# THE MIXED INTEGER NON-LINEAR PROGRAMMING FOR COMBINED HEAT AND MASS EXCHANGER NETWORK SYNTHESIS WITH THE EFFECT OF EMCD AND EMAT ON ECONOMIC ANALYSIS

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science The Petroleum and Petrochemical College, Chulalongkorn University in Academic Partnership with The University of Michigan, The University of Oklahoma, Case Western Reserve University, and Institut Français du Pétrole 2020

บทคัดย่อและแฟ้มข้อมูลฉบับเต็มของวิทยานิพนธ์ตั้งแต่ปีการศึกษา 2554 ที่ให้บริการในคลั<mark>มปัญญาทุฬาห</mark>(¢µ**ห**) เป็นแฟ้มข้อมูลของนิสิตเจ้าของวิทยานิพนธ์ที่ส่งผ่านทางบัณฑิตวิทยาลัย <sup>3869511871</sup>

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# The Mixed Integer Non-Linear Programming for Combined Heat and Mass Exchanger Network Synthesis with The Effect of EMCD and EMAT on Economic Analysis

Miss Eleonora Amelia

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# การโปรแกรมไม่เชิงเส้นผสมจำนวนเต็มสำหรับการสังเคราะห์ระบบเครื่องแล กเปลี่ยนความร้อนและมวลแบบรวมกับผลของ EMCD และ EMAT ต่อการวิเคราะห์ทางเศรษฐกิจ.

น.ส.เอเลโอโนรา อเมเลีย

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต สาขาวิชาเทคโนโลยีปีโตรเลียมและพลังงาน ไม่สังกัดภาควิชา/... วิทยาลัยปีโตรเลียมและปิโตรเคมี จุฬาลงกรณ์มหาวิทยาลัย ปีการศึกษา 2562 ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย

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### **GRAPHICAL ABSTRACT**

## The Mixed Integer Non-Linear Programming for Combined Heat and Mass Exchanger Network Synthesis with The Effect of EMCD and EMAT on Economic Analysis

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Combined Heat and Mass Exchanger Network Synthesis (CHAMENS)

#### **Graphical Abstract**

The Combined Heat and Mass Exchanger Network Synthesis (CHAMENS) which comprised a win-win strategy simultaneously diminishing the emission alongside maximizing the profits of the whole systems has been accomplished in this work. The novelty comes from the development of the original stage-wise superstructure (SWS) by (*Grossman and Sargent, 1978*) to be able to overcome CHAMENS problem. The Total Annual Cost (TAC), the number of units needed, some advantages and limitations of the other methods have been compared and analyzed. The results for the application of this work in CHAMENS have been achieving a significant TAC reduction of \$ 235,306  $a^{-1}$  for a year operational time compared to the other previous literature.

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**Keyword:** Combined Heat and Mass Exchanger Network (CHAMENS)/ Heat Exchanger Network Synthesis (HENS)/ Mass Exchanger Network Synthesis (MENS)/ Stage-Wise Superstructure (SWS)

เอเลโอโนราอเมเลีย: การโปรแกรมไม่เชิงเส้นผสมจำนวนเด็มสำหรับการสังเคราะห์ระบบเครื่องแลกเปลี่ยนความร้อนและ มวลแบบรวมกับผลของ EMCD และ EMAT ก่อการวิเคราะห์ทางเศรษฐกิจ (The Mixed Integer Non-Linear Programming for Combined Heat and Mass Exchanger Network Synthesis with The Effect of EMCD and EMAT on Economic Analysis) อ.ที่ปรีกทา หลัก: ก็ดีพัฒน์ สีนานนท์

งานนี้ได้ทำการสังเคราะห์ระบบเครื่องแลกเปลี่ยนความร้อนและมวลแบบรวม (CHAMENS) ซึ่ง ประกอบด้วยวิธีแบบได้ประโยชน์ทั้งสองฝ่ายพร้อมกัน ด้วยการลดการปล่อยพลังงานไปพร้อมกับการทำให้ระบบ ทั้งหมดได้ประโยชน์สูงสุด นวัตกรรมนี้เกิดจากการพัฒนาการแบ่งระบบโครงสร้าง (SWS) แบบเดิมให้สามารถ แก้ปัญหาด่าง ๆ ได้แก่ การพิจารณาต้นทุนในรายละเอียดโดยใช้สูดรที่ถูกต้องแม่นยำกว่าในการกำหนดโครงแบบ ของเครื่องแลกเปลี่ยนความร้อน การกำหนดค่าตั้งดิน ขอบเขตที่เอื้ออานวยต่อการจัดการความชับซ้อน ตัดจำนวน เครื่องแลกเปลี่ยนความร้อน การกำหนดค่าตั้งดิน ขอบเขตที่เอื้ออานวยต่อการจัดการความชับซ้อน ตัดจำนวน เครื่องแลกเปลี่ยนความร้อน และมวล และลด TAC วัตถุประสงค์ของงานนี้คือการกิดค้นวิธีใหม่ที่น่าสนใจและ ยึดหญ่นในการนำไปปฏิบัติ โดยให้ผลที่ถูกต้องแม่นยำกว่าสำหรับกรณีศึกษา MENS, HENS, CHAMENS โดยใช้ GAMS มีการเปรียบเทียบและวิเคราะห์ด้นทุนรวมต่อปี (TAC) จำนวนเครื่องที่ต้องใช้ประโยชน์และข้อจำกัดบาง ประการของแต่ละวิธี การใช้งานนี้ใน CHAMENS ส่งผลให้ TAC ลดลงอย่างมีนัยสำคัญที่ \$ 235,306 ล' ในช่วงหนึ่ง ปปฏิบัติการเมื่อเทียบกับวิธีพินช์ลอย

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เทคโนโลซีปิโตรเลียมและพลังงาน 2562 

#### # # 6173004063 : MAJOR PETROLEUM AND ENERGY TECHNOLOGY KEYWOR Combined Heat and Mass Exchanger Network (CHAMENS)/ Heat D: Exchanger Network Synthesis (HENS)/ Mass Exchanger Network Synthesis (MENS)/ Stage-Wise Superstructure (SWS)

Eleonora Amelia : The Mixed Integer Non-Linear Programming for Combined Heat and Mass Exchanger Network Synthesis with The Effect of EMCD and EMAT on Economic Analysis. Advisor: Asst. Prof. KITIPAT SIEMANOND, D.Eng.

The Combined Heat and Mass Exchanger Network Synthesis (CHAMENS) which comprised a win-win strategy simultaneously diminishing the emission alongside maximizing the profits of the whole systems has been accomplished in this work. The novelty comes from the development of the original stage-wise superstructure (SWS) to be able to overcome the problems including detailed cost considerations by using more accurate formularies to determine the exchanger configurations, initializations, favorable boundaries to solve the complexities, eradicate the number of the heat and mass exchangers, and decrease the TAC. The purpose of this work is to generate the new applicable method which is noticeable and flexible to be implemented with a better accuracy output for the case studies, MENS, HENS, CHAMENS using GAMS. The Total Annual Cost (TAC), the number of units needed, some advantages and limitations of each method have been compared and analyzed. The results for the application of this work in CHAMENS have been achieving a significant TAC reduction of \$ 235,306  $a^{-1}$  for a year operational time compared to the floating pinch method.

Field of Study: Academic Year:

Petroleum and Energy Technology 2019 Advisor's Signature

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# CHAPTER 1 INTRODUCTION

The energy and the environmental problems take the important parts in the industrial worldwide. Hence, a poor energy system alters environmental destruction such as the uncontrollable air pollution, high GHG emission of the industry, and global warming. Therefore, some of the main aspects in the industrial and manufacturing processes are how to deal efficiently with the emission standard, the energy used and consequently the cost of the whole systems. Based on the authority of International Energy Agency (IEA) annual data, the global energy demand is expected to grow up about 25% from 2016 to 2040. Consequently, increased global energy demand leads to exorbitant energy prices. In fact, one of the most energy-intensive industries is refinery. Based on the U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis by the US department of energy, the process heating used about 90% of onsite fuel, 65% direct used and 23% to generate the steam used in process heating for a refinery.

The issues such as the energy efficiency needs, energy crisis, costly energy prices, and sustainability of the process plants have enhanced the advancement of the optimum integration in both heat and mass exchanger network. Therefore, the combined heat and mass network synthesis in the same manner with the win-win strategy simultaneously diminishing the emission and the TAC of the whole system should be applied. The Total Annual Cost (TAC) involves the capital and operational expenses that is possible to be turned down depending on the design of the network such as the stream pairs, the number of the utilities required or the network areas needed of both Heat Exchanger Network (HEN) and Mass Exchanger Network (MEN) related to the heat and mass exchange, heating or cooling process streams.

In order to meet the desired criteria as mentioned above, this thesis is focused on both the enrichment of the synthesis in the subsystems and the approaches which streams to link them from more than one subsystem in MENS, HENS, and CHAMENS case studies. The aim of this thesis is to solve the combined heat and mass exchanger network (CHAMENS) simultaneously to produce the same output with the highest energy saving of the process with the lowest TAC. The result of this work is analyzed and compared to the other literatures depending of many factors such as the energy saving, the Total Annual Cost (TAC), computation time, the number of units needed, the advantages and the limitation of each method. The rigorous modeling in the real industrial application is a challenge for the former to develop the sustainable industrial energy systems.

# CHAPTER 2 THEORETICAL BACKGROUND AND LITERATURE REVIEW

In this chapter, the reasons of the selected method for synthesizing combined heat and mass exchanger network used in this thesis can be found as compared to the characteristics of the other existing methods, the purpose and the characteristics of the Mass Exchanger Network Synthesis (MENS), Heat Exchanger Network Synthesis (HENS), and Combined Heat and Mass Exchanger Network Synthesis (CHAMENS) are described from many difference literatures.

#### 2.1. Mass Exchanger Network Synthesis (MENS)

Mass Exchanger Network Synthesis (MENS) is defined as the optimization model producing the optimum network configuration with optimal flows and stream pairings that minimizes the amount of expensive mass cleaning agent used and the total annual cost using recycling scheme or direct contact mass transfer units. In the industrial or chemical process, the mass exchanger network is usually used to selectively remove the pollutants (rich streams) to meet the emission standards by using minimum the external mass separating agent as the lean streams. The construction of HENS is possible to be used as MENS with some modifications. The differences between MENS and HENS are shown. The processes of MENS are usually used in industry for examples absorption, adsorption, stripping, leaching, ion exchange, solvent extraction, and hybrid distillation-pervaporation.



Outlet lean streams containing the emissions (Mass Separating Agents)

Figure 2.1 Mass exchange flow pattern scheme.



**Figure 2.2** a) Mass flow pattern for a single contaminant, b) Mass flow pattern for multiple contaminants (Alva-Arga'ez 1999).

The different between the mass flow pattern for single and multiple contaminants is demonstrated in figure 2.2a and 2.2b. The mass flow pattern for multiple contaminants contains the input of the residual mass load at the top concentration interval, and the output of the residual mass load in the bottom interval. In contrast, the mass flow pattern for a single contaminant does not have them. Moreover, connected to Fig. 2.3 and Fig. 2.4, the figures show the evidences the new stage-wise superstructure model benefits as compared to the traditional mass exchanger network synthesis (Short, Isafiade, Biegler, & Kravanja, 2018). Those figures depict that the new stage-wise superstructure has fewer mass exchangers than the traditional method impacting to the higher additional cost savings without lowering the performance of the mass exchanger duties. As it can be seen from Fig. 2.4, it has fewer stream exchanged because of the robust MINLP optimization including the correction factor to become more realistic and solve the large differences between the fixed parameters in MINLP and NLP. The minimum TAC can be provided without neglecting the pressure drop, the costs of internals, packing sizes and diameters.



**Figure 2.3** The example of mass exchange network using traditional method (Short, Isafiade et al. 2018).



Figure 2.4 The example of mass exchange network using the new stage-wise superstructure (Short, Isafiade et al. 2018).

## 2.1.1. Stage Wise Superstructure (SWS)

The original concept SWS of heat exchanger network (Yee T. F 1990) has been adapted to a novel SWS method proposed (Szitkai Z. 2006) that is capable to synthesize mass exchanger networks using MINLP. The lean streams of MENS are not corresponding to the cold streams of HENS because the external lean streams in MENS does not always mean the leanest. On the contrary, the cold utilities in HENS mean that they are always the coldest.

Each rich and lean stream are not allowed to be matched more than once in this method. The Big M as the logical constraint averts the numerical problems by providing the reasonable lower bounds for mass exchanged. Sizing the mass exchangers, LMCD Chen's approximation (Chen 1987) is used. Driving forces are the variables. In this method, equal mixing concentration, counter-current flow, splitting, mixing, no separate inlet and outlet concentrations for the exchanger are used for single component. Packed columns are identified as mass exchanger for a single component.

If the multiple components are used, the assumption of equal mixing concentration is not used because of a lack the degree of freedom. The model must be extended analogous to multiperiod optimization. Kremser equation (Shenoy and Fraser 2003) is used in a case of either the multiple component using trayed column or the single component with staged column. To make the computational time lower and stabilize the numerical solution, Integer-Infeasible Path MINLP (IIP-MINLP) is also used in this method.

### 2.1.1.1. The Limitation Stage Wise Superstructure (SWS)

The limitation of SWS is that it does not consider the pressure drop. Moreover, mass transfer coefficient in SWS for each pair is equal. In fact, the mass transfer coefficient for each pair in each column is not always equal. The assumption of SWS that only the stream with equal concentration can be mixed is unreliable to be applied in a case of multicomponent problems. Moreover, the overall efficiency of the tray, inactive height and tray spacing used in the cost function are unclear, and they cannot be constant. These factors impact to the result that are unreliable. This method can be applied to ammonia removal, sulfur dioxide (SO<sub>2</sub>) removal, and COG sweetening.

#### 2.1.2. The Enhancement of SWS

Isafiade et al., (Isafiade 2018) have developed SWS method (Szitkai Z. 2006) into a reduced superstructure by adopting the method proposed by Isafiade et al., (2015) to overcome MENS with two steps solved by using MINLP. The first step entails solving the problems with the SWS method. Then, the selected stream matches and the existing matches of the original network of the first step are used to set up the reduced superstructure in the second step to minimize the binary variables.

Not only reusing the existing exchangers in the original network but also adjusting the capital cost component are used in the objective function to add the new exchangers with the minimum exchanger area required. This method depends on the number of stages, the equilibrium concentration difference, the driving force, the composition of supply and target, and the flowrate of each pair.

#### 2.1.2.1. The Advantage of New Stage Wise Superstructure (SWS)

The advantages of this method are it has less computationally intensive, lower payback period and fewer binary variables. This method is possible to be used for the case which includes continuous contact column. This reduced superstructure has been applied to the coke-oven gas sweetening process.

### 2.1.3. The Hybrid Optimization

The model (Short, Isafiade et al. 2018) transformed the HENS model (Short et al., 2016) to be able to solve Mass Exchange Network Synthesis (MENS) problems using two steps. In the first step, MINLP combined with the correction factors is used to produce the boundary conditions for the first and last element for the supply and target concentration, mass balance, and network topology accurately based on modified SBS (Azeez, Isafiade et al. 2013) which accommodates unequal mixing composition. The amount of change that a correction factor can undergo should no more than 5 % to prevent drastic solution space. In MINLP, the diameters, mass transfer coefficients, packing characteristic are assumed to be constant, and the pressure drops are not considered.

In contrast with MINLP, NLP provides the solution of the optimization for the second step by applying detailed equation and considering the flooding limitations, optimum packing sizes, diameters, heights, flux changes along the column, variation in the overall mass transfer coefficients, actual pressure drop across the column etc. Orthogonal Collocation on Finite Elements (OCFE), the Lagrange polynomial, the big M formulation, the LMCD approximation (Chen 1987) are used to produce feasible solution.

#### 2.1.3.1. The Limitation of New Hybrid Method

However, this hybrid method may be difficult to be solved as high non-convexities and very complex. This method has been applied to hydrogen sulfide removal from a Claus unit, and contaminant ammonia removal.

#### 2.2. Heat Exchanger Network Synthesis (HENS)

Heat Exchanger Network Synthesis (HENS) is a network of process synthesis that attains a maximum heat exchange of both hot and cold stream while markedly saving energy, improving the heat transfer area and minimizing the total annual cost by identifying the optimum pairs of the stream matches. In the heat exchanger network, the bypass is used to control the process stream target temperatures by overcoming the disturbances from the temperature and/ or flowrates of incoming streams. Moreover, the splitter is used to separate the outlet flow, and the mixer is usually placed prior to each exchanger.

Figure 5 shows the possible structural modification in HEN retrofitting proposed by (Pavão, Costa et al. 2019) and inspired by (Floudas 1989). The first structure in Fig. 2.5 shows the replaced of the original heat exchanger with another heat exchanger without re-piping. Number 2 is the same as number 1 but it includes repiping. In the number 3, one associated re-pipping is included in an original heat exchanger, and if one stream differs from the original stream, re-sequencing is applied. Based on number 4, an original heat exchanger is re-pipped. Number 5 shows the replacement of an original heat exchanger with a new heat exchanger before an original heat exchanger is moved without re-pipping. Number 6 is related to number 5, but it contains one of the streams re-pipped, purchasing new heat exchanger, and single-stream re-piping. In the end, number 7 shows a new match of a new heat exchanger for example the piping changes required for the two streams. Based on Fig. 2.6, there are two types of streams, the vertical and the nonvertical streams. it shows that the heat transfer coefficients which are different significantly from one to the other heat transfer coefficients are handled by the nonvertical stream to get the minimum network area. However, the minimum network can still be achieved by applying the mathematical programming method to heat exchanger network synthesis.



**Figure 2.5** Possible structural modification in HEN retrofitting (Pavão, Costa et al. 2019).



**Figure 2.6** the application of the non-vertical stream to minimize the network area (Linnhoff 1990).

## 2.2.1. Pinch Technology

The pinch technology firstly introduced by (Linnhoff 1983) which use "feasibility criteria" to identify the restriction and "thick-off heuristic" to produce fewest possible units. This method is possible to be overcome by hand calculation. The supply of the new hot utility must be above the pinch, and the supply of the new cold utility must be below the pinch. The heat transfer is not allowed to across the pinch. They used partitioning and cascading. To determine the pinch location, they used the algorithm table by (Linnhoff 1978).

#### 2.2.1.1. The Limitation of Pinch Technology

The limitations of pinch are it depend only on the pinch point and thermodynamically target, and it cannot be optimized simultaneously. The maximum heat integration is limited. They applied pinch in an individual plant.

## 2.2.2. Stage-Wise Superstructure

SWS was originated by (Yee T. F 1990) to abolish the limitation sequential method as it does not rely on pinch point, without using temperature or enthalpy intervals and, without partitioning into subnetworks to determine the different trade-offs simultaneously. This method extends the model proposed by (Grossman and Sargent, 1978). In this method, the heat exchange occurs between each hot and cold stream at each stage.

The advantages of the original SWS are it can be applied for the different heat transfer coefficients, and multi-stream heat exchangers. Moreover, the original SWS method is also better than the spaghetti method, because it has lower number of the heat exchangers than the spaghetti method since the number of intervals does not have to be the same as the number of stages. In this method, they use splitting, crisscross heat exchange, non-zero heat load and iso-thermal mixing assumption solved by using NLP formulation. They also used LMTD from Chen approximation (Chen 1987).

#### 2.2.2.1. The Limitation of SWS

The limitations of the SWS for HENS are SWS cannot be applied in the large retrofit industrial cases such as the crude oil distillation unit pre-heat train proposed by (SMITH, JOBSON ET AL. 2010) because it cannot deal with the case which comprising series of heat exchangers in single stream split branches. As isothermal mixing is used, the heavy computational burdens because of nonlinear terms such as neglecting a few structures. This method was applied to cryogenic plants.

