	37191.00
C4	29.00	172.00	41.80	1	5977.00
C5	228.00	246.00	185.70	1	3343.00
C6	170.00	184.00	285.90	1	6803.00
C7	174.00	178.00	1983.80	1	7935.00
C8	150.00	153.00	3004.00	1	9012.00
C9	92.00	120.00	172.80	1	4838.00
C10	104.00	105.00	601.80	1	602.00
HU	496.00	496.00	—	3.5	—
CU	7.00	10.00	—	3.5	—

Table 13: Stream data case three

Cost of Heat Exchangers ($): $8,000.0 + 500(Area)^{0,75}$
Cost of Cooling Utility ($): $20 * \dot{Q}_{CU}$
Cost of Heating Utility ($): $200 * \dot{Q}_{HU}$

5.3.2 Possible Number of Matches

In this case, the number of possible matches is not the same for EMAT 1,2 and 3. For EMAT 3 (5K) $min\ Z$ are 110. The possible matches are shown in Table 14. For EMAT 1 and 2 (1.25K and 2.5K) $min\ Z$ are 111. EMAT 1 and 2 has the same possible matches ass EMAT 3, but since the EMAT is reduced it is also possible to match stream H5 with C5.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	CU
H1	1	1	1	1	1	1	1	1	1	1	1
H2	1	1	1	1	0	0	0	0	1	1	1
H3	1	1	1	1	1	1	1	1	1	1	1
H4	1	1	1	1	0	1	1	1	1	1	1
H5	1	1	1	1	0	1	1	1	1	1	1
H6	1	1	1	1	1	1	1	1	1	1	1
H7	1	1	1	1	0	1	1	1	1	1	1
H8	1	1	1	1	1	1	1	1	1	1	1
H9	1	1	1	1	1	1	1	1	1	1	1
H10	1	1	1	1	0	0	0	0	1	1	1
HU	1	1	1	1	1	1	1	1	1	1	0

Table 14: Possible Matches between streams with EMAT 3

5.3.3 Minimum Energy Consumption Sub-problem

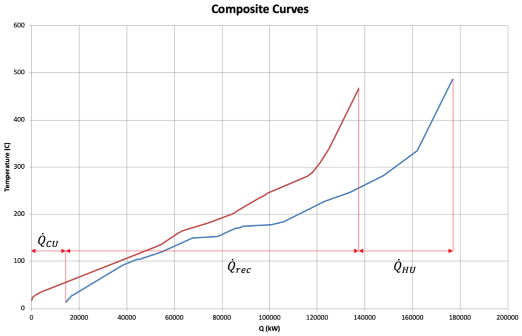


Figure 17: Composite Curve for 21TP1

Figure 20 shows the Composite Curve for 21TP1 with Heat Recovery Approach Temperature (HRAT) at 12.5K. The result from Minimum Energy Consumption in SeqHENS gives $\dot{Q}_{HU}$ at 39,317.31 kW, $\dot{Q}_{HU}$ at 14,605.91 kW and $\dot{Q}_{rec}$ at 122,836.78 kW.

5.3.4 Minimum Number of Units Sub-problem

In this case the first loop for the Stream Match Generator Sub-problem will be with the minimum number of units, and for each loop the number of units will increase by one. From Equation 2.15

the minimum number of units is 22. The results from the Minimum Number of Units sub-problems also give us 23 heat exchangers, for the minimum number of units. This means that SeqHENS finds a higher minimum number of units then the Equation 2.15, and it will not find any result below 23 heat exchangers.

5.3.5 Stream Match Generator Sub-problem

When testing the Stream Match Generator Sub-problem, this study will try to decrease the number of temperature intervals (TI) as discussed in Section 3.3.3. This will be done by first running the case through SeqHENS with four levels of temperature intervals, then with three levels of temperature intervals, and two levels of temperature intervals. The results from this test will be compared by using solution time, total annualized cost and errors in the results due to the removal of temperature intervals.

TI Generation method	Number of hot TI's	Number of cold TI's
Secondary	39	39
Tertiary	59	61
Quaternary	75	77

Table 15: Temperature intervals for case 21TP1

The number of temperature intervals in each case is shown in Table 15. The number of hot and cold temperature intervals is reduced from 75/55 with Quaternary temperature intervals to 39/39 with Secondary temperature intervals. Solution time for the Stream Match Generator sub-problem is calculated from the average of EMAT 1,2 and 3 for each number of heat exchangers, starting with the minimum number of units. In some cases, SeqHENS did not find any solution, in these cases the time is removed from the calculation, thus the average time from EMAT 1,2 and 3 with solutions. The solution time for the Stream Match Generator sub-problem is plotted in Figure 18.

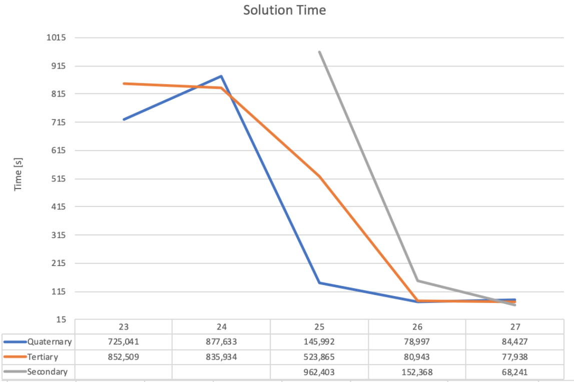


Figure 18: Stream Match Generator Solution time for Case 21TP1

From Table 18 we can see that SeqHENS didn't find any results for 23 heat exchangers with Secondary temperature intervals. From this case we can see that the case with Quaternary temperature intervals has the overall fastest solution time with the exception of 26 and 27 heat exchangers where Secondary and Tertiary temperature intervals had similar solution times.