### 2.2.3. The Transshipment Model

The first transshipment model was proposed by (Papoulias 1983) using MILP. In transshipment model, the sources are the heating utilities and the hot streams, and the destinations are the cooling utilities and the cold stream. The intermediate nodes are the temperature intervals. The heat from the hot utilities flows to the temperature intervals, then flows to the cold streams. Moreover, the excess heat flows to the next lower temperature intervals. The partitioning methods from ((Cerda et al., 1981), (Grimes et al., 1980), (Linnhoff 1978)) are usually used. Transshipment model has the smaller size than the transportation model proposed by (Cerda et al., (1981)). Preventing the forbidden matches and treating the restriction separately are the key of this method.

The advantages of the transshipment model are it is available to handle the restricted matches caused by the plant layout, safety requirements, or process control difficulties. Moreover, this method is available to handle the stream splitting, cyclic network, and multiple utilities. All the heat exchangers that were used were the counter-current heat exchangers. It is suitable for small scale problems.

## 2.2.3.1. The Limitation of The Transshipment Model

The limitations of this method are it does not explain about how the flow rates or the streams are distributed because the original transshipment model only considers to the heat flows or the heat configurations not to the mass flows.

#### 2.2.4. The Development of the Original Superstructure.

Conquering the large-scale industrial problem which involve the long pipe length is the challenge for the researchers nowadays due to the high risk, the high computational time and the high computational complexity. If the pipe has the large size, the pressure drop is difficult to be overcome. The more pump and compressor are needed to handle the pressure drop the higher cost will be expensed not only to overcome the pressure drop but also for the safety.

Huang et al., (Huang and Karimi 2013) combined two superstructures in single step monolithic mathematical programming formulation. A specific utility cannot be used more than once by a process stream. Moreover, in the inlet exchanger mixer, the different hot/cold streams of the sub-stream are not allowed to be mixed. The advantages are they apply the cross flows, cyclic matching, series matches on a sub-stream, the multiple utilities at any stage, and utility placement at any stage. They also eliminate the redundant permutation and use accurate LMTD. Therefore, the heat exchanger area based on this model is smaller.

As the limitations, Huang et al., (Huang and Karimi 2013) did not concern on the computational speed to solve the large-scale problems, and they still have nonlinear constraints. Difficulties have been found since they have wider bounds on temperature variables and a lot of binary variables due to solve moderate to large scale problems. They also used a lot of high-pressure steam and the medium-pressure steam that make the TAC higher.

Flourishing the SWS network to be copacetic for tackling the largeindustrial problems a hybrid method which is derivative-free methods has been disclosed (Pavão, Costa et al. 2019). They adopted the SWS (PAVÃO, COSTA ET AL. 2018) and formulating the solution method based on meta-heuristics, the Simulated Annealing-Rocket Fireworks Optimization (SA-RFO) (Pavão, Costa et al. 2017) adding stream splits, steams sub-splitting, cross flows, partial mixing, serial units in a single stream branch, and the allocation of heaters/ coolers at intermediate positions with Parreto efficiency concepts. After a split, cross flows are not allowed to appear at the first sub-stage. This model is available to handle over/ undersized heat exchangers that usually happen because of poor temperature estimation and unpractical design. They also neglect the re-pipping cost because the re-pipping cost is so small compared to energy related cost. If the project lifetime increases, the energy requirement decreases with the increasing of the investments on area.

The limitation of a hybrid method (Pavão et al., 2019) are high of complexity problem and high computation time due to overcome the real-world large-scale industrial problems. This method was applied to industries such as industries based on oil refineries, crude oil distillation units, Fluid Catalytic Cracking (FCC) plant, and aromatic plant.

The model (Xu, Cui et al. 2019) has been proposed the heuristic method the Relaxation Strategy for Fixed Capital Cost-the Random Walk algorithm with Compulsive Evolution (RSFCC-RWCE) for accomplishing the industrial problems from the small-scale problem to the large-scale problems. The key of this method is to overcome the sudden increases of fixed capital cost by randomly shrinking or expanding the heat load by RWCE, so it can generate and eliminate the heat exchanger effectively using RSFCC, and reduce the TAC using adequately relaxation strategy by setting the coefficient of relaxation strength that is not too high to produce reliable result and not too small to overcome the obstacle. The advantages of this method are suitable for solving the problems from the small-scale problems to the large-scale problems, high speed of computational time, and producing reliable result.

## 2.2.5. The Development of The Transshipment Model

Hong et al., (Hong, Liao et al. 2017) has modified the original transshipment model (Papoulias 1983) into the new intra-transshipment direct HEN type MINLP model in one step with linear constraints including the heat and mass flow pattern of the hot and cold streams to determine the flowrate stream in each heat transfer match. They applied stream splitting, stream by-pass, isothermal, non-isothermal mixing, recycling mass flows leading to direct heat transfer, and the multiple utilities both in the last stage and in an intermediate stage.

Each hot or cold utility is only allowed to be matched in one temperature interval in series or parallel. Each hot or cold stream is split into several sub streams, then each hot or cold sub stream exchanges heat with at the most one hot or cold sub stream in each temperature interval. The model (Hong et al., 2017) considers the exchanger area cost to get the better results. The heat exchanger area of this method is more accurate than the model proposed by Barbaro and Bagajewicz (Barbaro and Bagajewicz 2005) which apply one step MILP method. However, the model (Huang and Karimi 2013) has more accurate LMTD than the model proposed by (Hong, Liao et al. 2017). To overcome the limitation of the method (Hong, Liao et al. 2017), they have transformed their model into the new transshipment model of intra- and inter- plant heat exchanger network for direct Inter- Plant Heat Integration (IPHI) by process stream to produce larger heat saving and fewer number of the heat exchangers required (Hong, Liao et al. 2019). The piping and pumping cost are included. Moreover, they consider the distance between each pair of the plants and
neglect the heat loss during the transportations. They used the heat and mass flow patterns, the countercurrent heat exchanger, by-pass stream, non-isothermal mixing, a stream branch passing through two heat exchangers in series, multiple utilities in both the last temperature intervals and the other temperature intervals. The heat exchange of each hot/cold process stream is available for any hot/ cold process stream in any plant. They examined their model in splitting and no-splitting condition.

# 2.2.5.1. The Advantage of The Transshipment Model

The advantages of the method (Hong, Liao et al. 2019) are more structure possibilities than the SWS method (Yee T. F 1990) and the lower TAC resulted because the low-pressure steam and the medium-pressure steam are mainly used than the high-pressure steam. Moreover, this method is easy to solve because MINLP with all linear constraints is formulated. However, the limitation is that this model has large of the binary variables. For the application of this method, the method has been applied to three-plant problems.

## 2.2.6. The Development of the Graphical Method

Pouransari and Maréchal (POURANSARI AND MARÉCHAL 2014) has been disclosed heat exchanger network synthesis to surmount the large-scale industrial problem using HLD model and MILP based on sequential approach in indirect exchange to produce advance realistic network sketch by applying this method into a real chemical industry. However, HLD method is still expensive to overcome the large-scale problem since they use the sequential based.

Lai et al., (LAI, WAN ALWI ET AL. 2019) has developed HEN retrofit by using the two combination of the graphical tools which are the improvement of Stream Temperature versus Enthalpy Plot (STEP) for simultaneous diagnosis and retrofit of existing HEN based on the Pinch rule and four retrofit heuristics (Lai, Wan Alwi et al. 2018), and the plot of heat exchanger area versus enthalpy (A vs H) to determine the capital-energy-trade-off in HEN retrofit, adopting the Investment vs Annual Savings (IAS) plot with the Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) strategies to detect the economic performance. They used four types block and focused on the existing heat exchangers, and the additional units to overcome A vs H diagram. However, the total payback period must be equal or smaller than desired payback period. To make the total payback period smaller, the SHARPS strategies are applied by intensification or substitution options. Moreover, multiple utilities are used. This method can provide the smaller heat exchanger area, and low TAC. However, the investment is mainly affected by the number of units required than the heat exchanger area to achieve more energy saving.

The limitations of this method are it will be difficult to implement A vs H plot for the large-scale industries, and no exact range of exchanger area or enthalpy is provided. Moreover, some Pinch rule violations are found. This method has been applied to sunflower oil plant.

## 2.3. Combined Heat and Mass Exchanger Network synthesis (CHAMENs)

The combination of both heat and mass exchanger network plays an important role in the industrial process whether the industry has a good prospect or not. To minimize the resource consumption, the excess of effluent is reused to cool or heat the process. In Fig. 2.7 and Fig. 2.8, the figure shows that the heating or cooling temperature of each pair rich or lean streams in mass exchanger network cannot be neglected. Therefore, the Mass Exchanger Network (MEN) has an essential interaction with the Heat Exchanger Network (HEN).



Figure 2.7 the Onion model proposed by (SAVULESCU, KIM ET AL. 2005).



Figure 2.8 The representation of CHAMENS (Isafiade and Fraser 2009).

Combined heat and mass exchanger network synthesis represents the relations of the temperatures to the equilibrium relations. For examples in a case of absorption, the lower temperatures are needed to get better equilibrium, and the process of stripping is overcome at higher temperature to achieve better equilibrium relations (Seader and Henley, 1998).

# 2.3.1. Pinch Technology

A graphic based method which relies on thermodynamic analysis is recently cultivated by linking Mass Pinch Technology for MENS with Pseudo Temperature Enthalpy Diagram for HENS (LIU, DU ET AL. 2013). Pinch technology was applied to MENS in many works ((Linnhoff 1978); (Linnhoff 1979); (El-Halwagi 1989); (HALLALE 2000). Pinch Technology recovers the mass from the process as much as possible, so the quantity of the external MSA can be reduced. It means that Pinch Technology lowers the AOC.

In the initial step, the plot of each rich mass stream is made to establish a composite of all rich streams on the concentration-load diagram by using the equilibrium concentration and minimum driving forces. The composite curves in concentration load diagram (LIU, DU ET AL. 2013) is different from the diagram proposed by (EL-HALWAGI 1989). They replaced the real concentration of the lean streams with the equilibrium concentrations. The mass transfer pinch point in that method is the point in which the rich composite line touches the equilibrium composite line. Then, combining the small interval into a larger one to decrease the number of small loads unit. Decomposing the composite curves into the real stream by accumulating the mass load depends on the concentration of rich composites curves and the equilibrium composite curves. The real stream can be split into substream and formed the MEN for each interval to be formed overall MENs.

The Pseudo Temperature Enthalpy Diagram is a heuristic method finding the match of the heat transfer streams based on pseudo temperature representing heat transfer energy level that contains the real temperature and the heat transfer temperature difference contribution (HTTDC) values. The procedure for synthesizing HENS in CHAMENS using P-H diagram entails some known mass flowrates, start and target temperatures, thermal capacities, film heat transfer coefficients for the streams to determine the pseudo temperatures. Pinch point depends on the hot and cold stream composite curve which are made by summing the heat loads at each temperature intervals. In order to reduce amount of interval, the small intervals are merged into the large intervals. After this step, constructing the small HENs according to the heat load and connecting them to yield the overall HEN are important to determine the TAC as counter current heat exchanger type is usually assumed.

Some assumptions from the previous network (Srinivas 1994) are used in (LIU, DU ET AL. 2013). The operation condition of this method is isothermal for mass exchange network due to the small temperature change. The mass moved in a system is small, so it causes a small temperature change. Based on this condition, the mass exchange temperature depends on the lean stream temperatures. They also use the lean bypass stream in mass exchange network to reduce the concentration of the emission and to decrease associated costs.

A paralleled genetic algorithm-simulated annealing algorithm (GA-SA), the stochastic or meta-heuristic optimization, is also used in their works. GA-SA is copacetic to figure out the large-scale, non-convex, non-continuous problem without using gradient. GA-SA is more accurate because it has no gradient, and simplifying is not needed to search the optimal solution. Moreover, GA-SA has less

CPU time. The other benefit of GA-SA is that it has lower required memory. OCX operator, EC operator, and mutation operator are used to maximize GA-SA performance.

## 2.3.1.1. The Limitation of The Pinch Technology

The limitation of pinch technology is that it still has the flaw to generate the real global optimal solution for a large HENS problem, non-equivalent concentration and temperature. Pinch technology method is not possible to overcome the case with the change of concentration and pressure because pinch technology uses only temperature as a quality parameter of the streams. It also has high computation time due to the sequential nature. Since the mass is not allowed to be transferred above the pinch region, it leads to the small driving force. The small driving force means more cost is needed to use more external MSA required to remove mass by the lean stream.

Pinch technology has been applied in aromatic plant, ammonia removal (Hallale, 1998), dephenolization of aqueous wastes (El-Halwagi, 1997), coke-oven gas removal (EL-HALWAGI 1989), dephenolization of coal conversion waste (KATERINA 1993).

# 2.3.2. Hyper structure

Hyper structure is a method which broadens the "maximal" structure or superstructure to synthesize the heat and mass exchanger network without any decomposition at the minimum total annual cost. A cyclic network is not comprised by the pure hyper structure network in that the streams are not allowed to appear twice in sequence. It means that the two streams are not permitted to be matched more than once. All possible matches in the regenerating streams, the rich and the lean stream determine the hyper structure network.

Moreover, the total mass and energy balances at the pure heat exchangers in which no contact between the condensate and heavy product with the heating or cooling streams occurs also affect the hyper structure network. Furthermore, the concentration and the phase defining constrains resolve the minimum driving force for the heat and mass transfer. The stream direction, the concentration and the temperature of the stream are important to set whether the streams are the hot/rich streams or the cold/lean streams. The rich streams represent the streams that has a decreasing concentration during the process. Different from rich streams, the streams that has the concentration increasing during the process is specified as the lean stream.

Hyper structure is also capable to deal with either conventional or unconventional units and processes (KATERINA 1993). They used hyper structure network to accomplish the case of the distillation column including the homogenous reaction, splitter, mixer, bypass, and the pure heat exchangers.

The simultaneous synthesis of the heat and mass exchanger network using hyper structure and multiperiod MINLP approach is proposed by (KATERINA 1993). In their method, some assumptions are used. The temperature and composition difference of the two streams is important to determine the maximum number of the heat and mass exchanger needed between the two streams. When the heat and mass exchange does not take place in the same exchanger, isothermal mass transfer is used. Furthermore, they use mixing, splitting, and bypass of inlet and outlet streams at the constant operating pressure which the heat capacities and heat transfer are as the function of the composition of the streams not as the function of temperature. To obtain the optimal network, an objective function, mass and energy balances of each heat exchanger are used in each period of operation and the logical constraint to connect the network.

#### 2.3.2.1.The Limitation of Hyper Structure

The limitations of the hyper structure network are high computation time due to highly nonconvex and nonlinear. When the hyper structure is combined with MINLP based, it will be more difficult to be solved since including the numerous binary variables. As the cyclic network is excluded, the heat exchanger area is high. The function of the cyclic network is to decrease the heat exchanger area and give the number of heat exchanger unit required at the less TAC. From the literature, Floudas and Ciric (Floudas 1989) established the hyperstructure for non-isothermal mixing and cross flow based on pinch transshipment to figure out heat exchanger network. The pinch-transshipment uses the Temperature Interval Approach Temperature (TIAT) to partition the temperature range into interval that leads to a suboptimal network and the tradeoffs between the utility costs, the number of stream matches, the number of heat exchanger requirement and the minimum investment cost are not taken into account appropriately.

The hyperstructure network has been found in dephenolization, and it is applicable in the production of ethylene glycol.

#### 2.3.3. Interval Based MINLP Superstructure (IBMS)

IBMS proposed by (Jide 2007) is a mathematical method which consists of the superstructure interval boundaries depending on the supply and target temperatures/compositions of the hot/rich streams or the cold/ lean streams to synthesize CHAMENS simultaneously. The basis of IBMS in HENS is the highest supply temperature of the hot stream used as the first temperature location, and the lowest target temperature of the hot stream used as the last temperature location. In a case of MENS, when the operation condition is isothermal, IBMS method concerns on the different mass exchange temperature of the lean streams and the equilibrium relations. In addition, the regeneration of TAC is only affected by the flow and concentration differences of the lean streams since the function of regenerating stream is to remove the mass load. The intermediate temperatures are variable.

By combining the IBMS equation of MENS and HENS, gradient based solver such as MINLP is usually used. IBMS can be applied for isothermal and isocomposition. Multiperiod IBMS method use different temperatures, flowrates, heat duties for each time period. IBMS method is better to handle multiple utilities, and multiperiod operation than NLP method as IBMS does not include the non-linear heat and mass balance.

## 2.3.3.1. The Limitation of IBMS

The limitation of IBMS is that the heat exchange is only originated to all the hot streams at the supply and target temperatures. Therefore, the exchange heat cannot occur freely to both hot and cold streams. It contributes to less interval and less opportunity stream matches. Moreover, another impact of this is the TAC will be high. IBMS has been applied to the ammonia removal, dephenolization of coal conversion waste, and coke-oven gas removal.

## 2.3.4. Supply-Based Superstructure (SBS)

SBS is a simultaneous superstructure mathematical approach which the superstructure interval boundaries are created by the supply temperatures of the hot and cold streams for HENS, and the supply compositions of the rich and lean streams for MENS. The variables are the temperatures that crosses the boundaries.

The SBS method has been proposed by (Azeez, Isafiade et al. 2013) to solve HENS and MENS problems. The superstructure method is characterized by the hot and cold process streams at different initial temperature location. At the first temperature location, the hot process streams are started and ended at the last temperature location. In the other words, the hot process streams are started from left to the right while the temperature decreased. The opposite direction is the cold process streams. The structure descends from the highest supply temperature at the top (hot streams) to the lowest supply temperature at the bottom (cold streams).

Prior to HENs, if the temperature intervals are higher than the supply temperature, the heat exchange are not possible for the hot stream. In contrast, the heat exchanges are also not possible for the temperature intervals which are lower than the supply temperature for the cold streams. In each interval, it is possible to put stream splitting at isothermal operation. SBS does not strictly depend on the pinch technology because the intermediate temperature is variable. It has more intervals than SWS method. The heat exchange of a hot stream is not allowed for the temperature intervals that are higher than the supply temperature. Conversely, the heat exchange of the cold streams is not allowed for the temperature interval that has lower temperature than the supply. The total enthalpy change must be balance. In case of MENs, if the compositions of the intervals are higher or equal than the supply composition value, the mass exchanges of the rich streams are not possible. The lean stream is only possible to exchange mass if the compositions of the intervals are higher than the supply value.

The advantages of SBS can deal with different heat transfer coefficient and the large problem. It has more heat exchange available because the heat exchange can freely occur on both the hot and cold streams depending on the intervals. Not only the opportunity of the heat exchange but also the mass exchange is high. The mass exchange opportunity is high because the mass exchange can occur on both the process and the external lean streams.

## 2.3.4.1. The Limitation of SBS

The limitation of SBS is not suited for the smaller problems. Although SBS has more interval than SWS, it does not always give the lower TAC as the number of the intervals increasing. The TAC depends on the intervals used. If the number of intervals used is fewer than the interval existed, the TAC will be higher. The applications of SBS network are dephenolization of coal, coke oven gas removal, dephenolization of aqueous waste, aromatic plant, and ammonia removal.

# 2.3.5. Stage Wise Superstructure (SWS)

Stage Wise Superstructure (SWS) is a method that the stage temperature is not fixed, so it can handle the streams enclosing significantly different heat transfer coefficient. In SWS, the supply temperature at the first temperature location is adopted by all the hot streams. Conversely, the supply temperature at the last temperature location is adopted by all the cold streams. The boundaries temperatures/composition of all streams are variable, but the number of intervals is fixed. The number of enthalpy intervals are higher than the number of stages. The advantage of SWS is suitable to handle the high capacity of production and uncertain mass exchange temperature. Moreover, it accomplishes such a better result at nonisothermal and non-equal concentration mixing. Based on the previous chapter, since 1990s the SWS network has been popularized by Yee and Grossman, and the another SWS was proposed by Shenoy (Shenoy, 1995) to solve HENs problem. MENs, equally important, has been proposed using SWS (Chen 2005) and (Szitkai Z. 2006)). The Stage Wise Superstructure method is combined with Indistinct HEN Superstructure (IHS) proposed by (Liu, Du et al. 2015) to minimize the difficulties during synthesizing sub-HENs and sub-MENs. They construct the superstructure method in the beginning before synthesizing at non-equivalent mixing condition. Moreover, they also use NLP for optimization. NLP has many functions because NLP consists of the hybrid Genetic Algorithm-Simulated Annealing Algorithm (GA-SA) which can effectively determine the minimum TAC and identify the tradeoffs between HEN and MEN simultaneously with capital cost and operation cost. The hot streams are important to calculate the heat exchange. The number of the potential heat exchange streams depend on the start temperature, the mass exchange temperature, and the target temperature of each stream.

## 2.3.5.1. The Advantage of SWS

The advantage of the SWS is that SWS has many stages assisting the more combinations of the stream matches. The more combinations lead to the lower TAC. The SWS network is also suitable for the small problem and the large problem. SWS has the structural stages which all of heat exchange possible can be found in different branch of splits. The application of SWS in industries can be found on coke oven gas removal, dephenolization of aqueous wastes, ammonia removal, and aromatic plant.

# 2.4. Logarithmic Mean Composition Difference (LMCD)

LMCD can be calculated by using Chen's approximation (Chen 1987) that is commonly used to avoid the problems of singularities in the LMCD calculations. The LMCD formulation in eq. 1 is cited by (Short, Isafiade et al. 2018). Some literature ((Short, Isafiade et al. 2018), (Isafiade and Short 2016), (Azeez, Isafiade et al. 2013), (Isafiade and Fraser 2009)) also have used this approximation. The result of actual LMCD to the LMCD by using Chen's first approximation has been compared, the result shows that if the ratio of the composition difference at an exchanger's rich end to that at the lean end increases, the accuracy of the LMCD decreases (Isafiade and Short 2016). Based on the comparison LMCD proposed by (Shenoy and Fraser 2003), the error of Chen 1<sup>st</sup> approximation was the worst, 4.67%. In contrast, the Chen 2<sup>nd</sup> approximation performed the best than the LMCD of the Underwood (1970) and the Patersen (1984) in which the error of the LMCD 2 Chen 2<sup>nd</sup> approximation is 0.53%.

Moreover, the effect of the rate absorption to the LMCD is also reported (Suresh 2011). As the rate of absorption at lower temperature increases, the LMCD increases because the mass transfer coefficient is lower at low inlet temperature.

$$LMCD_{r,l,k} = \left[\frac{(dy_{r,l,k})(dyrl_{r,l,k})(dy_{r,l,k} + dyrl_{r,l,k})}{2}\right]^{1/3}$$
(1)

The Chen 1<sup>st</sup> approximation for LMCD formulation (Chen 1987)

$$LMCD_{r,l,b} = \left[ (dy_{r,l,b}) \cdot (dy_{r,l,b+1}) \cdot (dy_{r,l,b} + dy_{r,l,b+1})/2 \right]^{1/3}; r \in \mathbb{R}; l \in S; b \in B$$
(2)

The Chen 2<sup>nd</sup> approximation for the LMCD formulation (Chen 1987)

$$LMCD = \left[\frac{1}{2} \left( \left( y_{r,b} - y_{l,b}^* \right)^{0.3275} + \left( y_{r,b+1} - y_{l,b+1}^* \right)^{1/0.3275} \right) \right]$$
(3)

The LMCD approximation of Underwood (Underwood, 1970)

$$LMCD = \left[\frac{1}{2} \left[ \left( y_{r,b} - y_{l,b}^* \right)^{1/3} + \left( y_{r,b+1} - y_{l,b+1}^* \right)^{1/3} \right] \right]^3$$
(4)

The LMCD proposed by Paterson (Paterson, 1984)

$$LMCD_{r,b,l} = \frac{2}{3} \left[ \left( y_{r,b} - y_{l,b}^* \right) \cdot \left( y_{r,b+1} - y_{l,b+1}^* \right) \right]^{1/2} + \frac{\left( y_{r,b} - y_{l,b}^* \right) + \left( y_{r,b+1} - y_{l,b+1}^* \right)}{6}$$
(5)

#### 2.5. Logarithmic Mean Temperature Difference (LMTD)

The LMTD is used to determine the temperature driving force for heat transfer. It is also important to determine the area cost coefficient for heat exchangers. Fig. 9 represents the comparison of log-mean approximation errors from many difference literatures proposed by (Azeez, Isafiade et al. 2013).



**Figure 2.9** The comparison of log-mean approximation errors (Azeez, Isafiade et al. 2013).

Based on Fig. 2.9, the Chen's  $2^{nd}$  approximation performed better than the Patterson's approximation over the range  $\Delta T_2/\Delta T_1$  values from 1.5 to 10, but it is slightly fewer accurate than Underwood's approximation at a ratio of 1.5 and at a ratio below 5. Moreover, the Chen's  $1^{st}$  approximation performed worse than the other approximations at ratio above 2. However, if the driving forces are equal, the <sup>1st</sup> Chen's approximation is better to be used than the 2<sup>nd</sup> Chen's approximation because it is more accurate, as the comparison of the results for this case has been made by (Azeez, Isafiade et al. 2013).

The Chen 1<sup>st</sup> approximation for LMTD formulation (Chen 1987)

$$LMTD_{i,j,k} = \left[ \left( dt_{i,j,k} \right) \cdot \left( dt_{i,j,k+1} \right) \cdot \left( dt_{i,j,k} + dt_{i,j,k+1} \right) / 2 \right]^{1/3}; i \in I; j \in J; k \in ST$$
(6)

The Chen 2<sup>nd</sup> approximation for the LMTD formulation (Chen 1987)

$$LMTD = \left[\frac{1}{2} \left( \left( ti_{i,k} - tj_{j,k}^* \right)^{0.3275} + \left( ti_{i,k+1} - tj_{j,k+1}^* \right)^{1/0.3275} \right) \right]$$
(7)

The LMTD approximation of Underwood (Underwood, 1970)

$$LMTD = \left[\frac{1}{2} \left[ \left( ti_{i,k} - tj_{j,k}^* \right)^{1/3} + \left( ti_{i,j+1} - tj_{j,k+1}^* \right)^{1/3} \right] \right]^3$$
(8)

The LMTD proposed by Paterson (Paterson, 1984)

$$LMTD_{i,j,k} = \frac{2}{3} \left[ \left( ti_{i,k} - tj_{j,k}^* \right) \cdot \left( ti_{i,k+1} - tj_{j,k+1}^* \right) \right]^{1/2} + \frac{\left( ti_{i,k} - tj_{j,k}^* \right) + \left( ti_{i,k+1} - tj_{j,k+1}^* \right)}{6}$$
(9)

## 2.6. Intra- and Inter- plant Heat Exchanger Network Synthesis

For choosing the suitable method to synthesize HENs in intra- and interplant heat exchanger network, this section will detail some selected methods to ensure that those methods were robust with special focuses on either minimizing TAC or maximizing the NPV due to the exchanger location, the waste heat recovery, the stream transports over long distances, etc. by both inter- and intra- plant heat exchanger network. The plants are separated in the different locations in which each hot/cold process stream can exchange heat with any cold/ hot process stream in any plant and any enterprise due to the high degree of freedom during the transportation of the process stream as it has thermodynamically feasible.

There are three kinds of the heat integrations, direct integration, indirect integration, and the combination heat integration. Direct IPHI is better to be used due to larger heat saving, fewer number of utilities, less risk to the leakage and safety. High energy recovery is possible to be achieved by using both inter- and intra- plant heat exchanger network. The disadvantages of indirect heat integration are less energy efficiency and high demand of heating or cooling utilities because indirect heat integration uses twice heat transfers which are the intermediate fluids and the process streams.



**Figure 2.10** Three schemes of inter plant heat integration proposed by Hong et al., 2019).

The model (Hong, Liao et al. 2019) used the new transshipment strategy as the development of the transshipment model (Hong, Liao et al. 2017) considering the heat and mass flow pattern using IPHI direct by process streams. In Fig. 2.10, the scheme 1 represents the stream exchange of the hot process stream from the plant 1 to the plant 2. The scheme 2 is related to the scheme 1 but the stream exchange is transported from the plant 2 of the cold process stream into the plant 1. The scheme 3 including the three plants that is only available to be used when the stream heat exchange occurs by at least one of the two existed process stream with any process stream in the third-party plant to obtain fewer piping and pumping cost than either the scheme 1 or the scheme 2. Their strategies (Hong, Liao et al. 2019) are (1) Minimizing the TAC consisting of the utility cost, the heat exchanger cost, the pipping and pumping cost (2) Considering heat and mass flow schemes (3) Using new constraint, big-M formulation and merging heat transfer matches into one heat exchanger (4) Using DICOPT/GAMS to lower the computational time. However, the method proposed (Hong, Liao et al. 2019) still has the limitation as they neglect the heat losses during the transportation. The heat losses should not be neglected because the heat losses are important related to the energy saving. The more heat losses are, the fewer energy saving is.

The new MINLP model (Nair, Soon et al. 2018) as the enhancement of their previous model (Nair et al., 2016). They used some strategies (1) Maximizing NPV

by computing CAPEX and OPEX considering the ambient heat losses/ gains, the pipping cost, the pumping cost, and the exchanger (2) Selecting the optimum HEN location either the centralized HEN or the distributed HEN (3) Collaborating multiplant multi-enterprise heat integration by using inter- and intra- plant consideration. (4) Using SCIP as MINLP solver in GAMS (5) The possibilities to merge two stages into one stage.

#### 2.6.1. The Mass Flow Pattern of The Transshipment Method

The model (Hong, Liao et al. 2019) used the modified transshipment model (Hong, Liao et al. 2017) to construct their network. They built the interval level according to the constant starting/ ending temperature of the process streams and  $\Delta T_{min}$  to keep the minimum heat transfer difference. Each cold/ hot process stream is divided into sub-stream which exchanges heat with one sub-stream in each temperature interval. Mass flow exists between sub-streams in each interval.



Figure 2.11 Mass flow pattern belong to the hot stream (Hong, Liao et al. 2019).

$$flsk_{p,l,ls,k-1} + \sum_{ls' \in LS} flr_{p,l,ls',ls,n} = flsk_{p,l,ls,k} + \sum_{ls' \in LS} flr_{p,l,ls,ls',n}$$
(10a)

$$flsk_{p,l,ls,k} = flsk_{p,l,ls,k-1} + \sum_{ls' \in I,S} flr_{p,l,ls',ls,n} - \sum_{ls' \in I,S} flr_{p,l,ls,ls',n}$$
(10b)

$$\forall (p,l) \in HP, (p,l,ls) \in HLS, k \in TI, ns_{p,l} < k = n$$
(10c)

$$flsk_{p,l,ls,k} \le fl_{p,l} \ x \ zflsk_{p,l,ls,k} \forall (p,l) \in HP, (p,l,ls) \in HLS, k \in TI, ns_{p,l} \le k$$
(10d)

From Fig. 2.11, the eq. 10a-d which represent the mass balance between two adjacent of each sub-stream belong to the hot process stream can be made (Hong, Liao et al. 2019). Based on eq. 10b, both the total of recycling mass flow from p,l,ls' to p,l,ls in temperature level n and the flow rate of the sub-stream p,l,ls in the previous temperature interval (k-1) as the inputs must be equal to both the total of the recycling mass flow from p,l,ls to p,l,ls' in temperature level n and the flow rate of the substream p,l,ls in temperature interval k as the outputs. The eq. 10cd are used to ensure the mass balance of each sub-streams between two adjacent temperature intervals in eq. 10a-b.

Figure 2.12 Mass flow pattern belong to the cold stream (Hong, Liao et al. 2019).

$$fmr_{p,m,ms,ms',n}$$
  
 $fmsk_{p,m,ms,k}$   $fmsk_{p,m,ms,k+1}$   
 $fmr_{p,m,ms',ms,n}$ 

Moreover, the mass balance between two adjacent of each sub-stream belonging to the cold process stream is represented by eq. 11.

$$fmsk_{p,m,ms,k} = fmsk_{p,m,ms,k+1} + \sum_{ms' \in MS} fmr_{p,m,ms',ms,n} - \sum_{ms' \in MS} fmr_{p,m,ms,ms',n'}$$
(11a)

$$\forall (p,m) \in CP, (p,m,ms) \in CMS, k \in TI, k < ns_{p,m} - 1, n = k + 1$$
 (11b)

 $fmsk_{p,m,ms,k} \leq fm_{p,m}xzfmsk_{p,m,ms,k} \forall (p,m) \in CP, (p,m,ms) \in CMS, k \in TI, k < ns_{p,m}$ (11c)

According to Fig. 2.12, the eq. 11a-d which represent the mass balance between two adjacent of each sub-stream belong to the cold process stream can be made (Hong, Liao et al. 2019). Based on eq. 11a, both the total the total of recycling mass flow from p,m,ms' to p,m,ms in temperature level n and the flow rate of the sub stream p,m,ms in the previous temperature interval (k-1) as the inputs must be equal to both the total of the recycling mass flow from p,m,ms to p,m,ms' in temperature level n' and the flow rate of the sub-stream p,m,ms in temperature interval k as the outputs. The eq. 9b-c are used to ensure the mass balance of each sub stream between two adjacent temperature intervals in eq. 11a.

The new transshipment model presented (Hong, Liao et al. 2019) used the big-M formulation as represented in eq. 12 and eq. 13.

$$\begin{aligned} flsk_{p,l,ls,k} &\leq fl_{p,l} \ x \ zflsk_{p,l,ls,k} \forall (p,l) \in HP, (p,l,ls) \in HLS, k \in TI, ns_{p,l} \\ &< k \end{aligned} \tag{12}$$

 $fmsk_{p,m,ms,k} \le fm_{p,m} x z fmsk_{p,m,ms,k} \forall (p,m) \in CP, (p,m,ms) \in CMS, k \in TI, k < ns_{p,m}$ (13)

The number of non-convexities from non-linear equation of the disjunction can be decreased by using the big-M formulation. Moreover, it also reduces the state of space search. Grossman and Lee (Grossmann 2003) cited that the big-M formulation is weaker than the convex hull relaxation. However, the big-M relaxation has fewer variables (Hooker, 2007). The value of the parameter M in big-M formulation must be not too small and not too large. The cut-off of the solution will happen when the value is too small. In contrast, the problem will be difficult to be solved, if the value is too large (Onishi 2015).

#### 2.6.2. The Energy Flow Pattern of The Transshipment Method

The energy balance for hot process stream can be stated in eq. 14.

$$flsk_{p,l,ls,k}x(tn_{n} - tn_{n+1}) + rqhs_{p,l,ls,n} = rqhs_{p,l,ls,n+1} + \sum_{\substack{(p',m,ms) \in CMS, (p',m) \in C_{k} \\ (p,l,ls) \in HLS, (p,l) \in HP, n \in TL, k \in TI, n = k, ns_{p,l} \le k} q_{p,l,ls,p',m,ms,k}$$
(14)



Figure 2.13 Heat flow pattern of the hot process stream (Hong, Liao et al. 2019).

Fig. 2.13 represented the energy balance of the eq. 14. It shows that the input both the energy hot sub-stream released  $flsk_{p,l,ls,k}$  ( $tn_n$ - $tn_{n+1}$ ) in temperature interval ( $ns_{p,l} \le k$ ) and the residual energy of the hot process stream from the previous interval must be equal to the output, the sum of energy exchanged by heat transfer matches  $\sum q_{p,l,ls,p',m,ms,k}$  and the residual energy to the next temperature interval  $rqhs_{p,l,ls,n+1}$ .



Figure 2.14 Heat flow pattern of the cold process stream (Hong, Liao et al. 2019).

Based on Fig. 2.14, the inputs are known which are the energy of the cold sub-stream released  $fmsk_{p,m,ms,k}$   $(tn_n-tn_{n+1})$  in the interval  $(k < ns_{p,m})$  and the residual energy of the cold process stream to the next temperature interval  $rqcs_{p,m,ms,n+1}$ . The input must be equal to the output that are the sum of energy exchanged by the heat transfer of the cold process  $\sum q_{p',l,ls,m,ms,k}$  and the residual energy from the previous interval  $rqcs_{p,m,ms,n}$ .

$$fmsk_{p,m,ms,k}x(tn_n - tn_{n+1}) + rqcs_{p,m,ms,n+1} = rqcs_{p,m,ms,n} + \sum_{(p',l,ls)\in HLS(p',l)\in H_k} q_{p',l,ls,p,m,ms,k}$$
(15)  
$$\forall (p,m,ms)\in CMS, (p,m)\in CP, n\in TL, k\in TI, n = k, k < ns_{p,m}$$

Based on the explanation above, this thesis compares novel Stage-Wise Superstructure to the new transshipment strategy proposed (Hong, Liao et al. 2019) overcoming the heat exchanger network at intra- and inter- plant.

#### 2.7. Heat exchanger locations

This thesis uses the distributed heat exchanger location because the distributed heat exchanger location gives more benefits than the centralized heat exchanger location for inter- and intra- plant heat exchanger network synthesis. The heat loss, pressure drop, pipping and pumping cost are all affected by the heat exchanger locations. The types of heat exchanger locations are divided into a centralized location and distributed location. In centralized heat exchanger, the heat resource needs to be transferred to the centralized location, but the heat resource for the case of the distributed heat exchanger location is transferred to each exchanger located at each enterprise or each plant. The distributed heat exchanger network also consists of the intra- and inter- plant heat integration.

The distributed HENs location increases the NPV about 30% and IROR about 100% by using the development of stage wise superstructure (Nair, Soon et al. 2018). They also showed that none of centralized heat exchanger location used in their examples has the best result. The distributed HENs location is also affordable to be used solving the large-scale problem.

$$\sum_{p \in P_i} Z_{ikp'p} = z_{i(k-1)p'} \qquad 1 \le i \le I; 1 \le k \le K + 1; p' \in P_i$$
(16)

$$\sum_{p' \in P_i} Z_{ikp'p} = z_{ikp} \qquad 1 \le i \le I; \ 1 \le k \le K + 1; p \tag{17}$$

$$\sum_{p \in P_j} Z_{jkp'p} \stackrel{c}{=} \stackrel{D}{Z_{j(k+1)p'}} \qquad 1 \le j \le J; 0 \le k \le K; p' \qquad (18)$$

$$\sum_{p' \in P_j} Z_{jkp'p} \stackrel{-}{=} \stackrel{-}{Z_{jkp}} \qquad 1 \le j \le J; 0 \le k \le K; p \qquad (19)$$

$$Z_{jkp'p} = z_{jkp}$$
  $1 \le j \le J; 0 \le k \le K; p$  (19)

$$\sum_{p \in P_s} Z_{skpp} \ge 1 - y_{sk} \qquad 1 \le s \le S; 1 \le k \le K$$

$$(20)$$

The model (Nair, Soon et al. 2018) is set  $Z_{s(K+1)ps} = Z_{s0ps} = 1$  and  $Z_{s(K+1)p} = Z_{s0p} =$ 0 for  $p \in P_s$  and  $p \neq p_s$  since the stream is transported twice, transported from its own plant and return to its own plant. They tracked the stream movement by using eq. 16-20. They also minimized unnecessary transport by using eq. 20.



Figure 2.15 The example of heat exchanger network synthesis using the centralized heat exchanger location. (Nair et al, 2016).



**Figure 2.16** The example of heat exchanger network synthesis using the distributed heat exchanger location (Nair, Soon et al. 2018).

The evidence of the distributed heat exchanger location benefit was occurred in Fig. 2.15 and Fig. 2.16 that the distributed heat exchanger maximized all of the stream exchanges. The distributed heat exchanger location is better than the centralized heat exchanger location due to the drawbacks of centralized heat exchanger location which are less stream exchanges, less NPV, less IROR, higher number of streams, and higher CAPEX because of the high transport needed. In contrast, the distributed HENs use less hot and cold utilities, so it commits to lower the pipe cost by prioritizing inter- heat exchange over intra- heat exchange and to maximize the stream exchanges.