5.3.6 SeqHENS results and Difficulty Indicator

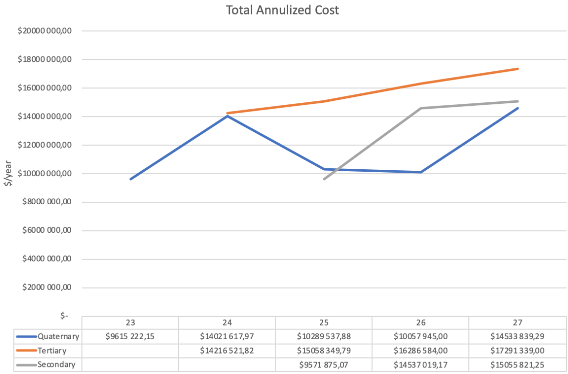


Figure 19: Total Annualized Cost for 21TP1

In this case the Total Annualized Cost has a great variation between the results as shown in Figure 19. In the lowest Total Annualized Cost with 9,571,875.07 $/year from two levels of temperature intervals with 25 heat exchangers as the lowest Total Annualized Cost and 17,291,339.00 $/year from three levels of temperature intervals with 27 heat exchangers as the highest Total Annualized Cost. The main reason for this big variation in the Total Annualized Cost in this case comes down to the driving forces. In cases with high Total Annualized the Logarithmic Mean Temperature Difference (LMTD)is equal to one in a lot of the heat exchangers, thus the area for these heat exchangers get very big.

As shown in Figure 19 the lowest Total Annualized Cost for the network is 9,571,875.07 $/year from two levels of temperature intervals with 25 heat exchangers. The lowest Annualized Cost for four and three levels of temperature intervals is 9,615,22.15 $/year (23 heat exchangers) and 14,216,521.82 $/year (24 heat exchangers). The result from SeqHENS gives the following network. In the tables Hot and Cold is the streams on hot and cold side of the heat exchanger. T is temperature in Kelvin, $\dot{Q}$ is heat transfer in the heat exchanger in Kilowatt, A is the heat transfer area in m^2 and LMTD is in Kelvin.

Hot	Cold	$T_{hot,in}$	$T_{hot,out}$	$T_{cold,in}$	$T_{cold,out}$	$\dot{Q}$	A	LMTD
H2	CU	82.90	24.00	7.00	10.00	12586.08	421.47	38.39
H5	CU	64.64	17.00	7.00	10.00	2019.77	98.79	26.29
HU	C1	496.00	496.00	206.97	306.27	12861.68	98.79	235.91
H5	C1	233.00	63.57	15.00	227.56	2322.67	235.77	19.70
H6	C1	209.79	34.90	15.00	205.08	22543.46	4275.18	10.55
H11	C1	453.24	22.17	15.00	424.75	16992.25	2199.42	15.45
H2	C2	136.00	61.35	26.90	134.41	6509.85	1219.07	10.68
H7	C2	181.00	160.00	134.41	166.04	1915.20	193.46	19.80
H11	C2	417.55	33.44	26.90	392.53	23308.79	3384.41	13.77
HU	C3	496.00	496.00	216.04	486.00	26455.69	419.84	81.02
H1	C3	240.50	131.80	106.50	135.12	2804.46	99.93	56.13
H8	C3	287.80	245.00	135.12	216.04	7930.84	177.29	89.47
H5	C4	233.00	55.42	29.00	205.09	4214.13	310.32	27.16
H10	C4	151.00	35.00	29.00	127.68	1763.22	276.42	12.76
H11	C5	465.00	417.55	228.00	246.00	3342.59	32.78	203.92
H3	C6	310.00	207.00	177.60	184.00	3110.67	93.72	66.38
H4	C6	201.00	197.50	170.00	171.72	835.65	58.88	28.38
H9	C6	340.00	192.00	171.72	177.60	2856.26	83.62	68.31
H6	C7	281.00	219.44	174.00	178.00	7935.21	225.63	70.34
H4	C8	197.50	165.00	150.41	153.00	7768.40	579.30	26.82
H6	C8	219.44	209.79	150.00	150.41	1243.64	38.68	64.30
H2	C9	136.00	97.75	92.00	120.00	4838.44	966.17	10.02
H5	C10	233.00	111.67	104.00	105.00	601.81	28.16	42.74

Table 16: Heat exchanger network from SeqHENS with four levels of temperature intervals

Hot	Cold	$T_{hot,in}$	$T_{hot,out}$	$T_{cold,in}$	$T_{cold,out}$	$\dot{Q}$	A	LMTD
H2	CU	58.40	8.00	7.00	10.00	8971.45	944.71	12.21
H5	CU	62.05	8.00	7.00	10.00	1910.16	190.13	12.92
H6	CU	219.38	171.00	7.00	10.00	2022.15	14.00	185.77
HU	C1	496.00	496.00	342.30	494.89	14776.83	613.81	30.95
H2	C1	134.55	16.00	15.00	125.77	10124.36	5652.93	3.58
H5	C1	233.00	62.05	60.89	232.00	7248.23	13465.13	1.08
H11	C1	427.97	16.00	15.00	426.97	22570.41	45140.82	1.00
H6	C2	200.09	37.67	28.29	199.09	12239.88	6539.83	3.74
H10	C2	151.00	35.00	26.90	150.00	1763.18	1038.97	3.39
H11	C2	436.00	44.72	43.72	435.00	17730.60	35461.20	1.00
HU	C3	496.00	496.00	244.48	494.89	24540.47	683.21	46.18
H1	C3	240.50	131.80	124.12	236.35	2804.46	977.44	5.74
H7	C3	181.00	160.00	159.00	179.35	1913.10	2946.82	1.30
H8	C3	287.80	245.00	205.87	286.80	7930.84	1525.48	10.40
H6	C4	173.00	30.00	29.00	172.00	5968.46	11936.93	1.00
H11	C5	465.00	230.17	228.00	246.00	3342.61	142.31	46.98
H6	C6	223.77	171.00	170.00	184.00	6802.58	1292.38	10.53
H3	C7	310.00	207.00	176.43	178.00	3110.60	89.72	69.34
H4	C7	198.59	175.00	174.00	174.99	1968.05	550.63	7.15
H9	C7	340.00	192.00	174.99	176.43	2856.54	88.24	64.75
H4	C8	192.53	164.76	150.79	153.00	6635.84	540.09	24.57
H6	C8	173.43	151.00	150.00	150.79	2376.19	685.19	6.94
H2	C9	134.28	97.35	92.00	120.00	4838.39	1063.44	9.10
H6	C10	233.77	219.38	104.00	105.00	601.80	9.87	121.96