# 2.7.1. Pressure-drop

Many literatures ((Athier 1998), (Bochenek 2006), (Jeżowski, Bochenek et al. 2007), (Rezaei and Shafiei 2009), etc) including the simplification have no pressure drop consideration or ignores the effect of the pressure drop. However, if the pressure drop is not considered, the result will be unrealistic because a false sense of energy efficiency will be appeared in HENs. As the pressure drop has the important part in the heat transfer and total annual cost, the pressure drop must be controlled to be less or equal to the maximum allowable pressure drop for each stream. Soltani et al (Soltani and Shafiei 2011) have controlled the pressure drop by using the penalty term. Nair et al (Nair, Soon et al. 2018) calculated the pressure drop depending on both the pressure drop of the pipeline and the pressure drop of the heat exchangers. The pipeline pressure drop formulation used by (Nair, Soon et al. 2018) in eq. 22 is different from the formulation used (Hong, Liao et al. 2019) in eq. 24.

$$\Delta p^L = \frac{2f\rho v^2}{D_{in}} \tag{21}$$

$$\Delta P_{pipe} = 4x f_a x \frac{Lx \rho x v^2}{2x D_{in}} \tag{22}$$

According to the distinction, both the pipeline and exchanger pressure drop proposed (Hong, Liao et al. 2019) in eq. 24 are multiplied by two because the process streams are carried to go from initial plant and then go back to the initial plant. Moreover, the transportation distance between the plants are not neglected. Chang et al., (Chang, Chen et al. 2017) also used the same formulation of the pipe pressure drop as Hong et al (2019) cited in eq. 24.

Many formers ((Nair, Soon et al. 2018); (Hong, Liao et al. 2019)) used the formulations proposed by (Soltani and Shafiei 2011) to calculate the pressure drop of the heat exchanger using Genetic Algorithm (GA) combined with Linear Programming (LP) and Integer Linear Programming (ILP) method. The method for calculating the pressure drop heat exchanger in parallel is more complex than the heat exchanger arranged in series that can be calculated by summing the individual pressure drop.

$$\Delta P = \Delta P_{pipe} + \Delta P_{ex} \tag{23}$$

$$\begin{split} \Delta P &= f_{pipe}^{dp}(L, fcp, cp, \rho, \mu) + \sum_{p' \in P, p' \neq p} 2xpl_{p,l,p'} x f_{pipe}^{dp}(dd_{p,p'}, fl_{p,l}, cp_{p,l}, \rho_{p,l}, \mu_{p,l}) \\ &+ f_{shell}^{dp}(fl_{p,l}, cp_{p,l}, \rho_{p,l}, \mu_{p,l}, \kappa_{p,l}, h_{p,l}, Area_{p,l}) + \sum_{p \in P, p \neq p'} 2xpm_{p,m,p'} x f_{pipe}^{dp}(dd_{p,p'}, fl_{p,m}, cp_{p,m}, \rho_{p,m}, \mu_{p,m}) \\ &+ f_{tube}^{dp}(fl_{p,m}, cp_{p,m}, \rho_{p,m}, \mu_{p,m}, \kappa_{p,m}, h_{p,m}, Area_{p,m}) \end{split}$$

(24)

However, some equations proposed by (Chang, Chen et al. 2017) are incorrect to calculate the exchanger pressure drop as the original equations from (Soltani and Shafiei 2011) are correctly presented in eq. 25-28.

$$K'_{s} = \frac{67.L_{t}.(L_{t} - Dt_{out}).F_{s}.De^{1.1}.\mu_{s}^{1.3}}{Dt_{out}.\rho_{s}.\kappa_{s}^{3.4}.cp_{s}^{2.7}}.\left(\frac{\mu_{s}}{\mu_{r}}\right)^{0.868}$$

$$K'_{t} = \frac{0.023^{-2.5} \cdot F_{t} \cdot D_{tin}^{1/2} \cdot \mu_{t}^{11/6}}{\rho_{t} \cdot \kappa_{t}^{7/3} \cdot cp_{t}^{13/6}} \cdot \frac{Dt_{in}}{Dt_{out}} \left(\frac{\mu_{t}}{\mu_{r}}\right)^{-0.63}$$
(26)

$$K_t = \frac{1}{(0.023)^{2.5}} x D^{1/2} x \mu_t^{11/6} x \frac{1}{M_t \rho_t k_t^{7/3} C p_t^{7/6}} x \frac{D}{D_t} x \left[ \left( \frac{\mu_t}{\mu_{tw}} \right)^{-0.14} \right]^{4.5}$$
(27)

$$K_{s} = \frac{67.L_{tp}.(L_{t} - D_{t}).De^{1.1}.\mu_{s}^{1.3}}{D_{t}.M_{s}.\rho_{s}.k_{s}^{3.4}.Cp_{s}^{2.7}}.\left[\left(\frac{\mu_{s}}{\mu_{sw}}\right)^{-0.14}\right]^{6.2}$$
(28)

Moreover, the pressure drop can be controlled by designing the appropriate heat exchanger according to the Tubular Exchanger Manufacturers' Association (TEMA) standards. For shell and tube heat exchanger that is commonly used in industry, the pressure drop is controlled by designing this exchanger including the number of shell and tube. The dead zones must be excluded to get better heat transfer. The number of tubes and shells determine the velocity occurred which impacts to the pressure drop and heat transfer area in the shell and tube heat exchanger. The more tubes used, the lower velocity of the fluid but higher heat transfer area. The number of tubes must be appropriate because if the number of tubes are too low, the excessive pressure drop will appear as the result of the high velocities. Equally important, the number of the shell has the important role to keep the optimal flow and prevent underestimated the size required of the heat exchanger by preventing non-existent either the counter flow or the counter-current flow in the heat exchanger.

# 2.7.2. Heat losses consideration

If the heat exchanger network is wide including more than two plants, more than one enterprise, and using long pipes or long-distance transportations, the heat losses cannot be neglected because of the reduction of energy saving or the utility cost saving and the reduction of exchange duties. The temperature of the intermediate fluid should be high enough to handle the heat sink for indirect heat integration. Overcoming the heat losses means that many parameters must be adjusted such as the

(25)

pump power, the flowrate of the heat sources, and the diameter of the pump. In a case of long distance, the pump power influences the annual operating cost less than the pipeline and the heat loss. Chang et al (Chang, Wang et al. 2015) added the heat loss to calculate the electric cost by using indirect heat integration as stated in eq. 29-33.

$$Q_{loss} = \frac{T_w - T_e}{R} x L \tag{29}$$

$$R = \left(\frac{1}{2\pi k} \ln\left(\frac{r_T}{r_P}\right)\right) \tag{30}$$

$$D_{in} = \sqrt{\frac{4M}{\rho \cdot \pi \cdot u}}$$

$$H_T = \lambda \cdot \frac{L}{D_{in}} \cdot \frac{u^2}{2g} \tag{32}$$

$$Pumping \ cost = \ \frac{M.g.H_T}{\eta}.P_e.\ 8000$$
(33)

#### 2.7.3. Pumping and pipping cost

The pumping and piping cost are not included in heat exchanger network model proposed by Wang et al., (2015). However, the capital and operation expenses are dominated by the pumping and pipping cost. These costs also cannot be neglected because the pumping and pipping cost has the important impact due to the long-distance stream transportation in the large-scale problem.

Nair et al., (Nair, Soon et al. 2018) stated that the essential factors to determine the piping cost are the distances used for the stream to be travelled either the distances from plat p to plant p' or no plant-to-plant distances. The HENS (Hong, Liao et al. 2019) has the same factors as the Nair's statement. Based on eq. 34, not only is the transportation distance as the main factor but also the heat capacity flowrate, the specific heat capacity, and the density.

(21)

 $Pipping = f_{pipping}(L, fcp, cp, \rho)$ 

$$PIC = \sum_{\substack{(P,L) \in HP \\ + \\ (p',m) \in CP}} \sum_{p \in P, p \neq p'} 2xpl_{p,l,p'} xf_{piping}(dd_{p,p'}, fl_{p,l}, cp_{p,l}, \rho_{p,l}) + \sum_{\substack{(p',m) \in CP \\ p \in P, p \neq p'}} 2xpm_{p',m,p} xf_{piping}(dd_{p,p'}, fm_{p',m}, cp_{p',m}, \rho_{p',m})$$
(34)

They used the piping cost formulation the same as above that is multiplied by two because the process stream is transported twice including to the centralized HEN or distributed HEN and transported back to its original plant. Total pumping cos proposed (Hong, Liao et al. 2019) has been represented in eq. 35. The pumping cost and pipping cost are more determined by inter- plant heat exchanger than intra- plant heat exchanger. It consists of both the capital cost and the operating power cost.

$$PMC = \sum_{(p,l)\in HP} \left[ PexHyx \frac{fl_{p,l}x\Delta P_{p,l}}{cp_{p,l}x1000x\rho_{p,l}x\eta} + Afx \left( a + bx \left( \frac{fl_{p,l}x\Delta P_{p,l}}{cp_{p,l}x\rho_{p,l}} \right)^c \right) \right] + \sum_{(p,m)\in CP} \left[ PexHyx \frac{fm_{p,m}x\Delta P_{p,m}}{cp_{p,m}x1000x\rho_{p,m}x\eta} + Afx \left( a + bx \left( \frac{fm_{p,m}x\Delta P_{p,m}}{cp_{p,m}x\rho_{p,m}} \right)^c \right) \right]$$
(35)

The power of pump and the pressure drop of pump between plants are important to calculate the total pumping cost due to transport the stream in long distance against the pressure drop. The parameter, thermal conductivity, determines the pressure drop. However, the high capacities of the pump are also needed due to transport the stream in long-distance. Another option to increase the pump capacities is by increasing the impeller size or rotating speed of the pump. If the new pump is needed, the equation proposed by (Nair, Soon et al. 2018) in eq. 36 is possible to be used.

$$CP_{s} \geq FCP_{s}NP_{s} + VCP_{s}(E_{s})^{\alpha_{s}} - \left(VCP_{s}\left(K.VF_{s}.\frac{\Delta p_{s}^{HE}}{\eta_{s}}\right)\right)^{\alpha_{s}} (1 - NP_{s}) \ ; 1 \leq s \leq S$$
(36)

This equation shows that if the new pump is needed, the requirement of the pump will be  $NP_s=1$ . In contrast, if the new pump is not needed, the cost given by eq. 36 will be zero.

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# CHAPTER 3 EXPERIMENTAL

All the methodologies in this work are resolved in GAMS 24.2.1 (General Algebraic Modeling System), and the platform server with 1.80 GHz Intel ® Core TM i7-8550 and 20 GB of RAM are operated.

#### 3.1. **Objectives**

- 1. To produce the results of combined heat and mass exchanger network synthesis which are better than the previous literatures and reliable to be applied with the minimum TAC by using Stage-Wise Superstructure (SWS).
- 2. To get all the minimum possible stream matches by using MENS to reduce the TAC and to reduce the usage of the external of MSA.
- 3. To overcome inter- and intra- plants Heat Exchanger Network Synthesis (HENS).
- 4. To compare the different methods for overcoming the case studies of MENS, HENS, and CHAMENS.
- 5. To use more accurate LMTD formulation for the area calculations than the original stage-wise superstructure.

## 3.2. The scope of the research

The scope of this research will cover the following:

- 1. The effectiveness of the model used to save the energy, produce the minimum TAC and fewer computational time of the method used to solve the problems.
- 2. The effect of EMAT and EMCD to the proposed model as applied to solve the problems.
- 3. The comparison of the proposed model to the previous formers' results by obtaining the fewer TAC.

## 3.3. Mass Exchanger Network Synthesis (MENS)

The step to overcome MENS is cited in Figure 5.1. The stage wise superstructure needs the good initialization to make the model working well. It works well when deviation by zero is not appeared or (LMCD  $\neq$  0). The set of the boundaries and the good initialization are needed to overcome the infeasible solution. The initialization that is used in MENS part comes from the previous result of the previous literature.



Figure 3.1 The methodology of MENS.

#### 3.3.1. The Methodology of MENS

#### 3.3.1.1. The Data Usage

The data used in the case study is adapted from (Abdulfatah M.Emhameda and Fraser 2007). The detail of the stream data can be found in Chapter 6, Table 6.1 and Table 6.2. The ammonia is removed from 5 gaseous rich streams using2 lean process streams and an external lean stream Mass Separating Agent (MSA)with gas-liquid operation. Moreover, the mass exchange happens in the shell activesection depicted in Figure 5.2. A cylindrical shell is used. When the mass istransferred vertically inside the shell active continuous-contact packed column, itcreates the driving force. This driving force is affected by the area of mass activesection (Area), the overall mass transfer coefficient with the dimension masstransferred per unit time per volume  $(K_{va})$  and the Logarithmic Mean CompositionDifference (LMCD) as it can be seen in eq. 37. Moreover, the driving force means the difference between the actual composition and the equilibrium provided composition  $(\Delta v)$ . Thevalue (Kya)is by the equipment manufacturer related to the mass transferbased on the surface area (Ky) and interfacial surface area per unit volume (*a*).



Figure 3.2 The continuous-contact column.

The TAC is compared among the other literatures in the same conditions. The column is costed mainly from the shell cost in eq. 38. Based on (Peters and Timmerhaus, 1991), the parameters are known depending on the material constriction of the packed column (carbon steel). *M* is the mass transfer in the shell.

Cost (shell, installed) =  $618 M^{0.66} (M \text{ in } kg)$  (38)

# 3.3.1.2. The Initial Values, Boundaries, and The Null Matches.

The initial values of MENS depend on the target and the supply composition that can be placed at the stage as the initial values. MENS's initialization is not harder than HENS, so it does not need the complex initialization. Then, the possible stream matching is generated to get the initialization of the area by using the area as parameter solved by using MINLP. The result of this initialization is used to minimize the area that is included in the objective function as the variable. The process lean streams (L<sub>1</sub> and L<sub>2</sub>) are bounded to prevent the overlapped internal process MSA usage. The bounds of L<sub>1</sub> and L<sub>2</sub> can be any number, but it must no more than the maximum flowrates, 1.8 and 1 kg/s. The results must be feasible and satisfied the tolerance based on the boundaries used. The external MSA, L<sub>3</sub>, is not bounded. To create the feasible result which contains no division by zero or eliminate the null matches, the LMCD must be bounded. The lower bound of LMCD should be equal to Exchanger Minimum Composition Difference (EMCD).





# 3.3.2. Supplementary of MENS

Based on Figure 5.3, the detailed supplementary can be seen in the description below.

# **Notations Subscripts**

k	the flowrate interval
Ri	the flowrate of the rich stream
i	rich stream
$L_j$	the flowrate of the lean stream
j	lean stream
S	supply
Т	target
$x_j$	mass fraction of the lean stream
<i>Yi</i>	mass fraction of the rich stream
me	mass exchanger matching between the rich stream and the lean stream
$\Delta y_{min}$	the minimum allowance composition difference
$K_{\rm w}$	the lumped mass transfer coefficient
Af	the annual cost coefficient
PC	the cost coefficient of the continuous packed column installed
Height	the height of the continuous packed column installed
Cj	the mass fraction differences between the target and the supply mass fraction
β	the working hours
α	the cost coefficient of the external MSA $L_3$
γ	the area cost exponent for mass exchangers
Sets	
Ι	Rich stream, I = R1, R2, R3, R4, R5,,Rn
J	Lean stream, J= L1, L2, L3,,Ln
Κ	Stage, K= K1, K2, K3,, Kn

# **Parameters**

 $YIN_i$ the supply composition of the rich stream i, i = 1,2,3,4,5,...,n $YOUT_i$ the target composition of the rich stream i, i=12,3,4,5,...,n $XIN_j$ the supply composition of the lean stream j, j= 1,2,3,4,5,...,n $XOUT_j$ the target composition of the lean stream j, j=1,2,3,4,5,...,n $KOUT_j$ the target composition of the lean stream j, j=1,2,3,4,5,...,n $F_i$ the flowrate of the rich stream i, i=1,2,3,4,...,nEPSthe minimum allowance composition difference

# **Positive Variables**

$F_j$	The flowrate of the lean stream
$dy_{(i,j,k)}$	The composition approach between the rich stream $i$ and lean stream $j$ at the stage $k$
me <sub>(i,j,k)</sub>	The mass exchange matching between rich stream $i$ and lean stream $j$ at the stage k
yi <sub>(i,k)</sub>	the mass fraction composition of the rich stream $i$ at the stage $k$
$x j_{(j,k)}$	the mass fraction composition of the lean stream $j$ at the stage $k$

# Variables

 $ddy_{(i,j,k)}$  the real composition approach temperature between the rich stream *i* and the lean stream *j* at the stage *k*;

## **Binary variables**

 $z_{(i,j,k)}$  the appearance of the stream matchings between the rich stream *i* and the lean stream *j* at the stage *k*. The stream matching appears when z equals to 1, and it is not appeared when z equals to 0.

#### 3.3.3. Mathematical model

# 3.3.3.1. The Stage Mass Balances for Each Rich and Lean Stream

The stage mass balances are used to determine the composition at each stage for both rich and lean streams. As  $y_{i,k}$  and  $x_{j,k}$  are the continuous variables, the outlet of the streams at the stage k will be the inlet of the streams at the stage k+1 for each equilibrium composition of the lean and rich stream.

$$R_{i}(y_{i,k} - y_{i,k+1}) = \sum_{j \in L} me_{i,j,k}, \ i \in R, j \in L, k \in ST (39)$$
$$L_{i}(x_{j,k} - x_{j,k+1}) = \sum_{i \in R} me_{i,j,k}, \ i \in R, j \in L, k \in ST (40)$$

#### 3.3.3.2. The Overall Mass Balances for The Lean and Rich Streams

In order to procure their target compositions, the overall mass balances demonstrate the mass flowrate of either rich or lean stream  $(R_i, L_j)$  multiplied by the composition difference of its stream must be equal to the total masses exchanged between the lean and rich stream  $(me_{i,j,k})$ .

$$R_{i}(yin_{i} - yout_{i}) = \sum_{k \in ST} \sum_{j \in L} me_{i,j,k}, \ i \in R, j \in L, k \in ST$$
(41)
$$L_{j}(xout_{j} - xin_{j}) = \sum_{k \in ST} \sum_{i \in R} me_{i,j,k}, \ i \in R, j \in L, k \in ST$$
(42)

#### 3.3.3.3. The Logical Constrains of The Rich Streams

By connecting the model with the logical constrains of the rich streams in eq. 43-45, the rich streams become cleaner from the left at the stage k to the right at stage k+1. In the other words, the compositions of the rich streams are monotonically decrease from the left at stage k to the right at stage k+1. At these logical constrains, the stream supply is the highest composition which is the same as the composition of the rich stream at the first stage. In contrast to the supply composition, the target composition is the lowest, and lower than the composition of the rich stream at the last stage.

$$y_{i,k} \ge y_{i,k+1}, i \in R, k \in ST \quad (43)$$
$$y_{i,T} \le y_{i,k}, \quad i \in R, k \in Last ST \quad (44)$$
$$y_{i,k} = y_{i,S}, \quad i \in R, k \in First ST \quad (45)$$

#### 3.3.3.4. The Logical Constrains for The Lean Streams

The lean streams are either the process MSA or the external MSA. MSA can be absorbent or solvent to take up the pollutants. The more pollutant is taken up by the lean stream, the more composition of the lean stream will be. This condition is represented in eq. 46-48. As the reverse of the rich streams, the lean streams are monotonically increase from the right at stage k+1 to the left at stage k. The supply of the lean streams, either the fresh water or MSA, have the lowest compositions which are the same as the compositions at the last stages, and the target compositions of the lean streams are higher than the compositions at the first stages.

 $\begin{aligned} x_{j,k} &\geq x_{j,k+1} \quad j \in L, \ k \in Last \ ST \quad (46) \\ x_{j,k} &\leq x_{j,T}, \quad j \in L, \ k \in First \ ST \ (47) \\ x_{j,k} &= x_{j,S}, \quad j \in L, \ k \in Last \ ST \ (48) \end{aligned}$ 

#### 3.3.3.5. The Other Logical Constrains

The existence of the stream matching can be obtained by using the binary variable  $(z_{i,j,k})$  and the logical constrains represented in eq. 49-51. The value of the binary variable  $(z_{i,j,k})$  is one, if the stream matching exists under other condition there will be no stream matching. In order to assist the existing of the stream matching, the upper bound  $\Omega_{i,j}^{UP}$  is used.  $\Omega_{i,j}^{UP}$  depends on the maximum flow rates, target and supply composition of each lean and rich streams. To prevent the negligible sized mass exchangers, the eq. 49, the converse of the upper bound, is applied.

$$me_{i,j,k} - \Omega_{i,j}^{UP} z_{i,j,k} \leq 0 \quad i \in R, j \in L, k \in ST \quad (49)$$
$$me_{i,j,k} - \Omega_{i,j}^{LOW} z_{i,j,k} \geq 0 \quad i \in R, j \in L, k \in ST \quad (50)$$
$$\Omega_{i,j}^{UP} = min\{L_j^{max}(x_{j,T} - x_{j,S}); R_i(y_{i,S} - y_{i,T})\} \quad (51)$$

#### 3.3.3.6. The Calculation of The Driving Forces

The driving forces relate to the cost of the external MSA usage. The fewer driving force is used, it leads to the higher of the cost external MSA usage. The variable ( $\Gamma_{i,j,k}$ ) is the upper bound depicted to maintain the binary variable ( $z_{i,j,k}$ ). This variable ( $\Gamma_{i,j,k}$ ) will be inactive, if there is no stream matching existed.

$$\begin{aligned} dy_{i,j,k} &\leq y_{i,k} - x_{j,k} + \Gamma_{i,j,k} (1 - z_{i,j,k}) \ i \in R, \ j \in L, \ k \in ST \ (52) \\ dy_{i,j,k} &\geq y_{i,k} - x_{j,k} - \Gamma_{i,j,k} (1 - z_{i,j,k}) \ i \in R, \ j \in L, \ k \in ST \ (53) \\ dy_{i,j,k+1} &\leq y_{i,k+1} - x_{j,k+1} + \Gamma_{i,j,k} (1 - z_{i,j,k}), \ i \in R, \ j \in L, \ k \in Last \ ST \ (54) \\ dy_{i,j,k+1} &\geq y_{i,k+1} - x_{j,k+1} - \Gamma_{i,j,k} (1 - z_{i,j,k}), \ i \in R, \ j \in L, \ k \in Last \ ST \ (55) \end{aligned}$$

## 3.3.3.7. The Logarithmic Mean Concentration Difference (LMCD)

The LMCD used in the model is important because the division by zero is possible to appear due to the numerical difficulties and nonlinearities depending on the driving forces at each stage. Based on the comparisons using actual logarithmic mean among the other logarithmic mean concentration difference (LMCD) in (Shenoy and Fraser 2003), the second Chen's approximation performed best results with the lowest error 0.53%. Then, the second Chen's LMCD approximation is better than the first Chen's LMCD approximation because the first Chen's LMCD approximation has the overestimation of the number of the stages that leads to the highest deviation or error 4.67% as compared to the actual logarithmic mean (Shenoy and Fraser 2003).

The second Chen's LMCD approximation:

$$LMCD \approx \left[\frac{1}{2} \left( dy_{i,j,k}^{0.3275} + dy_{i,j,k+1}^{0.3275} \right) \right]^{\frac{1}{0.3275}} \quad i \in R, \ j \in L, \ k \in ST \ (56)$$

#### 3.3.3.8. The area of the mass exchangers

The area of the mass exchangers can be calculated by diving the existing mass exchanged with the lumped mass transfer coefficient ( $K_w$ ) and LMCD.

$$Area_{i,j,k}K_W LMCD_{i,j,k}{}^{\gamma} = me_{i,j,k} \quad i \in R, j \in L, k \in ST$$
(57)

# 3.3.3.9. The Objective Function of MENS

The objective function in MENS part is to minimize the TAC. It forces the height and the unit of the mass exchangers to be minimum. Moreover, it also minimizes the usage of the external MSA. The steps to overcome HENS can be seen in Figure 5.4.

$$Min. \ TAC = \alpha.\beta \sum_{j \in L} c_j L_j + Af. \left( \sum_{i \in R} \sum_{j \in L} \sum_{k \in ST} z_{i,j,k} \right) + PC \left( \frac{Me_{i,j,k}}{K_w.LMCD} \right)^{\gamma} (58)$$

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Figure 3.4 The methodology of HENS.
## 3.4.1. Methodology of HENS

3.4.1.1. The Stream Data

The case study proposed by *(Hong et al., 2019)* is used as the stream data that can be found in Chapter 6, Table 6.5 using 3 plants, intra- and interplant heat exchangers.

## 3.4.1.2. Initializations

The initialization is used to know the values of the areas of the heat exchanger matchings, the cold utility, and the hot utility before minimizing them as the stage-wise superstructure does not work without the initializations. CPLEX as MIP solver is used to overcome this initialization. In MIP synthesize, the areas are calculated as the parameter. In the first initialization, the program calculates the area after minimizing the stream matching as the objective function, so they are located after "Solve" the same as the picture below.

```
option domiim = 100;
option realim = 100;
MODEL CASESTUDY1 /ALL/ ;
CASESTUDY1.uptfile-1;
fonechi > dicopt.opt
naturpile: 1005
Soffecho
 SOLVE CASESTUDY: USING MIP HINTHIZING TAC;
 FARAMETERS
              0,UT(I),UJ(J)
              HI(I)
HJ(J)
HFUEL
                                      the best transfer coefficient of the hot stream 1 in the source plant,
the heat transfer coefficient of the cold stream 2 in the sink plant
Hot ut
cold UT;
                                                                                                                                                       /H1=1, H2=1.2, H2=1.1, H4=1.4/
                                                                                                                                                        (01-1.4, 02-1.7, C0-111, C4-1.1, C9-1.3)
              HWATER
             HWAITER GOLD UT:

HWAITER-1:

U(I_A) = ( (HI(I)+BJ(J))/ (HI(I)+BJ(J)) (I

U(I_A) = ( (HI(I)+BJ(J))/ (HI(I)+BJ(J)) (I

UJ(J) = ( SHAITER-BJ(J))/ (HWAITER-BJ(J) );
display U.UI.UJ:
parameter
Areal, ul
Areal, ql
Area3, q3
g1* q.1(*82',*82');
Ares1 = {q.1(*82',*62',*83'); U(*82',*62')*((*00.1(*82',*62',*83')**0.3275)*(00.1(*82',*62',*84')**0.3275));///
|-=

g2= q.L('H2','C5','K3')/( D('H2','C5')+((((dt.L('H2','C5','K3')++6.3275)+(dt.L('H3','C5','K4')++0.3275))/3)/*(1/0.3275)) )) /

Are+z = (q.L('H2','C5','K3')/( D('H2','C5')+((((dt.L('H2','C5','K3')++6.3275)+(dt.L('H3','C5','K4')++0.3275))/3)/*(1/0.3275)) )) /
0
g= q.L('H1','C1','K4')/
Azea3 = (g.L('H1','C1','K4')/( U('H1','C1')+((((qt.L('H1','C1','K4')++0.3276)+(qt.L('H1','C1','K6')++0.3276))/2)**(L/0.3275)) }) ±
Areas
DISPLAY
Areal, ql
Area2, q2
Area3, q3
DISPLAY zeu.1, zhu.1,z.1,g.L.geu.L.geu.L.ghu.L.ghu.L.ghu.L.TAC.L.gt.L.mi.L.ti.L.tj.L?
```

**Figure 3.5** The initialization of the stream matching in HENS by using areas as the parameter to be calculated.

After getting the values of the areas (*Area*), the temperatures of the hot and cold streams at each stage (ti and tj), the heat load (q), the stream matching as the parameters (z,zcu,zhu), the hot and cold utilities (qcu, qhu), these values are inputted to the next step to minimize the areas as they are cited in the objective functions of HENS. The initial values are inputted before "solve" to make them as the variables to be minimized. DICOPT as MINLP solver is used in this part. Based on the values of the initialization placed, the program gives the minimum areas required that can be the same as the initial values or lower than the initial values. By using the same technique, the minimum areas of hot and cold utilities are possible to be known.

		NITIAL VALUE TI ANI	(T
t1.1	('H1', 'K1') =250.	000;	
t1.1	('H2', 'K1') =500.	000;	
ti.1	('H3','K1') =125.	000;	
ti.1	('H4','H1') =200.	000;	
tj.1	('C1', 'K8') =185.	000;	
tj.1	('C2','K8') =139.	1000	
tj.1	('C3','K8') =20.0	00;	
tj.1	('C4','K8') =110.	000;	
tj.1 option	('C5','K8') =195. domlim = 100;	000:	
option	reslim = 400000;		
MODEL C	CASESTUDY1 /ALL/ :		
CASESTU	DY1.optfile=1;		
Conecho	> dicopt.opt		
maxcycl	1000 Les		
Soffech	10		
		AREA	
*1			
Area.1	('H2','C2','K3')	=4791.667 ;	
q.1	('H2','C2','K3')	=34500.000 ;	
z.1	('H2', 'C2', 'K3')	=1;	
Area.1	('H2', 'C5', 'R3')	#3338.675;	
q.1	('H2', 'C5', 'R3')	=25000.000 ;	
2.1	('H2','C5','K3')	=1;	
1.3			
Area.1	('HI', 'C1', 'K4')	#2142.857:	
q.1	('H1','C1','K4')	=15000.000 ;	
z.1	(.H1,',CI,',K4.)	=1;	
qcu.1('	H1 *)=10600.000;		
qcu.1('	H2')=7750.000;		
qcu.1('	H3')=15000.000;		
qcu.1('	H4')=21500.000 ;		
qhu.1(	C1')=1000.000;		
qhu.1('	C2')=3000.000 ;		
SOLVE C	ASESTUDY1 USING MIN	LP MINIMIZING TAC;	
DISPLAY	zcu.1, zhu.1, U, UJ,	UI1, UI2, UI3, UI4, z.1	,q.L,qcu.L,qcs.L,qhu.L,qhs.L,TAC.L,dt.L,ddt.L,ti.L,tj.L;
Display			An anna a' an anna an an an an an an an
Q.L.L1.	L, L2. L, LHTD. 1, Area.	17	

Figure 3.6 The initialization placed to minimize the areas.

## 3.4.1.3. The Boundaries

The boundaries used in HENS are to provide the results with no division by zero (LMTD $\neq 0$ , area  $\neq 0$ ) and satisfy the tolerance. The tolerance depends on the boundaries used. The boundaries are described in eq. 59-62. Moreover, LMTD should be bounded. The lower bound of LMTD should be equal to EMAT. It means that the minimum values of the LMTD between the hot stream *i* and the cold stream *j* at the stage *k* must be equal to the EMAT (Exchanger Minimum Approach of Temperature).

 $dt_{i,j,k} \ge EMAT (59)$  $dtcu_i \ge EMAT (60)$  $dthu_j \ge EMAT (61)$  $LMTD_{lo(i,j,k)} = EMAT (62)$ 

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## 3.4.2. Supplementary of HENS

Based on Figure 5.7, the detailed supplementary can be seen in the description below.

## **Notations Subscripts**

i	hot process stream	
j	cold process stream	
k	the flowrate interval	
S	supply	
Т	target	
Sets		
CS	Cold process stream	
CU	Cold utility	
HS	Hot process stream	
HU	Hot utility	
ST	Stage in the superstructure (1,, k+1)	
Parameters		
а	the exponent for investment pumping cost	
Al	the parameters of schedule 80 steel pipes parameters	
A2	the parameters of schedule 80 steel pipes parameters	

*A3* the parameters of schedule 80 steel pipes parameters

*A4* the parameters of schedule 80 steel pipes parameters

*b* the exponent for investment pumping cost

*c* the exponent for investment pumping cost

*CCU* the cost coefficient of the cold utility

*CHU* the cost coefficient of the hot utility

 $CPI_i$  Specific heat capacity of the hot process stream (kJ/°C. kG)

 $CPJ_j$  Specific heat capacity of the cold process stream (kJ/°C. kG)

*De* the equivalent diameter of tube (m)

Din <sub>i</sub>	the inner diameter of the pipeline for the hot process stream (m)
Dinj	the inner diameter of the pipeline for the cold process stream (m)
$Dout_i$	the outer diameter of the pipeline for the hot process stream $(m)$
<i>Dout<sub>j</sub></i>	the outer diameter of the pipeline for the cold process stream (m)
Dtin	the internal diameter of tube (m)
Dtout	the external diameter of tube (m)
EMAT	the minimum allowance temperature difference
$f_i$	the fanning friction factor of the hot stream
$F_i$	the flowrate of the hot stream i, $i=1,2,3,4,,n$
<i>fj</i>	the fanning friction factor of the cold stream
$F_j$	the flowrate of the cold stream j, $j=1,2,3,4,,n$
htc <sub>Cold</sub>	the heat transfer coefficient of the cold utility
<i>htc</i> <sub>Hot</sub>	the heat transfer coefficient of the hot utility
htc <sub>NH3</sub>	the heat transfer coefficient of the ammonia
$h_i$	the heat transfer coefficient of the hot process stream <i>i</i>
<i>h</i> <sub>j</sub>	the heat transfer coefficient of the cold process stream $j$
Ну	working hours per year (h)
Kshell	the film heat transfer coefficient of the shell side
K <sub>tube</sub>	the film heat transfer coefficient of the tube side
L	the distances among three plants (m)
Lp	the distance for one plant (m)
Lpp	the distances between two plants (m)
Lt	the tube pitch (m)
Pe	the electric price (\$/ kWh)
PIC	the total of the piping cost required (\$)
PICi	the pipping cost for the hot stream (\$)
PICj	the pipping cost for the cold stream (\$)
$Pl_i$	the pipe capital cost per unit length for hot stream ( $\/ m$ )
$Pl_j$	the pipe capital cost per unit length for cold stream (\$/m)

PMC 1	the total	of the	pumping	cost	(\$)
-------	-----------	--------	---------	------	------

 $Q_i$  the power required to drive the pump for the hot process stream

 $Q_i$  the power required to drive the pump for the hot process stream

 $TINCU_i$  the inlet temperature of the cold utility

 $TINHU_i$  the inlet temperature of the hot utility

 $TIN_i$  the supply temperature of the hot process stream i, i = 1,2,3,4,5,...,n

*TIN<sub>j</sub>* the supply temperature of the cold stream j, j=1,2,3,4,5,...,n

 $TOUTCU_i$  the outlet temperature of the cold utility

 $TOUTHU_i$  the outlet temperature of the hot utility

 $TOUT_i$  the target temperature of the hot stream i, i=1,2,3,4,5,...n

*TOUT<sub>j</sub>* the target temperature of the cold stream j, j=1,2,3,4,5,...,n

 $U_{(i,j)}$  the overall heat transfer coefficient of the heat exchanger matching

 $W_i$  the weight per unit length of the pipeline for the hot process stream (kg/m)

 $W_j$  the weight per unit length of the pipeline for the cold process stream (kg/m)

 $\alpha$  the cost coefficient for the process heat exchangers

 $\beta$  the cost coefficient of the area process heat exchangers

 $\gamma$  the cost coefficient of the area process heat exchangers

 $\Delta P_{Shell}$  the pressure drop in shell side caused by the heat exchanger (Pa)

- $\Delta Pip_i$  the pressure drops caused by the pipeline for the hot stream to one plant Lp=83 m (Pa)
- $\Delta Pipp_i$  the pressure drops caused by the pipeline for the hot stream between two plants Lpp=167 m (Pa)
- $\Delta Pippp_i$  the pressure drops caused by the pipeline for the hot stream among three plants L=250 m (Pa)
- $\Delta P_{Tube}$  the pressure drop in tube side caused by the heat exchanger (Pa)
- $\Delta P_j P_j$  the pressure drops caused by the pipeline for the cold stream to one plant Lp=83 m (Pa)
- $\Delta P j p p_j$  the pressure drops caused by the pipeline for the cold stream among three plants L p p = 167 m (Pa)
- $\Delta P j p p p_j$  the pressure drops caused by the pipeline for the cold stream among three plants *L*=250 m (Pa)

- $\kappa_i$  thermal conductivity of the fluid hot process stream flowing through shell side (W/m.°C)
- $\kappa_j \qquad \ \ thermal \ \ conductivity \ of the fluid \ \ cold \ \ process \ stream \ flowing \ through \ shell \ \ side \ (W/m.^{\circ}C)$
- $\mu_i$  the viscosity of the hot process stream flowing through shell side (Pa.sec)
- $\mu_j$  the viscosity of the cold process stream flowing through shell side (Pa.sec)
- $\mu_r$  the standard viscosity for water (Pa. sec)
- $v_i$  the velocity of the hot stream (m/s)
- $v_i$  the velocity of the hot stream (m/s)
- $\rho_i$  the density of the hot process stream (kg/m<sup>3</sup>)
- $\rho_j$  the density of the cold process stream (kg/m<sup>3</sup>)

## **Positive Variables**

- Area<sub>(i,j,k)</sub> The area of the heat exchanger matchings between hot stream *i* and cold stream *j* at the stage *k*.
- Area<sub>CU(i)</sub> The area of the heat exchanger between hot stream i and the cold utility at the end stage k.
- $Area_{HU(j)}$  The area of the heat exchanger between cold stream *j* and the hot utility at the first stage *k*.
- $dt_{(i,j,k)}$  The temperature approach between the hot stream *i* and cold stream *j* at the stage *k*
- $dtcu_{(i)}$  The temperature approach of the cold utility matching at the end stage k
- $dthu_{(j)}$  The temperature approach of the hot utility matching at the first stage k
- $LMTD_{(i,j,k)}$  The Logarithmic Mean Temperature Difference between the hot stream *i* and the cold stream *j* at the stage *k*.
- $LMTD_{CU(i)}$  The Logarithmic Mean Temperature Difference between the hot stream *i* and the cold utility at the end stage *k*.
- $LMTD_{HU(j)}$  The Logarithmic Mean Temperature Difference between the cold stream *j* and the hot utility at the first stage *k*.
- $q_{(i,j,k)}$  The heat exchange matching between hot stream *i* and cold stream *j* at the stage k

<i>qcu</i> <sub>(i)</sub>	The cold utility matching at the end of the stage k or at the end of the hot stream $i$ .
qhu <sub>(j)</sub>	The hot utility matching at the first stage k or at the end of the cold stream.
$ti_{(i,k)}$	the temperature interval of the hot stream $i$ at the stage $k$
$t j_{(j,k)}$	the temperature interval of the cold stream $j$ at the stage $k$
$x_{PE}$	the number of the inter-plant heat exchanger
XPA	the number of the intra-plant heat exchanger

## Variables

 $ddt_{(i,j,k)}$  the real approach temperature between the hot stream *i* and the cold stream *j* at the stage *k*;

## **Binary variables**

- $z_{(i,j,k)}$  the appearance of the stream matchings between the hot stream *i* and the cold stream *j* at the stage *k*. The stream matching appears when *z* equals to 1, and it is not appeared when *z* equals to 0.
- $zcu_{(i)}$  the appearance of the cold utility matching at the end stage k. The stream matching appears when zcu equals to 1, and it is not appeared when z equals to 0.
- $zhu_{(j)}$  the appearance of the hot utility matching at the first stage k. The stream matching appears when zhu equals to 1, and it is not appeared when z equals to 0.