Table 17: Heat exchanger network from SeqHENS with three levels of temperature intervals

Hot	Cold	$\text{T}_{hot,in}$	$\text{T}_{hot,out}$	$\text{T}_{cold,in}$	$\text{T}_{cold,out}$	$\dot{Q}$	A	LMTD
H2	CU	56.30	24.00	7.00	10.00	6904.86	303.53	29.25
H5	CU	56.75	17.00	7.00	10.00	1685.15	90.93	23.83
H6	CU	68.35	31.25	7.00	10.00	3238.70	107.23	38.83
H11	CU	56.74	29.00	7.00	10.00	2725.96	106.75	32.83
H2	C1	99.61	55.50	15.00	52.49	5863.34	268.17	43.74
H3	C1	310.00	220.51	194.36	246.81	2702.62	128.75	41.98
H5	C1	233.00	56.74	51.22	213.11	7423.23	1332.78	11.28
H10	C1	151.00	35.00	17.47	143.85	1763.20	304.65	11.58
H11	C1	431.58	55.84	52.49	385.42	36917.85	4524.91	16.32
HU	C2	496.00	496.00	172.17	318.97	6846.06	36.21	243.09
H2	C2	136.00	57.64	26.90	130.29	6335.49	852.29	14.87
H6	C2	281.00	68.35	59.92	260.12	18559.98	2704.45	13.73
HU	C3	496.00	496.00	154.66	486.00	32471.32	444.82	93.86
H1	C3	240.50	131.80	126.04	154.66	2804.46	189.25	29.64
H7	C3	181.00	160.00	106.50	126.04	1915.21	70.64	54.23
H6	C4	186.19	42.57	29.00	172.00	5977.41	861.72	13.87
H11	C5	465.00	431.58	228.00	246.00	3342.60	31.65	211.19
H6	C6	281.00	186.19	190.00	178.12	3946.10	168.37	46.88
H9	C6	340.00	192.00	178.12	184.00	2856.50	97.26	58.74
H8	C7	287U.80	245.00	174.00	178.00	7931.04	178.24	88.99
H11	C7	465.00	418.67	174.000	174.002	4.16	0.03	267.16
H3	C8	220.51	207.00	152.86	153.00	208.27	13.46	60.58
H4	C8	201.00	165.00	150.00	152.86	6603.73	605.49	28.42
H2	C9	136.00	99.61	92.00	120.00	4838.37	857.24	11.29
H11	C10	430.92	105.00	104.00	601.72	21.43	56.15	

Table 18: Heat exchanger network from SeqHENS with two levels of temperature intervals

This case has a lot of both temperature intervals and possible matches. This results in a long solution time, something that is visible in the difficulty indicators.
For DI1: $N_{matches} + N_{streams} = 131$
For DI2: $N_{matches} + N_{TI,hot} + N_{TI,cold} = 262$
For DI3: $N_{matches} * N_{streams} = 2310$
For DI4: $N_{matches}^2 + N_{TI,hot} + N_{TI,cold} = 12528$
The numbers put into the difficulty indicator are from the case with four levels of temperature intervals, and will be compared with the other cases.

5.3.7 Discussion and Results

In this case most of the result from SeqHENS had infeasible matches between streams. With four levels of temperature intervals only the solutions with 27 heat exchangers had all three result with infeasible matches, the rest of the results had at least one solution where all matches were feasible (EMAT 1,2 or 3). Four the result with three and two levels of temperature intervals all the result had infeasible matches between streams minimum two streams. The infeasible matches came in two variants. The first and most common was that the superstructures produces for some streams had more than five heat exchangers. When this happens SeqHENS prints a superstructure with five heat exchangers for the streams and gives the stream more than five matches in the results where the matches are printed. In this case these resulted in two different problems. The first one, and the easiest to solve was when the temperature out of the superstructure did not match the target temperature for the stream. This was solved by adding a superstructure with one or two heat exchangers after the excising superstructure. The second problem is that one of the exciting heat exchangers given in the superstructure did not match with any of the streams. This was solved by finding the stream that SeqHENS had match with the stream but didn't match with any of the other heat loads from the superstructure. From the heat load in that stream, the heat load was split in two, with the heat load form the working superstructure as the target. The other new heat exchanger was connected to the hot or cold utility. The second problem that resulted in infeasible matches was when the streams had negative driving forced (Temperatures on the cold side is higher than on the hot side). This problem only happened with three and two levels of temperature intervals. As all the other streams had matches from SeqHENS the only solution for this problem was to connect the stream hot stream to the cold utility, and the cold stream to the hot utility. All these problems in the result resulted in some consequences, manly that the solution calculated in the Total Annualized Cost can be different from the solution SeqHENS actually had calculated because some of the superstructures for the streams are manually made. One other big consequence is that the utility requirement for the hot and cold utilities is higher than the values set in the Minimum Energy Consumption Sub-problem, thus heat recovery in the network is reduced. In addition to the negative aspect in the networks, this kind of problems also increases the time used when calculating the total annualized cost a lot.

In the same way as in case two, the problems in the results increased when the number of temperature intervals was reduced. With four temperature intervals EMAT 1,2 or 3 had infeasible matches, but one or two of the results was working except for the results with 27 heat exchangers. When the number of temperature intervals is decreased all (EMAT 1,2 and 3) the result had infeasible matches. This amplify the theory from case two that the increased solution time when the number of temperature intervals can be a result of SeqHENS struggling to find the best network.