#### 3.4.3. Mathematical Model

## 3.4.3.1. The Overall Heat Balances

The target temperature can be obtained by using the overall heat balances. In this work, the heat capacities (Cp) used for the overall heat balance calculation in eq. 63-64 of each stream are constant due to make the same comparisons to the other literatures. However, in the reality, the heat capacity (Cp) is the function of the temperatures. It must not be the same at each stage as the temperature at each stage is not the same.

$$F_i.Cp_i.(TIn_i - Tout_i) = \sum_{k \in ST} \sum_{j \in CS} q_{i,j,k} + qcu_i, \ i \in HS, \ k \in ST \ (63)$$

$$F_{j} \cdot Cp_{j} \cdot (Tout_{j} - Tin_{j})F_{j} = \sum_{k \in ST} \sum_{i \in HS} q_{i,j,k} + qhu_{j}, \quad j \in CS, \ k \in ST \ (64)$$

#### 3.4.3.2. The Heat Balance at Each Stage

The temperatures at each stage are possible to be known by using the eq. 59-60. The isothermal condition adopted in eq. 65-66 means that it has fewer nonlinearities than the non-isothermal condition. Before entering to the next stage, the process streams are mixed isothermally.

$$(t_{i,k} - t_{i,k+1})F_i = \sum_{j \in CS} q_{i,j,k} \quad k \in ST, \ i \in HS \quad (65)$$
$$(t_{j,k} - t_{j,k+1})F_j = \sum_{i \in HS} q_{i,j,k} \quad k \in ST, \ j \in CS \quad (66)$$

## 3.4.3.3. The Feasibility of The Temperatures

The hot streams come from the left to the right, and the reverse is for the cold streams. Based on the eq. 67-68, the temperatures are monotonically decrease from the left at stage k to the right at stage k+1.

$$t_{i,k} \ge t_{i,k+1} \ i \in HS, \ k \in ST \ (67)$$
$$t_{j,k} \ge t_{j,k+1} \ j \in CS, k \in ST \ (68)$$

#### 3.4.3.4. The Temperature Feasibilities

The inlet of the hot streams which has the highest temperature is its temperature at the first stage k. The cold stream that has the lowest temperature enter the HENS superstructure at the last stage. As the cold stream enter the superstructure from the left to the right, its temperature will increase.

> $Tin_{i} = t_{i,k} \ i \in HS, \ k \in First \ ST$ (69)  $Tout_{i} \leq t_{i,k} \ i \in HS, \ k \in Last \ ST$ (70)  $Tin_{j} = t_{j,k} \ i \in HS, \ k \in Last \ ST$ (71)  $Tout_{j} \geq t_{j,k} \ i \in HS, \ k \in First \ ST$ (72)

3.4.3.5. The Logical Constrains

The binary variable  $(z_{i,j,k})$  depicts the stream matching existence as its integer value equals to "1". The cold utility matching appears as the binary variables  $(zcu_i)$  equals to "1". The same rule is applied for the hot utility matching using  $(zhu_j)$ . The binary variables  $(z_{i,j,k}, zcu_i, zhu_j)$  mean their values can be zero or one, the superstructure model forces the binary variables to be zero to get the minimum heat exchanger matchings. The variables  $(\Omega_{i,j}, \Omega_i, \Omega_j)$  are the upper bound of the heat loads to ensure the values of  $(z_{i,j,k}, zcu_i, zhu_j)$ .

$$q_{i,j,k} - \Omega_{i,j} \cdot z_{i,j,k} \leq 0 \quad i \in HS, j \in CS, k \in ST (73)$$
$$qhu_i - [F_i(Tout_i - Tin_i)] \cdot zhu_i \leq 0 \quad j \in CS (74)$$
$$qcu_i - [F_i(Tin_i - Tout_i)] \cdot zcu_i \leq 0 \quad i \in HS (75)$$

## 3.4.3.6. The Hot and Cold Utility Loads

In the HENS superstructure, the cold utilities are only possible to be located at the end of the stage depending on the temperature difference between the temperatures at the last stage and the target temperature. Moreover, the hot utilities are only possible to be placed at the first stage depending on the temperature difference between the temperature at the first stage and the target temperature.

$$(t_{i,k} - Tout_i)$$
.  $F_i = qcu_i$   $i \in HS$ ,  $k \in Last ST$  (76)  
 $(Tout_j - t_{j,k})$ .  $F_j = qhu_j$   $j \in CS$ ,  $k \in First ST$  (77)

#### 3.4.3.7. The Driving Forces

The driving forces can be calculated based on the eq. 78-81. In this part, the heat exchanger matching exists as the equation inside the bracket is forced to be zero because the integer value of  $(z_{i,j,k})$  is one. The variables  $(\Gamma_{i,j,k}, \Gamma_i, \Gamma_j)$ will activate the equations as the heat exchanger matching appears. If a match does not exist, they will inactivate the equations. These variables help to avoid numerical errors due to negative temperature difference because of no matching existed.

$$\begin{aligned} dt_{i,j,k} &\leq t_{i,k} - t_{j,k} + \Gamma_{i,j} (1 - z_{i,j,k}) \ i \in HP, \ j \in CP, \ k \in ST \ (78) \\ dt_{i,j,k+1} &\leq t_{i,k+1} - t_{j,k+1} + \Gamma_{i,j} (1 - z_{i,j,k}) \\ i \in HP, \ j \in CP, \ k \in ST \ (79) \\ dtcu_i &\leq t_{i,k+1} - Tout_{cu} + \Gamma_i (1 - z_{i,j,k}), \ i \in HS, \ j \in CS, \ k \in ST \ (80) \\ dthu_j &\leq Tout_{hu} - t_{j,k} + \Gamma_j (1 - z_{i,j,k}), \ i \in HS, \ j \in CS, \ k \in ST \ (81) \end{aligned}$$

## 3.4.3.8. The Logarithmic Mean Temperature Difference (LMTD)

The second LMTD's Chen approximation is used. Based on the comparison of the second LMTD Chen's approximation used in (Azeez, Isafiade et al. 2013), the second LMTD Chen's approximation has the fewest error. Moreover, it is better than the first Chen's LMTD approximation. Based on the comparison, the first Chen's LMTD approximation gave the underestimate the real values of LMTD (Krishna & Murty, 2007; Shenoy & Fraser, 2013). This second Chen's LMTD approximation is also useful to avoid the infinite and overestimate of heat exchanger area calculation.

The second Chen's Logarithmic Mean Temperature Difference (LMTD):

$$LMTD \approx \left[\frac{1}{2} \left(dt_{i,j,k}^{0.3275} + dt_{i,j,k+1}^{0.3275}\right)\right]^{\frac{1}{0.3275}} \quad i \in HP, \ j \in CP, \ k \in ST \ (82)$$

## 3.4.3.9. The Area at Each Heat Exchanger Matching

The area is as the function of the heat load, LMTD and the heat transfer coefficient  $(U_{i,j})$ . The area calculation is important because it is minimized and included in the objective function.

$$Area_{i,j,k} = \frac{q_{i,j,k}}{\left(LMTD_{i,j,k} \cdot U_{i,j}\right)} \quad i \in CS, \ j \in HS, \ k \in ST$$
(83)

3.4.3.10. The Piping Cost

The piping cost relates to the pressure drop, and it cannot be neglected because we need to control the pressure drop for delivering the fluid especially to the long distances in the inter-plant heat exchanger network. Moreover, the inter-plant HENS has longer distance than the intra- plant HENS, so the pressure drop in the inter-plant HENS is high. Based on the eq. 79-91, the higher the area of the heat exchanger network is, the higher the pressure drop will be. Additionally, the shell and tube heat exchanger and the schedule 80 pipe are used in this work.

$$Din_{j} = 0.363. F_{j}^{0.45}. Cp_{j}^{-0.45}. \rho_{j}^{-0.32}, j \in CS (84)$$
  

$$Din_{i} = 0.363. F_{i}^{0.45}. Cp_{i}^{-0.45}. \rho_{i}^{-0.32}, i \in HS (85)$$
  

$$Dout_{i} = 1.101. Din_{i} + 0.006349, i \in HS (86)$$
  

$$Dout_{i} = 1.101. Din_{i} + 0.006349, j \in CS (87)$$

$$W_{i} = 1,330 . Din_{i}^{2} + 75.18. Din_{i} + 0.9268, i \in HS (88)$$
$$W_{j} = 1,330 . Din_{j}^{2} + 75.18. Din_{j} + 0.9268, j \in CS (89)$$
$$Pl_{i} = A_{1}.W_{i} + A_{2}.Dout_{i}^{0.48} + A_{3} + A_{4}.Dout_{i}, i \in HS (90)$$
$$Pl_{j} = A_{1}.W_{j} + A_{2}.Dout_{j}^{0.48} + A_{3} + A_{4}.Dout_{j}, j \in CS (91)$$
$$PIC_{i} = AF x \left[ (x_{PE} . L . Pl_{i}) + (x_{PE}.L_{pp}.Pl_{i}) + (x_{PA}.Lp.Pl_{i}) \right] (92)$$
$$PIC_{j} = AF x \left[ (x_{PE} . L . Pl_{j}) + (x_{PE}.L_{pp}.Pl_{j}) + (x_{PA}.Lp.Pl_{j}) \right] (93)$$
$$Piping Cost = \sum_{i \in HP} PIC_{i} + \sum_{j \in CP} PIC_{j} (94)$$

3.4.3.11. The Pumping Cost

The pumping cost takes the same crucial part the same as the piping cost in the total investment cost. Mostly, the processing plants are located separately in different locations. The pressure drop in the pipeline can be calculated based on eq. 104-109 depending the distances of the heat exchange matchings. Moreover, the pressure drop of the heat exchangers can be calculated by summing up eq. 98 and eq. 99.

$$K_{Shell} = \frac{67.L_t \cdot (L_t - Dtout).F_s. De^{1.1}.\mu_s^{1.3}}{Dtout.\rho_s.\kappa_s^{3.4}.Cp_s^{2.7}} \cdot \left(\frac{\mu_s}{\mu_r}\right)^{0.868} (95)$$

$$K_{tube} = \frac{0.023^{-2.5}.F_t.Dtin^{1/2}.\mu_t^{11/6}}{\rho_t.\kappa_t^{7/3}.Cp_t^{13/6}} \cdot \frac{Dtin}{Dtout} \cdot \left(\frac{\mu_t}{\mu_r}\right)^{-0.63} (96)$$

$$De = \frac{4.Lt^2 - \pi.Dtout^2}{\pi.Dtout} (97)$$

$$\Delta P_{shell} = K_{Shell}.A.h_s^{3.5} (98)$$

$$\Delta P_{tube} = K_{Tube}.A.h_t^{5.109} (99)$$

$$v_i = \frac{4.F_i}{Cp_i.\pi.\rho_i.(Din_i)^2}, \ i \in HS (98)$$

$$v_j = \frac{4.F_j}{(Cp_j.\pi.\rho_j.(Din_j)^2)}, \ j \in CS (99)$$

$$Re_i = \frac{\rho_i.Din_i.v_i}{\mu_j}, \ i \in HS (100)$$

$$Re_j = \frac{\rho_j.Din_j.v_j}{\mu_j}, \ j \in CS (101)$$

$$f_i = \frac{0.046}{(Re_i)^{0.2}}, \ i \in HS (102)$$

$$f_j = \frac{0.046}{(Re_j)^{0.2}}, \ j \in CS (103)$$

$$\Delta Pip_i = 4.f_i.\frac{L_p.\rho_i.(v_i)^2}{2.Din_i}, \ i \in HS (104)$$

$$\Delta Pjp_j = 4.f_j.\frac{L_pp.\rho_i.(v_j)^2}{2.Din_i}, \ i \in HS (106)$$

$$\Delta Pjpp_j = 4.f_j.\frac{L_{pp}.\rho_j.(v_j)^2}{2.Din_j}, \ j \in CS (107)$$

$$\Delta Pippp_{i} = 4. f_{i}. \frac{L \cdot \rho_{i}. (v_{i})^{2}}{2. Din_{i}}, \ i \in HS \ (108)$$

$$\Delta P j p p p_{j} = 4. f_{j} \cdot \frac{L \cdot \rho_{j} \cdot (v_{j})^{2}}{2. Din_{j}}, \quad j \in CS \quad (109)$$

$$Q_{i} = \frac{0.001.F_{i}.Cp_{i}\Delta P}{Cp_{i}.\rho_{i}.\eta}, \quad i \in HS \quad (110)$$

$$Q_{j} = \frac{0.001.F_{j}.Cp_{j}\Delta P}{Cp_{j}.\rho_{j}.\eta}, \quad j \in CS \quad (111)$$

$$\Delta P = \Delta P_{pipe} + \Delta P_{HE} \quad (112)$$

$$Pumping \ Cost = \sum_{i \in HS} \left[ P_{e}.H_{y}.Q_{i} + Af.\left(a + b.\left(\frac{F_{i}.\Delta P}{Cp_{i}.\rho_{i}}\right)^{c}\right) \right] + \sum_{j \in CS} \left[ P_{e}.H_{y}.Q_{j} + Af.\left(a + b.\left(\frac{F_{i}.\Delta P}{Cp_{i}.\rho_{i}}\right)^{c}\right) \right]$$

$$+ Af.\left(a+b.\left(\frac{T_{l}\cdot \Delta I}{Cp_{j}\cdot\rho_{j}}\right)\right)$$
(113)

## 3.4.3.12. The Objective Function of HENS

The objective function forces the TAC to be minimum which includes minimizing the hot and cold utilities, the area cost for all matches, and the heat exchanger matchings. The TAC will decrease, as the value of  $\gamma$  is less than one. At the same heat loads,

$$Min. \ TAC = \sum_{i \in HS} CCu_i qcu_i + \sum_{j \in CS} CHu_j qhu_j$$

$$Af. \begin{cases} \alpha. \left( \sum_{i \in HS} \sum_{j \in CS} \sum_{k \in ST} z_{i,j,k} + \sum_{i \in HS} zcu_i + \sum_{j \in CS} zhu_j \right) + \\ \beta. \sum_{i \in HS} \sum_{j \in CS} \sum_{k \in ST} (A_{i,j,k})^{\gamma} + \\ \beta. \sum_{i \in HS} (Acu_i)^{\gamma} + \beta. \sum_{j \in CS} (Ahu_j)^{\gamma} \end{cases}$$
(114)

$$\sum TAC = Min. TAC + Pumping Cost + Piping Cost (115)$$

# 3.5. Combined Heat and Mass Exchanger Network Synthesize (CHAMENS)



The steps to overcome CHAMENS is cited in Figure 5.8.

Figure 3.8 The methodology of CHAMENS.

## 3.5.1. Methodology of CHAMENS

The CHAMENS method is a sequential method that contains two steps based on Figure 5.8. The first step is the mass allocation network to construct the network from source to the sink with the minimum fresh ammonia and the waste. The HENS is generated sequentially at the last step which is the same as the previous HENS methodology in this work.

3.5.1.1. Step 1: Mass Allocation Network

#### a. Data

The data used in CHAMENS can be found in (Ghazouani 2018). The purpose of this case study is to minimize the fresh ammonia used and determine the amount of unwanted ammonia that is the waste to be sent to the waste treatment plant. They must satisfy the concentration and temperature requirements at each sink. In this step 1, the mass balance has the important role to decide whether the program successfully producing a good result or not.

## b. The boundaries

Some of the existence matchings are used to be the upper and lower bounds in this part to get the feasible solution. The concentration of the fluid that goes to the sinks must not higher than the upper bound used.

```
COUTJ.UP('SINK1')=0;
COUTJ.UP('SINK2')=40;
COUTJ.UP('SINK3')=75;
COUTJ.UP('SINK4')=100;
ME.UP('SOURCE1',J,K)=530;
ME.UP('SOURCE2',J,K)=68;
ME.UP('SOURCE2',J,K)=68;
ME.UP('SOURCE3',J,K)=1130;
ME.UP('SOURCE4',J,K)=36;
```

Figure 3.9 The boundaries for CHAMENS.

## 3.5.1.2. Step 2: Heat Exchanger Network in CHAMENS

a. Data

In this case study based on Table 6.7 (Chapter 6), the fresh ammonia is supplied at the temperature 30°C. The waste transported must satisfy the temperature required 40°C to be accepted in the waste treatment plant. EMAT is set 35°C. The results of the flowrates sources and sinks from the step 1 are used to overcome HENS in Step 2. The supply temperatures are the temperature of the sources and the target temperatures are the temperatures of the sinks. The sources can be either hot or cold process streams.

b. The boundaries and the initial values

The initial values and boundaries used in step 2 are done in the same way in Figure 5.5. After the results of the Step 1 and Step 2 are produced, the results are combined and analyzed. 3869511871 CU iThesis 6173004063 thesis / recv: 28072563 01:49:28 / seq: 18



Figure 3.10 Enhanced CHAMENS (combined Step 1 and Step 2).

## 3.5.2. Supplementary of CHAMENS

Based on Figure 5.10, the detailed supplementary can be seen in the description below.

i. Step 1: Ammonia mono-contaminant recovery

## **Notation Subscripts**

- *i* source stream
- *j* sink stream

## Sets

- *SC* The source stream
- *SK* The sink stream
- ST Stage in the superstructure (1, ..., k+1)

## **Parameters**

- *FIN*<sub>*i*</sub> the inlet flowrate of the source i, i = 1,2,3,4,5,...,n
- *FOUT*<sub>*i*</sub> the outlet flowrate of the source i, i=1,2,3,4,5,...n
- $CIN_i$  the inlet concentration of the source *i*, i= 1,2,3,4,5,...,n
- *COUT<sub>i</sub>* the target temperature of the source *i*, i=1,2,3,4,5,...,n
- *FIN<sub>j</sub>* the inlet flowrate of the sink j, j = 1,2,3,4,5,...,n
- FOUT<sub>j</sub> the outlet flowrate of the sink j, j = 1, 2, 3, 4, 5, ... n
- $CIN_j$  the inlet concentration of the sink j, j=1,2,3,4,5,...,n
- *COUT<sub>j</sub>* the target temperature of the sink j, j=1,2,3,4,5,...,n
- $C_{fresh(j)}$  the cost coefficient for the flowrate of the fresh ammonia required
- $C_{waste(i)}$  the cost coefficient for the waste

## **Positive Variables**

$F_{i(i,k)}$	the flowrate interval of the source stream <i>i</i> at the stage <i>k</i>
$F_{j(j,k)}$	the flowrate interval of the sink stream $j$ at the stage $k$
$F_{fresh(i)}$	the flowrate of the fresh ammonia $i$ at the end stage $k$
$F_{waste(j)}$	the flowrate of the waste $j$ at the first stage $k$

$CIK_{(i,k)}$	the concentration interval of the source stream $i$ at the stage $k$
$CJK_{(j,k)}$	the concentration interval of the sink stream $j$ at the stage $k$
$Me_{(i,j,k)}$	the stream matching between the source and the sink at the stage k
$CAVG_{(i,j,k)}$	the average concentration between the source $i$ and the sink $j$ at the stage $k$ .

## ii. Step 2: HENS of CHAMENS

# Notations Subscripts

k	the flowrate interval
i	hot process stream
j	cold process stream
S	supply
Т	target
Sets	
CS	Cold process stream
CU	Cold utility
HS	Hot process stream
HU	Hot utility
ST	Stage in the superstructure (1,, k+1)
Paramet	ters
AF	Annualization factor
CCU	the cost coefficient of the cold utility
$C_{HE}^{Cap}$	the Nominal fixed cost for a heat exchanger (\$)
CHU	the cost coefficient of the hot utility
$C_S^{Cap}$	the nominal cost for heat exchanger area (\$)
EMAT	the minimum allowance temperature difference
$F_i$	the flowrate of the hot stream i, $i=1,2,3,4,,n$
$F_j$	the flowrate of the cold stream j, $j=1,2,3,4,,n$
$h_{CU}$	the heat transfer coefficient of the cold utility

<i>h</i> <sub>HU</sub>	the heat transfer coefficient of the hot utility	
$h_i$	the heat transfer coefficient of the hot process stream <i>i</i>	
<i>h</i> <sub>j</sub>	the heat transfer coefficient of the cold process stream j	
$h_{op}$	the operating hours	
n	the exponent of the actualization ratio	
N <sub>H1,H2</sub>	the number of the heat exchanger matchings (units)	
ra	the actualization ratio (%)	
$S_{H1,H2}$	the heat exchanger area (m <sup>2</sup> )	
TINCUi	the inlet temperature of the cold utility	
$TINHU_j$	the inlet temperature of the hot utility	
$TIN_i$	the supply temperature of the hot process stream i, $i = 1, 2, 3, 4, 5,, n$	
TINj	the supply temperature of the cold stream j, $j=1,2,3,4,5,,n$	
$TOUTCU_i$ the outlet temperature of the cold utility		
<i>TOUTHU</i> <sub>j</sub> the outlet temperature of the hot utility		
$TOUT_i$	the target temperature of the hot stream i, $i=1,2,3,4,5,n$	
$TOUT_j$	the target temperature of the cold stream j, $j=1,2,3,4,5,,n$	
$U_{(i,j)}$	the overall heat transfer coefficient of the heat exchanger matching	

## **Positive Variables**

$dt_{(i,j,k)}$	The temperature approach between the hot stream $i$ and cold stream $j$ at the stage $k$
dtcu <sub>(i)</sub>	The temperature approach of the cold utility matching at the end stage $k$
dthu <sub>(j)</sub>	The temperature approach of the hot utility matching at the first stage $k$
$q_{(i,j,k)}$	The heat exchange matching between hot stream $i$ and cold stream $j$ at the stage k
qcu <sub>(i)</sub>	The cold utility matching at the end of the stage k or at the end of the hot stream <i>i</i> .
qhu <sub>(j)</sub>	The hot utility matching at the first stage k or at the end of the cold stream.
ti <sub>(i,k)</sub>	the temperature interval of the hot stream $i$ at the stage $k$

- $LMTD_{(i,j,k)}$  The Logarithmic Mean Temperature Difference between the hot stream *i* and the cold stream *j* at the stage *k*.
- *LMTD<sub>CU(i)</sub>* The Logarithmic Mean Temperature Difference between the hot stream i and the cold utility at the end stage k.
- $LMTD_{HU(j)}$  The Logarithmic Mean Temperature Difference between the cold stream *j* and the hot utility at the first stage *k*.
- $Area_{(i,j,k)}$  The area of the heat exchanger matchings between hot stream *i* and cold stream *j* at the stage *k*.
- Area<sub>CU(i)</sub> The area of the heat exchanger between hot stream i and the cold utility at the end stage k.
- Area<sub>HU(j)</sub> The area of the heat exchanger between cold stream j and the hot utility at the first stage k.

## Variables

 $ddt_{(i,j,k)}$  the real approach temperature between the hot stream *i* and the cold stream *j* at the stage *k*;

## **Binary variables**

- $z_{(i,j,k)}$  the appearance of the stream matchings between the hot stream *i* and the cold stream *j* at the stage *k*. The stream matching appears when *z* equals to 1, and it is not appeared when *z* equals to 0.
- $zcu_{(i)}$  the appearance of the cold utility matching at the end stage k. The stream matching appears when zcu equals to 1, and it is not appeared when z equals to 0.
- $zhu_{(j)}$  the appearance of the hot utility matching at the first stage k. The stream matching appears when zhu equals to 1, and it is not appeared when z equals to 0.

## 3.5.3. Step 1 (CHAMENS): Mass recovery network.

#### 3.5.3.1. The Mass Balances for Each Flowrate and Concentration.

In this part, the mass is allocated from the sources to the sinks depending on the flowrate and the concentration of each source and sink correlated with the fresh water source and waste sink. In Step 1, the driving forces of each mass exchangers are not used. The total flowrate that comes from the sources must be the same as the total flowrate of each sink.

$$(Fin_{i} - Fout_{i}) = \sum_{j \in SK} \sum_{k \in ST} Me_{i,j,k} + Ffresh_{i} , i \in SC, j \in SK, k \in ST (116)$$

$$(Fout_{j} - Fin_{j}) = \sum_{i \in SC} \sum_{k \in ST} Me_{i,j,k} + Fwaste_{j}, i \in SC, j \in SK, k \in ST (117)$$

$$(Cin_{i} - Cout_{i}) = \sum_{j \in SK} \sum_{k \in ST} Cavg_{i,j,k} + Cfresh_{i} , i \in SC, j \in SK, k \in ST (118)$$

$$(Cout_{i} - Cin_{i}) = \sum_{j \in SK} \sum_{k \in ST} Cavg_{i,j,k} + Cwaste_{i} , i \in SC, j \in SK, k \in ST (119)$$

$$(Cout_j - Cin_j) = \sum_{i \in SC} \sum_{k \in ST} Cavg_{i,j,k} + Cwaste_j , i \in SC, j \in SK, k \in ST (119)$$

## 3.5.3.2. The Mass Balances at Each Stage

The stage balances are used to resolve either the flowrate or the concentration at each stage from stage k to stage k+1. The variables ( $F_{i,k}$ ,  $F_{j,k}$ , CIK<sub>i,k</sub>, CJK<sub>j,k</sub>) are the continuous variables corresponding to the flowrate and the concentration of the source i and the sink j at stage k. The flowrate/concentration of the source i at the stage k is the inlet for the flowrate/concentration of the source i at the stage k+1. Moreover, the flowrate/concentration of the sink j at the stage k+1 is the inlet for the flowrate/concentration of the sink j at the stage k.

$$(F_{i,k} - F_{i,k+1}) = \sum_{j \in SK} Me_{i,j,k} , i \in SC, j \in SK, k \in ST (120)$$
$$(F_{j,k} - F_{j,k+1}) = \sum_{i \in HS} Me_{i,j,k} , i \in SC, j \in SK, k \in ST (121)$$
$$(CIK_{i,k} - CIK_{i,k+1}) = \sum_{j \in SK} Cavg_{i,j,k} , i \in SC, j \in SK, k \in ST (122)$$
$$(CJK_{j,k} - CJK_{j,k+1}) = \sum_{i \in SC} Cavg_{i,j,k} , i \in SC, j \in SK, k \in ST (123)$$

Based on the superstructure model, the higher flowrate/concentration runs from the left side to the right side which has lower flowrate/ concentration. As the flowrate/ concentration goes from the left-side, its flowrate/concentration will decrease for each source i. Moreover, the reverse is for the sink j.

$$F_{i,k} \ge F_{i,k+1} , i \in SC, j \in SK, k \in ST (124)$$
  

$$F_{j,k} \ge F_{j,k+1}, i \in SC, j \in SK, k \in ST (125)$$
  

$$CIK_{i,k} \ge CIK_{i,k+1}, i \in SC, j \in SK, k \in ST (126)$$
  

$$CJK_{j,k} \ge CJK_{j,k+1}, i \in SC, j \in SK, k \in ST (127)$$

#### 3.5.3.4. The Constrains for Each Inlet and Outlet Flowrate/ Concentration

Based on eq. 114-121, The flowrate/ concentration at the first stage is the inlet for the source i, and the sink j has the inlet which is the flowrate/ concentration at the last stage. As the source i goes to the sink j, there are no target flowrate of the outlet source i. Moreover, the inlet of the sink j only comes from the source i. The characteristics of the superstructure is that it depends on both the source and the sink streams. Therefore, the flowrate of the source i at the first stage is the same as the inlet stream for the source i, and the flowrate of the sink j at the last stage k is the same as the inlet stream for the sink j.

 $Fin_{i} = F_{i,k}, i \in SC, k \in First ST (128)$   $Fin_{j} = F_{j,k}, j \in SK, k \in Last ST (129)$   $Fout_{i} \leq F_{j,k}, i \in SC, k \in Last ST (130)$   $Fout_{j} \geq F_{j,k}, j \in SK, k \in First ST (131)$   $Cin_{i} = CIK_{i,k}, i \in SC, k \in First ST (132)$   $Cin_{j} = CJK_{j,k}, j \in SK, k \in Last ST (133)$   $Cout_{i} \leq CIK_{i,k}, i \in SC, k \in Last ST (134)$   $Cout_{j} \geq CJK_{j,k}, j \in SK, k \in First ST (135)$ 

### 3.5.3.5. The Fresh Water and The Waste Load

The waste is the excess of the source i that can be calculated by using the difference between the flowrate at the last stage and the target flowrate of the source. To get the target flowrate/ concentration of the sink, the fresh water need to be calculated by using the difference between the outlet flowrate of the sink j and the flowrate/concentration at the first stage.

> $F_{i,k} - Fout_i = F_{Waste}, i \in SC, k \in Last ST (136)$   $Fout_j - F_{j,k} = F_{Fresh}, j \in SK, k \in First ST (137)$   $CIK_{i,k} - Cout_i = C_{Waste}, i \in SC, k \in Last ST (138)$  $Cout_j - CJK_{j,k} = C_{Fresh}, j \in SK, k \in First ST (139)$

#### 3.5.3.6. Concentration Average

The concentration average is the concentration when the concentration of the source i and the sink j are mixed. It depends on the flowrate of the sink j at the stage k+1 and the mass exchanged between the source i and the sink j. Moreover, the concentration of each source i and sink j at each stage also affects this eq. 140.

$$Cavg_{i,j,k} = \frac{\left[\left(CIK_{i,k}.Me_{i,j,k}\right) + \left(CJK_{j,k}.F_{j,k+1}\right)\right]}{Me_{i,j,k} + F_{j,k+1}}, \ i \in SC, \ j \in SK, \ k \in ST \ (140)$$

3.5.3.7. The Objective Function of Step 1: Mass Recovery.

In Step 1, the fresh water required, and the waste produced are minimized.  $C_{\text{fresh}}$  and  $C_{\text{waste}}$  are the cost coefficient of the fresh water and the waste.

$$TAC = C_{Fresh} \cdot \sum_{j \in SK} F_{Fresh} + C_{waste} \cdot \sum_{i \in SC} F_{Waste}, \ i \in SC, j \in SK \ (141)$$

#### 3.5.4.1. The Overall Heat Balances

The target temperature can be obtained by using the overall heat balances. In this work, the heat capacities (Cp) used for the overall heat balance calculation in eq. 142-143 of each stream are constant due to make the same comparisons to the other literatures. However, in the reality, the heat capacity (Cp) is the function of the temperatures. It must not be the same at each stage as the temperature at each stage is not the same.

$$F_i. Cp_i. (TIn_i - Tout_i) = \sum_{k \in ST} \sum_{j \in CS} q_{i,j,k} + qcu_i, \ i \in HS, \ k \in ST \ (142)$$
$$F_j. Cp_j. (Tout_j - Tin_j)F_j = \sum_{k \in ST} \sum_{i \in HS} q_{i,j,k} + qhu_j, \ j \in CS, \ k \in ST \ (143)$$

## 3.5.4.2. The Heat Balance at Each Stage

The temperatures at each stage are possible to be known by using the eq. 144-145. The isothermal condition adopted in eq. 144-145 means that it has fewer nonlinearities than the non-isothermal condition. Before entering to the next stage, the process streams are mixed isothermally.

$$(t_{i,k} - t_{i,k+1})F_i = \sum_{j \in CS} q_{i,j,k} \quad k \in ST, \ i \in HS \quad (144)$$
$$(t_{j,k} - t_{j,k+1})F_j = \sum_{i \in HS} q_{i,j,k} \quad k \in ST, \ j \in CS \quad (145)$$

## 3.5.4.3. The Feasibility of The Temperatures

The hot streams come from the left to the right, and the reverse is for the cold streams. Based on the eq. 146-147, the temperatures are monotonically decrease from the left at stage k to the right at stage k+1.

$$t_{i,k} \ge t_{i,k+1} \ i \in HS, \ k \in ST \ (146)$$
  
 $t_{i,k} \ge t_{i,k+1} \ j \in CS, \ k \in ST \ (147)$ 

## 3.5.4.4. The Temperature Feasibilities

The inlet of the hot streams which has the highest temperature is its temperature at the first stage k. The cold stream that has the lowest temperature enter the HENS superstructure at the last stage. As the cold stream enter the superstructure from the left to the right, its temperature will increase.

> $Tin_{i} = t_{i,k} \ i \in HS, \ k \in First \ ST$ (148)  $Tout_{i} \leq t_{i,k} \ i \in HS, \ k \in Last \ ST$ (149)  $Tin_{j} = t_{j,k} \ i \in HS, \ k \in Last \ ST$ (150)

 $Tout_i \ge t_{i,k} \ i \in HS, \ k \in First \ ST$  (151)

3.5.4.5. The Logical Constrains

The binary variable  $(z_{i,j,k})$  depicts the stream matching existence as its integer value equals to "1". The cold utility matching appears as the binary variables  $(zcu_i)$  equals to "1". The same rule is applied for the hot utility matching using  $(zhu_j)$ . The binary variables  $(z_{i,j,k}, zcu_i, zhu_j)$  mean their values can be zero or one, the superstructure model forces the binary variables to be zero to get the minimum heat exchanger matchings. The variables  $(\Omega_{i,j}, \Omega_i, \Omega_j)$  are the upper bound of the heat loads to ensure the values of  $(z_{i,j,k}, zcu_i, zhu_j)$ .

$$q_{i,j,k} - \Omega_{i,j} \cdot z_{i,j,k} \leq 0 \quad i \in HS, j \in CS, k \in ST (152)$$

$$qhu_j - [F_j(Tout_j - Tin_j)] \cdot zhu_j \leq 0 \quad j \in CS (153)$$

$$qcu_i - [F_i(Tin_i - Tout_i)] \cdot zcu_i \leq 0 \quad i \in HS (154)$$

#### 3.5.4.6. The Hot and Cold Utility Loads

In the HENS superstructure, the cold utilities are only possible to be located at the end of the stage depending on the temperature difference between the temperatures at the last stage and the target temperature. Moreover, the hot utilities are only possible to be placed at the first stage depending on the temperature difference between the temperature at the first stage and the target temperature.

$$(t_{i,k} - Tout_i)$$
.  $F_i = qcu_i$   $i \in HS$ ,  $k \in Last ST$  (155)  
 $(Tout_j - t_{j,k})$ .  $F_j = qhu_j$   $j \in CS$ ,  $k \in First ST$  (156)

#### 3.5.4.7. The Driving Forces

The driving forces can be calculated based on the eq. 157-158. In this part, the heat exchanger matching exists as the equation inside the bracket is forced to be zero because the integer value of  $(z_{i,j,k})$  is one. The variables  $(\Gamma_{i,j,k}, \Gamma_i, \Gamma_j)$ will activate the equations as the heat exchanger matching appears. If a match does not exist, they will inactivate the equations. These variables help to avoid numerical errors due to negative temperature difference because of no matching existed.

$$\begin{aligned} dt_{i,j,k} &\leq t_{i,k} - t_{j,k} + \Gamma_{i,j} (1 - z_{i,j,k}) \ i \in HP, \ j \in CP, \ k \in ST \ (157) \\ dt_{i,j,k+1} &\leq t_{i,k+1} - t_{j,k+1} + \Gamma_{i,j} (1 - z_{i,j,k}) \\ i \in HP, \ j \in CP, \ k \in ST \ (158) \\ dtcu_i &\leq t_{i,k+1} - Tout_{cu} + \Gamma_i (1 - z_{i,j,k}), \ i \in HS, \ j \in CS, \ k \in ST \ (159) \\ dthu_j &\leq Tout_{hu} - t_{j,k} + \Gamma_j (1 - z_{i,j,k}), \ i \in HS, \ j \in CS, \ k \in ST \ (160) \end{aligned}$$

#### *3.5.4.8. The Logarithmic Mean Temperature Difference (LMTD)*

The second LMTD's Chen approximation is used. Based on the comparison of the second LMTD Chen's approximation used in (Azeez, Isafiade et al. 2013), the second LMTD Chen's approximation has the fewest error. Moreover, it is better than the first Chen's LMTD approximation. Based on the comparison, the first Chen's LMTD approximation gave the underestimate the real values of LMTD (Krishna & Murty, 2007; Shenoy & Fraser, 2013). This second Chen's LMTD approximation is also useful to avoid the infinite and overestimate of heat exchanger area calculation.

The second Chen's Logarithmic Mean Temperature Difference (LMTD):

$$LMTD \approx \left[\frac{1}{2} \left(dt_{i,j,k}^{0.3275} + dt_{i,j,k+1}^{0.3275}\right)\right]^{\frac{1}{0.3275}} \quad i \in HP, \ j \in CP, \ k \in ST \ (161)$$

## 3.5.4.9. The Area at Each Heat Exchanger Matching

The area is as the function of the heat load, LMTD and the heat transfer coefficient  $(U_{i,j})$ . The area calculation is important because it is minimized and included in the objective function.

$$Area_{i,j,k} = \frac{q_{i,j,k}}{\left(LMTD_{i,j,k} \cdot U_{i,j}\right)} \quad i \in CS, \ j \in HS, \ k \in ST \quad (162)$$

## 3.5.4.10. The Objective Function of HENS

The objective function forces the TAC to be minimum which includes minimizing the hot and cold utilities, the area cost for all matches, and the heat exchanger matchings. The TAC will decrease, as the value of  $\gamma$  is less than one. At the same heat loads.

$$OPEX = h_{op} \left[ \sum_{hu \in HU} C_{HU} x Q_{HU} + \sum_{cu \in CU} C_{CU} x Q_{cu} \right] (163)$$
$$CAPEX = \sum_{i \in Hot} \sum_{j \in Cold} \left[ C_{HE}^{Cap} x N_{H1,H2} + C_s^{Cap} x S_{H1,H2} \right] (164)$$
$$Min. \ TAC = \frac{1}{N_{op}} x \left[ CAPEX + \sum_{n=1}^{Nop} \frac{OPEX}{(1+ra)^n} \right] (165)$$

## CHAPTER 4 RESULT AND DISCUSSION

To test the model working well, it is tested by using some case studies (MENS, HENS, CHAMENS).

## 4.1. Mass Exchanger Network Synthesis (MENS)

Based on the case study (Jide 2007), the process lean streams,  $L_1$  and  $L_2$ , are used to remove ammonia from 5 gaseous rich streams. One external high-priced MSA (L<sub>3</sub>) is also allocated when using only two free process lean streams is not adequate. Our task minimizes TAC by providing the minimum external MSA usage, unit of the mass exchanger required, and area of the continuous-contact packed column exchanger as it can be seen in Figure 6.5-6.9. In this thesis, Exchanger Minimum Composition Difference (EMCD) are varied from 0.0001, 0.0003, 0.0005, 0.0007 and 0.0009. All the results are based on the estimation that the external MSA used to get the L<sub>3</sub> target composition 0.017 is 10 times lower than the external MSA used in Figure 6.5-6.9 using L<sub>3</sub> target composition 0.0017. The stream data are depicted in Table 6.1 and Table 6.2. Based on Table 6.3 and Figure 6.1, the minimum TAC is found in point *EMCD* 0.0009 resulting in TAC \$ 65,481  $a^{-1}$ . Based on each case, z for the existence of the stream matching equals to 1 and equals to 0 if the stream matching does not exist. The mass exchanger network design at EMCD 0.0009 is chosen because it has the minimum TAC with the minimum total area 1,169  $m^2$  and the external MSA (L<sub>3</sub>) needed 2.487 kg.s<sup>-1</sup>.