In this case the Total Annualized Cost had a lot of variation, from 9,571,875.97 $/year to 17,291,339.00 $/year. Which results in an 80.65% increase within five heat exchangers. The main reason for this is the low driving forces in some of the networks from SeqHENS. This can clearly be seen when comparing the networks from Table 17 with Table 16 and Table 18. In this case the lowest Total Annualized Cost was with two levels of temperature intervals and 27 heat exchangers. In this case the potential Difficulty Indexers are very high compared with the Difficulty Indexers from case one and two, something that is reflected in the Solution Time.

5.4 Case Four - 21TP2

5.4.1 Stream Data

Stream	$T_{supply}[K]$	$T_{target}[^{\circ}C]$	$\dot{m}C_p[kW/K]$	h [kW/(m^2*K)]	$\Delta H[MW]$
H1	207.90	30.00	177.60	1	31.60
H2	207.90	20.00	177.60	1	31.60
H3	62.00	22.50	652.30	1	25.77
H4	62.00	40.60	850.80	1	18.21
H5	40.60	22.50	416.70	1	7.54
H6	-0.20	-10.50	1073.00	1	11.05
H7	35.00	30.10	6165.30	1	30.21
H8	30.40	-45.00	81.50	1	6.15
H9	38.30	21.60	1812.80	1	30.27
H10	21.90	8.00	20.90	1	0.29
H11	51.40	8.00	36.20	1	1.57
C1	2.00	75.20	241.10	1	17.65
C2	75.20	120.40	416.90	1	18.84
C3	2.00	75.20	241.1	1	17.65
C4	75.20	120.40	416.90	1	18.84
C5	206.10	226.00	1435.70	1	28.57
C6	206.10	226.20	1421.4	1	28.57
C7	87.00	88.70	13216.50	1	22.47
C8	-10.70	50.00	7.10	1	0.43
C9	82.86	82.90	579275.00	1	23.17
C10	51.00	51.20	135995.00	1	27.20
HU	236.20	235.20	—	3.5	—
CU	-55.00	-50.00	—	3.5	—

Table 19: Stream data case four

Cost of Heat Exchangers ($): $8,000.0 + 500(Area)^{0,75}$
Cost of Cooling Utility ($): $20 * \dot{Q}_{CU}$
Cost of Heating Utility ($): $200 * \dot{Q}_{HU}$

5.4.2 Possible Number of Matches

In this case, the number of possible matches is not the same for EAMT 1,2 and 3. For EMAT 2 and 3 (2.5K and 5K) $min\ Z$ are 30. The possible matches are shown in Table 20. For EMAT 1 (1.25K) $min\ Z$ are 34. The possible matches are shown in Table 21.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	CU
H1	0	0	0	0	0	0	1	1	1	1	1
H2	0	0	0	0	0	0	1	1	1	1	1
H3	0	0	0	0	0	0	0	1	0	1	1
H4	0	0	0	0	0	0	0	1	0	1	1
H5	0	0	0	0	0	0	0	1	0	0	1
H6	0	0	0	0	0	0	0	1	0	0	1
H7	0	0	0	0	0	0	0	1	0	0	1
H8	0	0	0	0	0	0	0	1	0	0	1
H9	0	0	0	0	0	0	0	1	0	0	1
H10	0	0	0	0	0	0	0	1	0	0	1
H11	0	0	0	0	0	0	0	1	0	0	1
HU	1	1	1	1	1	1	1	1	1	1	1

Table 20: Possible Matches between streams with EMAT2 and 3

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	CU
H1	0	0	0	0	1	1	1	1	1	1	1
H2	0	0	0	0	1	1	1	1	1	1	1
H3	0	0	0	0	0	0	0	1	0	1	1
H4	0	0	0	0	0	0	0	1	0	1	1
H5	0	0	0	0	0	0	0	1	0	0	1
H6	0	0	0	0	0	0	0	1	0	0	1
H7	0	0	0	0	0	0	0	1	0	0	1
H8	0	0	0	0	0	0	0	1	0	0	1
H9	0	0	0	0	0	0	0	1	0	0	1
H10	0	0	0	0	0	0	0	1	0	0	1
H11	0	0	0	0	0	0	0	1	0	0	1
HU	1	1	1	1	1	1	1	1	1	1	1

Table 21: Possible Matches between streams with EMAT1

5.4.3 Minimum Energy Consumption Sub-problem

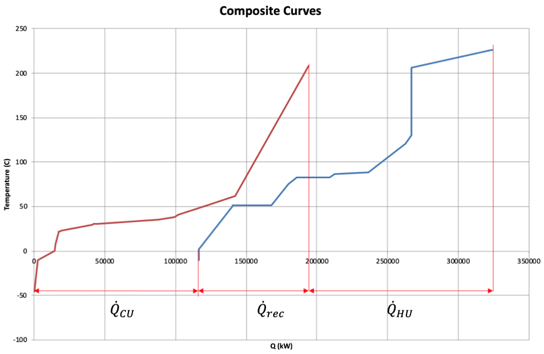


Figure 20: Composite Curve for 21TP2

Figure 20 shows the Composite Curve for 21TP12 with Heat Recovery Approach Temperature (HRAT) at 10.0K. The result from Minimum Energy Consumption in SeqHENS gives $\dot{Q}_{HU}$ at 129,623.64 kW, $\dot{Q}_{HU}$ at 116,506.69 kW and $\dot{Q}_{rec}$ at 77,740.75 kW.

5.4.4 Minimum Number of Units Sub-problem

In this case the first loop for the Stream Match Generator Sub-problem will be with the minimum number of units, and for each loop the number of units will increase by one. From Equation 2.15 the minimum number of units is 22. The results from the Minimum Number of Units sub-problems also give us 22 heat exchangers, for the minimum number of units.

5.4.5 Stream Match Generator Sub-problem

When testing the Stream Match Generator Sub-problem, this study will try to decrease the number of temperature intervals (TI) as discussed in Section 3.3.3. This will be done by first running the case through SeqHENS with four levels of temperature intervals, then with three levels of temperature intervals, and two levels of temperature intervals. The results from this test will be compared by using solution time, total annualized cost and errors in the results due to the removal of temperature intervals.

TI Generation method	Number of hot TI's	Number of cold TI's
Secondary	22	17
Tertiary	33	34
Quaternary	36	37

Table 22: Temperature intervals for case 21TP2

The number of temperature intervals in each case is shown in Table 22. The number of hot and cold temperature intervals is reduced from 36/37 with Quaternary temperature intervals to 22/17 with Secondary temperature intervals. Solution time for the Stream Match Generator sub-problem

is calculated from the average of EMAT 1,2 and 3 for each number of heat exchangers, starting with the minimum number of units. In some cases, SeqHENS did not find any solution, in these cases the time is removed from the calculation, thus the average time from EMAT 1,2 and 3 with solutions. The solution time for the Stream Match Generator sub-problem is plotted in Figure 18.

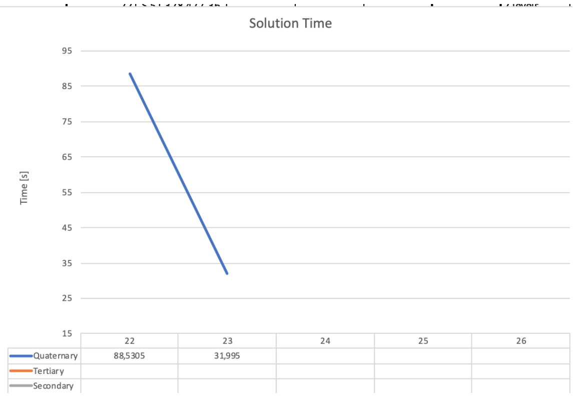


Figure 21: Stream Match Generator Solution time for Case 21TP2

From Table 21 we can see that SeqHENS didn't find many results in this case. The only result was EMAT1 and 2 for 22 heat exchangers, and EMAT1 for 23 heat exchangers with 23 heat exchangers. One big thing in this case is the solution time. This is a case with 21 streams; thus, it is a big case, but the solution times in this case is only 89 (22 heat exchangers) and 32 seconds (23 heat exchangers). The main factors for this short solution time are the low number of possible matches, and the low number of temperature intervals for a case of this size.

5.4.6 SeqHENS results and Difficulty Indicator

Figure 22: Total Annualized Cost for 21TP2

In this case it was only possible to obtain two results from SeqHENS. The lowest total Annualized Cost was with 22 heat exchangers and was 51,328,477.36 $/year. The result from SeqHENS gives the following network. In the tables Hot and Cold is the streams on hot and cold side of the heat exchangers. T is temperature in Kelvin, $\dot{Q}$ is heat transfer in the heat exchanger in Kilowatt and A is the heat transfer area in m^2.

Hot	Cold	$T_{hot,in}$	$T_{hot,out}$	$T_{cold,in}$	$T_{cold,out}$	$\dot{Q}$	A
H3	CU	62.00	22.50	-55.00	-50	25754.00	353.41
H4	CU	49.40	40.60	-55.00	-50.00	7476.00	98.61
H6	CU	-0.20	-10.50	-55.00	-50.00	11051.90	301.69
H7	CU	35.00	30.10	-55.00	-50.00	30209.97	456.69
H8	CU	30.40	-45.00	-55.00	-50.00	6145.10	233.93
H9	CU	38.30	21.60	-55.00	-50.00	30273.76	472.88
H10	CU	21.90	8.00	-55.00	-50.00	290.51	5.55
H11	CU	51.40	8.00	-55.00	-50.00	1571.08	25.04
H1	C1	115.94	30.00	2.00	61.00	10118.66	506.35
H5	C1	40.60	22.50	2.00	39.60	7542.26	2336.50
HU	C2	236.00	236.00	75.20	120.40	18842.88	176.90
H2	C3	128.37	6.45	2.00	39.60	6925.40	491.56
H4	C3	62.00	49.40	2.00	61.00	10718.27	1782.78
HU	C4	236.00	236.00	75.20	120.40	18842.88	176.90
HU	C5	236.00	236.00	206.10	226.00	28570.43	2021.77
HU	C6	236.00	236.00	206.10	226.10	28428.00	2019.99
HU	C7	236.00	236.00	87.00	88.70	22468.05	194.99
H1	C8	207.90	116.78	-10.0	50.00	426.00	6.01
HU	C9	236.00	236.00	82.86	82.90	23171.00	194.56
HU	C10	236.00	236.00	51.18	51.26	10382.24	199.43
H1	C10	207.90	115.90	51.00	51.26	10382.24	199.43
H2	C10	207.90	52.00	51.00	51.15	13975,66	907.10

Table 23: Heat exchanger network from SeqHENS with four levels of temperature intervals

For a case of this size this case has few possible matches and few temperature intervals. This results in a short solution time, something that is visible in the difficulty indicators.
For DI1: $N_{matches} + N_{streams} = 55$
For DI2: $N_{matches} + N_{TI,hot} + N_{TI,cold} = 107$
For DI3: $N_{matches} * N_{streams} = 714$
For DI4: $N_{matches}^2 + N_{TI,hot} + N_{TI,cold} = 1229$
The numbers put into the difficulty indicator are from the case with four levels of temperature intervals, and will be compared with the other cases.

5.4.7 Discussion and Results

In this case it was not a lot of results, in fact it was only three results. Two results with 22 heat exchangers, and one results with 23 heat exchangers. In this case The Stream Match Generator Sub-problem did find results for all the different number of heat exchangers with two, three and four levels of temperature intervals. The problems with this case was that the results did not work in the Network Generation and Optimization loop, so it was not possible to print any results from

these cases.
In this case the solution time is very low and goes from 89 second to 32 second which is reflected in the Difficulty Indicator. In this case the number of possible matches is very low for its size. This and the few numbers of temperature intervals can be the reason for the low solution time for this case. When comparing the Total Annualized Cost in this case, there not much to compare it with because of the lack of results from two and three levels of temperature intervals. As in the earlier cases, it looks like the problems with the solutions is amplified when the number of temperature intervals in the program is reduced.

5.5 Case Five

From Case three and four, where both had 21 streams. One of the had a lot of possible matches and temperature intervals, who resulted in a long solution time. The other one had few possible matches and few temperature intervals, who resulted in a short solution time. These cases indicated that the number of possible matches and the number of temperature intervals has a great impact on the solution time as predicted in the Chapter 3. To get a clearer test between the number of possible matches and the number of temperature intervals this case is constructed of two different networks. One where all the hot and cold stream has the possibility to match, but the streams has few different inlet and outlet temperatures for the streams. This will give few temperature intervals for the network. The second network will have a network where few temperatures has the possibility to match, but it will have a lot of different inlet and outlet temperatures. Thus, it will have a lot of temperature intervals.

In this case the solution time will be the important factor that will be compared between the different network. Solution time where SeqHENS didn't found any result will be removed from the average solution time. The Total Annualized Cost for the networks will not be presented, because this will not be possible to compare one with the other.

5.5.1 Stream data

Stream	$T_{supply}[K]$	$T_{target}[^{\circ}C]$	$\dot{m}C_p[kW/K]$	h [kW/(m^2*K)]	$\Delta H[MW]$
H1	75.00	41.00	2.00	1	68.00
H2	86.00	34.00	5.00	1	260.00
H3	94.00	57.00	3.00	1	111.00
H4	103.00	45.00	7.00	1	406.00
H5	220.00	95.00	20.00	1	2500.00
H6	56.00	55.00	2.00	1	2.00
H7	73.00	54.00	8.00	1	152.00
H8	89.00	50.00	9.00	1	351.00
H9	67.00	51.00	4.00	1	64.00
H10	95.00	56.00	6.00	1	234.00
H11	44.00	40.00	3.00	1	12
C1	120.00	121.00	3.00	1	3.00
C2	125.00	245.00	2.00	1	240.00
C3	126.00	162.00	5.00	1	180.00
C4	95.00	96.00	7.00	1	7.00
C5	250.00	251.00	2.00	1	2.00
C6	240.00	267.00	9.00	1	243.00
C7	230.00	249.00	4.00	1	76.00
C8	221.00	222.00	3.00	1	76.00
C9	201.00	234.00	7.00	1	231.00
C10	209.00	225.00	6.00	1	96.00
HU	400.00	400.00	—	3.5	—-
CU	10.00	15.00	—	3.5	—

Table 24: tab:Stream data Case Five TI

This case will have a lot of temperature intervals and will be called Case Five TI.

Stream	$T_{supply}[K]$	$T_{target}[°C]$	$\dot{m}C_p[kW/K]$	h [kW/(m^2*K)]	$\Delta H[MW]$
H1	180.00	40.00	2.00	1	280.00
H2	180.00	40.00	5.00	1	700.00
H3	180.00	40.00	3.00	1	420.00
H4	180.00	40.00	7.00	1	980.00
H5	180.00	40.00	1.00	1	140.00
H6	200.00	50.00	2.00	1	300.00
H7	200.00	50.00	8.00	1	1200.00
H8	200.00	50.00	9.00	1	1350.00
H9	200.00	50.00	4.00	1	600.00
H10	200.00	50.00	6.00	1	900.00
H11	200.00	50.00	3.00	1	450.00
C1	30.00	170.00	3.00	1	420.00
C2	30.00	170.00	2.00	1	280.00
C3	30.00	170.00	5.00	1	700.00
C4	30.00	170.00	7.00	1	980.00
C5	30.00	170.00	2.00	1	280.00
C6	40.00	190.00	9.00	1	1350.00
C7	40.00	190.00	4.00	1	600.00
C8	40.00	190.00	3.00	1	450.00
C9	40.00	190.00	7.00	1	1050.00
C10	40.00	190.00	6.00	1	900.00
HU	250.00	250.00	—	3.5	—
CU	10.00	15.00	—	3.5	—

Table 25: Stream data Case Five PM

This case will have a lot of possible matches and will be called Case Five PM (Possible Matches).
Cost of Heat Exchangers ($): $8,000.0 + 500(Area)^{0,75}$
Cost of Cooling Utility ($): $20 * \dot{Q}_{CU}$
Cost of Heating Utility ($): $200 * \dot{Q}_{HU}$ The cost data is the same for both cases

5.5.2 Possible Number of Matches

As presented in the introduction for this case. One of the cases will have a lot of matches, and the other will have a lot of temperature intervals. The possible number of matches for case five PM is presented in Table 26 and has a $min\ Z$ is 131 for EMAT 1,2 and 3. In this case all the streams can match with all the stream.
In Table 27 the possible number of matches for case five TI is presented for EMAT1 and 2. In this case $min\ Z$ is 28. For EMAT 3 $min\ Z$ is 28 and can also match between H4 and C4.

5.5.3 Minimum Number of Units Sub-problem

In this case the first loop for the Stream Match Generator Sub-problem will be with the minimum number of units, and for each loop the number of units will increase by one. From Equation 2.15 the minimum number of units is 22. The results from the Minimum Number of Units sub-problems

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	CU
H1	1	1	1	1	1	1	1	1	1	1	1
H2	1	1	1	1	1	1	1	1	1	1	1
H3	1	1	1	1	1	1	1	1	1	1	1
H4	1	1	1	1	1	1	1	1	1	1	1
H5	1	1	1	1	1	1	1	1	1	1	1
H6	1	1	1	1	1	1	1	1	1	1	1
H7	1	1	1	1	1	1	1	1	1	1	1
H8	1	1	1	1	1	1	1	1	1	1	1
H9	1	1	1	1	1	1	1	1	1	1	1
H0	1	1	1	1	1	1	1	1	1	1	1
H11	1	1	1	1	1	1	1	1	1	1	1
HU	1	1	1	1	1	1	1	1	1	1	0

Table 26: Possible Matches between streams for case five PM

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	CU
H1	0	0	0	0	0	0	0	0	0	0	1
H2	0	0	0	0	0	0	0	0	0	0	1
H3	0	0	0	0	0	0	0	0	0	0	1
H4	0	0	0	0	0	0	0	0	0	0	1
H5	1	1	1	1	0	0	0	0	1	1	1
H6	0	0	0	0	0	0	0	0	0	0	1
H7	0	0	0	0	0	0	0	0	0	0	1
H8	0	0	0	0	0	0	0	0	0	0	1
H9	0	0	0	0	0	0	0	0	0	0	1
H0	0	0	0	0	0	0	0	0	0	0	1
H11	0	0	0	0	0	0	0	0	0	0	1
HU	1	1	1	1	1	1	1	1	1	1	0

Table 27: Possible Matches between streams for case five TI

gives 22 heat exchangers for case five TI and 14 for case five PM.

5.5.4 Stream Match Generator Sub-problem

When testing the Stream Match Generator Sub-problem, this study will try to decrease the number of temperature intervals (TI) as discussed in Section 3.3.3. In this case the results will be compared between Case Five PM and Case Five TI and the number of temperature intervals for the cases is presented in Table 28. The results from this test will be compared by using solution time.

Case	Number of hot TI's	Number of cold TI's
Case Five TI	45	46
Case Five PM	12	12

Table 28: Temperature intervals for case five TI

Solution time for the Stream Match Generator sub-problem is calculated from the average of EMAT 1,2 and 3 for each number of heat exchangers, starting with the minimum number of units. In some cases, SeqHENS did not find any solution, in these cases the time is removed from the calculation, thus the average time from EMAT 1,2 and 3 with solutions. The solution time for the Stream Match Generator sub-problem is plotted in Figure 23 and 24.

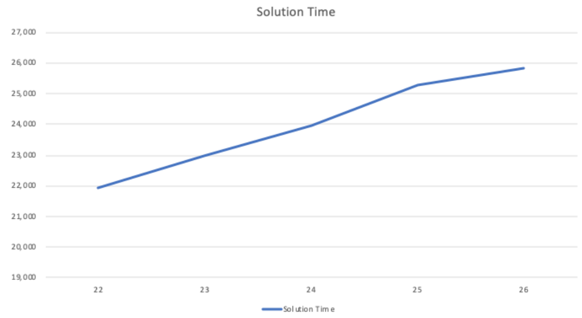


Figure 23: Stream Match Generator Solution time for Case Five TI

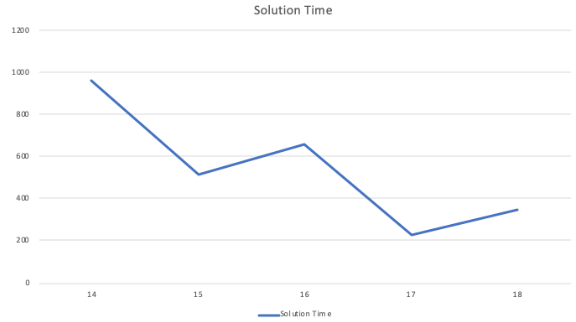


Figure 24: Stream Match Generator Solution time for Case Five PM

From Table 23 we can see that the solution time for Case Five TI is between 22 seconds and 26 seconds. This is a short solution time, but it differs from the other cases because the solution time increases when the number of heat exchangers increases. In this case the number of heat exchangers also did not increases after 23 heat exchangers, so the results from 24, 25 and 26 heat exchangers actually have 23 heat exchangers. This can be the reason for the increasing in solution time when the number of heat exchangers increases.

In Case Five PM the solution time is between 956 seconds and 229 seconds and are presented in Table 24. In this case EMAT3 did never find any results and are removed from the solution time.

5.5.5 Difficulty Indicator

In this case we can see from Table 23 and 24 that it is a big difference between the cases in solution time. And this can be seen when we take the number into the the Difficulty Indicators.
For case five TI:
For DI1: $N_{matches} + N_{streams} = 49$
For DI2: $N_{matches} + N_{TI,hot} + N_{TI,cold} = 120$
For DI3: $N_{matches} * N_{streams} = 588$
For DI4: $N_{matches}^2 + N_{TI,hot} + N_{TI,cold} = 875$
For case five PM:
For DI1: $N_{matches} + N_{streams} = 152$
For DI2: $N_{matches} + N_{TI,hot} + N_{TI,cold} = 155$
For DI3: $N_{matches} * N_{streams} = 2751$
For DI4: $N_{matches}^2 + N_{TI,hot} + N_{TI,cold} = 17185$

5.5.6 Discussion and Results

In this case we are not going to discuss the results from the networks, by we are going to compare the difficulty indicator with the time from Case Five TI and Case Five PM. From Table 23 and 24 it is clear that the number of possible number of matches increases the solution time a lot more than the increasing of temperature intervals.

6 Discussion

This chapter will start with a little summarizing of the discussions from each case, then it will have a discussion on a higher level based on all the cases.

In case study one, the case was quite simple compared with the other cases and the solution time was short between 18 and 28 seconds. The case had seven streams, three cold and four hot. All the streams had the possibility to match, but because the few numbers of streams the possible number of matches was quiet low. The same applies for the number of temperature intervals. The supply and target temperatures are different for each stream. This will give a lot of temperature intervals, but as with the possible number of matches a seven stream problem cannot create a large number of temperature intervals. When reducing the number of temperature intervals, the solution time, and the Total Annualized Cost got higher with some exceptions.

In case study two, the case had fifteen stream, eight hot and seven cold. The case had 69 possible matches, but not a lot of temperature intervals for a fifteen stream problem. The solution was between 112 to 35 seconds for levels four temperature intervals and between 1030 to 70 seconds for three levels temperature intervals. This is a very big increase in the solution time when the number of temperature intervals is reduced. This can be a result from the fact that SeqHENS struggled a lot in this case to find results for the network with the reduced number of temperature intervals.

In case study three it was a twenty-one stream problem, with eleven hot and ten cold streams. This case had a lot of possible matches, and temperature intervals. This resulted in a long solution time a predicted. The solution time went up when the number of temperature intervals was reduces in the same way as the other cases. As the only case in this study in this case the Total Annualized Cost was lowest with two levels of temperature intervals. This case also had a lot of infeasible matches in the results, and this problem did increase in size when the number of temperature intervals was reduced.

In case study four it was twenty-one streams as in case three, but in this case, it was few possible matches, and few numbers of temperature intervals. This made this case fast to solve in SeqHENS. In this case it was not possible to get any results when using two or three levels of temperature intervals. So, it is not possible to compare the performance when the number of temperature intervals is reduced within this case, but it amplifies the fact that SeqHENS gets problems with the results when the number of temperature intervals is reduced. As this case has the same number of streams as case three, butt the number of matches and the number of temperature intervals is very different this is a clear indication for that these two factors have a great importance for the solution time.

In case five the study did not compare the Total Annualized Cost within one network, but it did compare the solution time for two different cases. This was done to get a clear comparison between the effect the possible number of matches and the number of temperature intervals had on the solution time. In this case it was clear that the number of matches had a much greater impact on the solution time, then the number of temperature intervals.

In this case study all the solution times is from the same computer, and SeqHENS is the only program running. In that way all the cases have the exact same computing power during the timing for all the cases. Early in the study, it was quite clear that there were problems finding results at two levels with temperature intervals. So that the study would not end up with four cases without any results from two levels of temperature intervals, each case has been tested with several different HRAT and the one with the most results with two temperature intervals has been used in the rest of the cases. As we can see for the case study all cases with some exceptions the solution time went up, and the Total Annualized Cost went up when the number of temperature intervals was decreased. The reason for this increase in solution time, comes from two reasons. The first one is that SeqHENS is struggling a lot more to find the results with fewer numbers of temperature intervals. The second is that the number of temperature intervals does not affect the solution time predicted in theory. Also, when the number of temperature intervals is reduced the number of results is also reduced. In most of cases at least one of EMAT 1,2 or 3 did not contain any results for two and three temperature intervals.

When comparing the Difficulty Indicators for these cases we can see that the possible number of matches has a great impact on the solution time compared with the number of temperature intervals. This is especially clear in case five. Thus, the possible number of matches should have a greater impact on the Difficulty Indicator then the number of temperature intervals. This makes Difficulty Indicator number four the best candidate. If all four Difficulty Indicators are printed as graphs, with the DI as the vertical axis and the Solution time for U_{min} as the horizontal axis it is clear that Difficulty Indicator four is the best as shown in Figure 25.

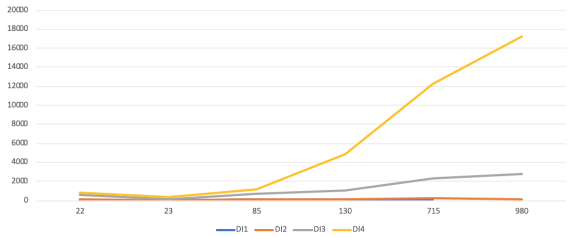


Figure 25: Difficulty Indicators and solution time

As shown in Figure 25 the Difficulty Indicator ranges from 400 to almost 20000. To make the Difficulty Indicator easier to read it should be divided by 1000. Thus, going from 0 to 20 for this case study. This will make a Difficulty Indicator that gives a clear indication for how long the solution time in SeqHENS will be, and it will be easy to read.

7 Conclusions and Further Work

In this thesis the main objectives are to make a way for SeqHENS to handle bigger cases witch the current version can't and make a Difficulty Indicator for SeqHENS. In this case study the current version of SeqHENS was compared with a version of SeqHENS with a reduced number of temperature intervals in four cases. As shown in the case study and the discussion the number of temperature intervals did not affect the solution time as predicted in the chapter 3. In fact, when the number of temperature intervals was reduced SeqHENS had a longer solution time and struggled a lot more to find results then in the original version. So, reducing the number of temperature intervals in the program is not a good way to reduce the solution time for bigger, and more difficult cases.

When constructing a difficulty indicator for SeqHENS the case study has compared six different sets of stream data. It is clear from this study that the number of possible matches has a great impact on the solution time. This is reflected in the difficulty indicator four as discussed in discussion. And the case study found that Equation 4.4 will predict when difficulty for a set of streams in SeqHENS.

For further work SeqHENS has some improvements. It is very easy to use SeqHENS, it is user friendly and as an engineer you can interact with SeqHENS through the problem. And as shown in the case studies SeqHENS does not use a lot of time to solve the problems, but this do not include the time spent making the superstructures after the results from SeqHENS. This work can be very time consuming. If SeqHENS had calculated the superstructures and printed out the finished network the program would have been more user-friendly. One easy and quick solution for this can be to make SeqHENS print the matches between streams with heat load, temperature in and out for each stream. This will make it possible to calculate the Total Annualized Cost without going through all superstructures for all the results.

The case study shows that the most efficient way to reduce the solution time for the Stream Match Generator Sub-problem is to reduce the number of possible matches within the case. This can be done by adding a minimum heat transfer load for each match, thus removing the possible matches with a small heat transfer. This Theory was presented in Chapter 3, but I was not able to make this work during this project. If this function is made available, it would most likely reduced the solution time in SeqHENS. This will also make the program better for solving industrial sized problem, where heat exchangers with small heat load is not wanted.

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