**Figure 4.1** The effect of EMCD to the TAC for Case Study 1: MENS. **Table 4.1** The rich streams data for Case Study 1: MENS

<b>Rich stream</b>	R(kg/s)	Supply ( <i>y</i> <sub>s</sub> )	Target (y <sub>t</sub> )
$R_1$	2	0.0050	0.0010
$R_2$	4	0.0050	0.0025
$R_3$	3.5	0.0110	0.0025
$R_4$	1.5	0.0100	0.0050
$R_5$	0.5	0.0080	0.0025

Table 4.2 The lean streams data for Case Study 1: MENS

Lean stream	L <sup>max</sup> ( <i>kg/s</i> )	Supply (x <sub>s</sub> )	Target $(x_t)$
$L_1$	1.8	0.0017	0.0071
$L_2$	1	0.0025	0.0085
L <sub>3</sub>	$\infty$	0	0.017

Table 4.3 The effect of EMCD to the TAC for Case Study 1: MENS

EMCD	Me	LMCD	Ν	F('L <sub>3</sub> ')	Area <sub>i,j,k</sub>	TCC	TAC
	$(kg. s^{-1})$		(units)	$(kg. s^{-1})$		$(\$.a^{-1})$	$(\$. a^{-1})$
0.0001	0.0581	0.0022	7	2.4871	1328	151,745	71,249
0.0003	0.0570	0.0017	7	2.4871	1637	174,187	81,776
0.0005	0.0570	0.0019	7	2.4871	1475	162,608	76,345
0.0007	0.0570	0.0020	7	2.4871	1446	160,513	75,362
0.0009	0.0580	0.0025	7	2.4871	1169	139,450	65,481

\*Based on the estimation of the results using target  $L_3$ = 0.0017, the MSA used to get target  $L_3$ =0.017 is 10 times lower than the MSA usage for target  $L_3$ =0.0017.

Mothods/ Paramotor	New hybrid method	FLM-SWS	IBMS	SWS
Withous/ 1 arameter	(Emhameda et al., 2007)	(Szitkai., 2006)	(Jide, 2007)	
Me $(kg.s^{-1})$	-	0.0579	0.0580	0.0570
LMCD	-	0.0015	0.0015	0.0020
N (Units)	10	8	7	7
$F('L3')(kg.s^{-1})$	2.543	2.9040	2.8090	2.4871
Area <sub>i,j,k</sub>	-	1,940	1,963	1,446
TCC ( <i>\$.a</i> <sup>-1</sup> )	-	203,879	196,358	160,513
$TAC^{a}(\$.a^{-1})$	134,399	134,000	133,323	111,785
$TAC^{b}(\$.a^{-1})$	-	91,471	92,185	75,362

**Table 4.4** The comparison of Case Study 1: MENS using this work (SWS) among the other literatures

<sup>a</sup>Without Cj <sup>b</sup>with Cj \*ME= The Mass Exchangers, \*Based on the estimation of the results using target  $L_3$ = 0.0017, the MSA used to get target  $L_3$ =0.017 is 10 times lower than the MSA used in target  $L_3$ =0.0017.

Acquiring the same comparison of this work among the other literatures using the same *EMCD* 0.0007, The IBMS method *(Jide 2007)* in Figure 6.3 provides the external MSA required 2.809 kg.s<sup>-1</sup> impacting to their TAC \$ 133,323  $a^{-1}$ . This TAC was affected by the cost coefficient that they used was \$ 14,670  $a^{-1}$  provided by the operational time ( $\beta$ ) 8,150 working hours per year and \$ 0.0005  $a^{-1}$  for the cost coefficient of the external MSA L<sub>3</sub> ( $\alpha$ ). The FLM-SWS, also cited in (Jide 2007) for the cost coefficient of the external MSA also should be corrected to \$ 0.0005  $a^{-1}$ .

Based on Table 6.4 using the same parameter without including  $C_j$  and with including  $C_j$  to make equitable comparison, the results of the TAC using SWS in this thesis are \$ 111,785  $a^{-1}$  and \$ 75,362  $a^{-1}$  with the external MSA required 2.487 kg.s<sup>-1</sup> and our result has the lowest TAC compared to the IBMS method, FLM-SWS and the hybrid method in *(Jide 2007)*.

Moreover, the target concentration of L<sub>3</sub> should be counted in their work to determine their TAC. Their TAC should be corrected to \$ 92,185  $a^{-1}$  in IBMS method. The TAC of FLM-SWS method should be corrected to \$ 91,471  $a^{-1}$  for 2.904 kg. s<sup>-1</sup> of the flowrate external MSA. According to the mass balance in Figure 6.3, the target concentration of the external MSA L<sub>3</sub> in IBMS method should be corrected from 0.0017 to be 0.017.

$$TCC = 1.1 N_{units} x \$618 \left(\frac{\sum_{i,j,k} Area_{i,j,k}}{N_{units}}\right)^{0.66} (165)$$
  
Min.  $TAC = \alpha.\beta \sum_{j \in L} c_j L_j + Af. \left(\sum_{i \in R} \sum_{j \in L} \sum_{k \in ST} z_{i,j,k}\right) + PC \left(\frac{Me_{i,j,k}}{K_y a. LMCD}\right)^{\gamma} (166)$ 

The annual cost per area for continuous contact columns installed (PC= \$618) influences the Total Capital Cost (TCC) and TAC based on eq. 165-166. Moreover, annualization factor  $(A_f)$  for the mass exchanger used is 0.225, and  $c_j$  is the target composition subtracted by the inlet composition of the lean stream. Area cost exponent of the mass exchanger ( $\gamma$ ) is 0.66. To calculate the area of the mass exchangers, the lumped mass transfer coefficient for this case  $(K_{\nu}a)$ , the sizing coefficient for, is 0.02 kg of NH<sub>3</sub>/ s.kg using the continuous contact packed column mass exchangers. The TAC using IBMS method is \$ 133,323  $a^{-1}$ . Concerning the same comparisons, this thesis still has the lowest TAC \$ 111,785  $a^{-1}$  in comparison among the other literatures using IBMS method, FLM-SWS, and New-hybrid method because the number of the mass exchanger needed 7 and the total area of our model are still the lowest. The flowrates of MSA1 and MSA2 usage are maximized 1.8 kg. s<sup>-</sup> <sup>1</sup>, and 1 kg. s<sup>-1</sup>. By maximizing the usage of the process MSA  $L_1$  and MSA  $L_2$ , the high-priced external MSA L<sub>3</sub> can be minimized. Futhermore, after checking the mass balance in Figure 6.2, the supply of the lean streams L<sub>1</sub> and L<sub>2</sub> should be corrected to 0.0017 and 0.0025 for further used.

**Table 4.5** The comparison of the SWS to the other methods for the case study 1:MENS

No.	Method	Dominance	Vice Versa		
1.	New hybrid	• The solution is close to global	•	High solving time.	
	method	optimum.	•	Partially using hand	
	(Emhameda et	• Clear step to overcome the		calculation	
	al., 2007).	infeasibilities	•	Non-simultaneous	
		• Using driving force plot analysis	•	Unsuitable for large-scale	
		• Using SWS and including detailed		problem	
		exchanger design.	•	Using Pinch technology	
		• Producing more than one local	•	Not guaranteed optimum	
		optima solution		solution.	
2.	Interval Based	• A straightforward method using	•	Less freedom of the heat/	
	MINLP	MINLP		mass exchange.	
	Superstructure	• A slight initialization involved	•	Fixed temperature/	
	, IBMS (Jide,	• Expeditious computational time		composition location.	
	2007)	• All hot and cold utilities being the	•	Less number of the	
		process streams		intervals.	
		• Compatible for a small-scale	•	Improper to be applied in	
		problem		the large-scale problem.	
			•	Only depends on the rich	
				stream.	
3.	SWS	• Uncomplicated to figure out the	•	Desire proficient	
		small-scale, moderate-scale, and		initializations.	
		large-scale problem using MILP,	•	Hot and cold utilities are	
		MINLP, NLP		only available at the end of	
		• High degree of freedom		the stage.	
		• Depends on both rich and lean	•	Difficult to handle a lot of	
		streams.		data or equation due to the	
		• Considerable for small EMAT		nonlinearities	

No.	Method	Dominance	Vice Versa
4	SWS in this work	• The interval temperatures are	• Difficult to disallow stream
		variables.	splitting.
		• Applicable to handle different	• Heavy computational times
		heat transfer coefficient, and	• A few structures are
		different heat capacities at	commonly neglected, such as
		each interval temperature.	stream by-pass, a stream
			branch passing through two
			heat exchangers in series, and
			non-isothermal mixing

**Table 4.6** The comparison of the SWS to the other methods (Continued)


**Figure 4.2** The final structure of FLM-SWS for Case Study 1 at EMCD 0.0007 (Szitkai et al., 2006).



**Figure 4.3** IBMS network for case study 1 featuring seven units with a 2-way split for a rich stream and a 3-way split for a lean stream for Case Study 1 at EMCD 0.0007 (Jide., 2007).



**Figure 4.4** The final structure of the new hybrid method for *Case Study 1* at EMCD 0.0007 (Emhameda et al., 2007).



Figure 4.5 The final structure of MENS for Case Study 1 by this work using SWS.



Figure 4.6 The final structure of MENS for Case Study 1 at EMCD 0.0003 by this work using SWS.



0.0025 0.0025 0.0050 0.0025 0.0017 0.0025 0.0010 0 K8 0.0025 0.0025 0.0050 0.0017 0.0025 0.0010 0.0025 0 STAGE 6 STAGE 7 A= 168 m<sup>2</sup> 0800.0 K7 0.0050 0.0025 0.0017 0.0025 0.0025 0.0050 0.00032 0.0025 K6 0.0050 0.00032 0.0025 0.0017 0.0025 0.0025 0.0050 0.0025 STAGE 4 STAGE 5 K5 0.00032 0.0017 0.0050 0.0025 0.0025 0.0025 0.0025 0.0050  $A = 60 \text{ m}^2$ 0.0027 K4 0.0080 0:00:0 0.0050 0.0025 0.0032 0.00032 0.0025 0.0025 STAGE 2 STAGE 3  $A = 220 \text{ m}^2$  $A = 322 \text{ m}^2$ 0.0242 0.0100 K3 0.0050 0.0050 0.0032 0.0025 0.0050 0.0094 0.0080 0.0017  $A = 208 \text{ m}^2$ 0900.0  $A = 20 \text{ m}^2$ 0.0015  $A = 51 \text{ m}^2$ 0.0055 R STAGE 1 0.0050 0.0100 1700.0 0.0085 0.0017 0.0050 0.0110 0.0080 KI 0800.0 0.0050 0.0110 0.0100 1700.0 0.0050 0.0085 0.0017 0.0085 0.0071 0.0017 0.0100 0800.0 0.0050 0.0110 R1 0.0050 R2 R3 1 1.2 13 R R5 4 kg/s 1.5 kg/s 0.5 kg/s 1.8 kg/s 3.5 kg/s 2 kg/s 1 kg/s 24.9 kg/s

Figure 4.8 The final structure of MENS for Case Study 1 at EMCD 0.0007 by this work using SWS.



Figure 4.9 The final structure of MENS for Case Study 1 at EMCD 0.0009 by this work using SWS.

## 4.2. Heat Exchanger Network Synthesis (HENS)

In this case study (Hong, Liao et al. 2019), the three plants are possible for exchanging heat across the plant. The distance among the plants is constant 0.25 km. The 7 stages are used to get the high degree of freedom with the faster computation times. In this thesis, EMAT is varied, 2, 4, 6, 8, 10, and 14. As the result of this work, EMAT 2 is preferred because it has the lowest TAC \$ 1,471,914. By using SWS, the computation time required to solve the HENS are deferred at the extensive EMAT.

Table 4.7	The streams	data for	HENS	case	studv
	I ne bu camb	aaca 101	110110	ease	Staaj

Stream Number	F.Cp (kW/°C)	T <sub>in</sub> (°C)	Tout (°C)	h (kW/°C.m²)	C <sub>p</sub> (kJ/°C.kg)	P (kg/m <sup>3</sup> )	μ.10 <sup>-3</sup> (Pa.s)	К (W/m.°C)
$H_1(P_1)$	300	250	120	1.0	10	621	0.2363	0.6
$H_{2}(P_{2})$	250	500	120	1.2	10	802	0.2721	0.6
$H_{3}(P_{3})$	2500	125	119	1.1	50	830	0.2875	0.6
$H_{4}(P_{3})$	200	200	30	1.3	10	725	0.2421	0.6
$C_{1}(P_{1})$	500	185	220	1.4	8	640	0.2734	0.6
$C_{2}(P_{2})$	150	139	500	1.2	3	680	0.2632	0.6
$C_{3}(P_{2})$	100	20	250	1.1	4	760	0.2722	0.6
$C_4(P_3)$	250	110	160	1.1	5	780	0.2831	0.6
C <sub>5</sub> (P <sub>3</sub> )	2500	195	205	1.3	50	810	0.2755	0.6
Water	-	15	20	1.0	-	-	-	-
LP	-	150	149	1.2	-	-	-	-
MP	-	220	219	1.5	-	-	-	-
HP	-	280	279	1.8	-	-	-	-
Fuel	-	800	750	2.5	-	-	-	-

 $CCU_{Water} =$  10/*kW.y*,  $CHU_{LP} =$  40/*kW.y*,  $CHU_{MP} =$  100/ *kW.y*,  $CHU_{HP} =$  160/ *kW.y*,  $CHU_{Fuel} =$  200/ *kW.y*.

Table 4.8 The effect of EMAT 2-10°C in HENS to the TAC

Computational time	t 0.047 s	, 1.533 s	9.369 s	5 1 <i>min</i> :24.51 <i>s</i>	p 22h:41min:31.65s	83h:20min:20.63s	
TAC (\$.a <sup>1</sup> )	1,471,914	2,236,557	2,114,592	2,290,996	1,847,594	2,696,801	
PMC (\$.a <sup>-1</sup> )	170,292	213,759	244,882	323,218	213,703	198,294	
PIC (\$.a <sup>-1</sup> )	281,375	351,367	423,918	559,193	183,121	456,145	
Min. TAC ( <i>§</i> . <i>a</i> <sup>-1</sup> )	1020247.1	1671430.6	1445791.3	1408585.1	1450770.7	2042362.4	
CAPEX (\$.a <sup>-1</sup> )	448747.1	1036930.1	748292.26	641091.08	417261.71	284352.37	
<i>OPEX</i> (\$.a <sup>-1</sup> )	571500	634500.5	697499	767494	1033509	1758010	
Area HE (m <sup>2</sup> )	9970.146	24805.92	17495.39	14732.59	9090.083	5696.834	
N (units)	12	14	17	22	14	16	
б (ИМ)	131850	131550	131250	130916.7	129650	126200	ond.
Area Qc (m²)	1272.507	1273.835	1272.213	1289.789	1333.27	1321.182	iute, s= sec
Qс (kW)	51150	51450.1	51749.9	52083.4	53349.9	56800	min= min
Area Q <sub>H</sub> (m <sup>2</sup> )	1.3436901	2.6770742	4.0003119	5.4587203	10.89271	45.266517	in $h=hour$ ,
Q <sub>H</sub> (kW)	300	009	006	1233.3	2500.05	5950.05	ional time
EMAT	2	4	9	8	10	14	Computat



Figure 4.10 The effect of EMAT 2-14°C to the TAC.

Livin 11 10 C.	•			
Parameters/ Methods	Modified SWS (Chang et al., 2017)	Modified SWS (Chang et al., 2017)	New Transhipment (Hong et al., 2019)	This Work (SWS)
Unit HE (Units)	20	14	14	9
Inter-plant (Units)	0	4	5	3
PIC (\$.a-1)	0	51789	65,188	183,121
PMC (\$.a-1)	48,837	54238	106,099	213,703
HU/CU (kW)	15,500/35,000	6,250/57,100	2,776/ 53,626	2,500/53,350
HUC/CUC (kW.\$-1)	2,752,399/350,000	1,090,000/571,000	427,620/ 536,262	500,000/ 533,500
EXC (\$.a-1)	705,624	460,404	535,855	417,262
TAC, \$.a-1	3,856,860	2,227,431	1,671,024	1,847,594

Table 4.9	The result	comparisons	of the case	e study 2	among the	other liter	atures at
EMAT = 1	10°C.						

\*EXC= Exchanger Cost PMC= Pumping Cost, PIC=Piping Cost, HUC= Hot Utility Cost, CUC=Cost

## Utility Cost

Table 4.10 The comparison of SWS to the other methods.

No.	Method	Dominance	Vice Versa
1	The Enhancement of the transshipment model (Hong et. al. 2019)	<ul> <li>Capable to resolve no splits.</li> <li>Profitable for detail cost included.</li> <li>Multiple utilities comprised because the high temperature difference for the hater.</li> <li>A stream by-pass, a stream branch passing through two heat exchangers in series, and non-isothermal mixing involved.</li> <li>The small, moderate, large scale problem overcome.</li> <li>Simultaneous method.</li> <li>Minimizing the piping and pumping cost.</li> <li>All constraints keep linear while allowing non-isothermal mixing.</li> <li>Provide the lowest TAC.</li> <li>DICOPT for MINLP. CONOPT for NLP solver. CPLEX for MILP.</li> </ul>	<ul> <li>Fixed temperature intervals at the first and the last temperature interval.</li> <li>Incompatible for small EMAT.</li> <li>More binary variables required.</li> <li>More complexities.</li> <li>Indirect heat integration.</li> </ul>
2	The enhancement of the SWS model (Chang et al., 2017)	<ul> <li>Direct heat integration</li> <li>Less inter-plant heat exchangers</li> <li>Minimizing the piping and pumping cost on the objective function</li> <li>Simultaneous method</li> <li>Using the multiple intervals</li> <li>Simultaneous</li> <li>KNITRO for NLP. DICOPT for MINLP.</li> </ul>	<ul> <li>Isothermal</li> <li>Low chance to get the varieties of the hot utility usage</li> <li>Without overall energy heat balance</li> </ul>
3	This Work (SWS)	<ul> <li>Low exchanger cost</li> <li>More accurate on the area calculation</li> <li>Low complexities (it does not contain many binary variables and equations)</li> <li>Direct heat integration</li> <li>DICOPT for MINLP</li> </ul>	<ul> <li>The piping and pumping costs are not minimized</li> <li>Isothermal</li> <li>Non-simultaneous</li> </ul>

The optimal solution provided (at EMAT=10) in this work is compared to the other literatures which used advancement of the SWS (Chang, Chen et al. 2017) and Transshipment model (Hong, Liao et al. 2019) in the Table 6.7 at the same conditions.

The result of the process heat exchanger cost by using SWS is the second lowest as compared to the current results. The results by using this work salvages the process heat exchanger cost 17% lower than the current best of the advancement transshipment model in (Chang, Chen et al. 2017). When TAC of this thesis using SWS is compared, it is 9.6% higher than the current best result of the new transshipment model *(Hong, Liao et al. 2019)*.

This work achieves the process heat exchanger cost which is cheaper than the transshipment model (*Hong, Liao et al. 2019*) because by doing the initialization in SWS the nonlinearities will be decreased for the next step. When the inter-plant heat exchangers are not used in (*Chang et al., 2017*), the process heat exchanger cost will be higher. As shown in Figure 6.14, the three perceived inter-plants heat exchangers facilitate the network to diminish the energy demand by utilizing the excess of energy in the plant to become the additional heating/cooling source for the other plant in this thesis. However, if the number of the inter-plant heat exchangers are too much, the piping and pumping cost will be higher as the pressure drop increases and the further of the distance used to deliver the fluid. The numbers of the heat exchangers in this work are the fewest in contrast to the other literatures, and the heat exchanger cost of this work is still the second lowest.

The second fewest TAC can be obtained because based on the step in Figure 5.4 of this model. The minimum area heat exchanger matchings from Step 1 are minimized again in Step 2 with the minimum area required. In this work, the temperature intervals are not fixed that can make the model has more possibilities to get the heat exchanger matchings. Based on this result, the number of the heat exchangers which are the lowest with the small area can cause the TAC reduction. The piping and pumping cost are calculated separately as the parameters. They are not minimized in this thesis. However, the competitive TAC still can be obtained.







Figure 4.13 The optimal HENS at EMAT 10 by using this work (SWS).



Figure 4.14 The optimal HENS at EMAT 2 by using this work (SWS).



Figure 4.15 The optimal HENS at EMAT 4 by using this work (SWS).











Figure 4.18 The optimal HENS at EMAT 14 by using this work (SWS).

## 4.3. Combined Mass and Heat Network Synthesis (CHAMENS)

4.3.1. CHAMENS: Ammonia Recovery

This case study is obtained in *(Ghazouani 2018)*. The ammonia waste produced in the calcium chloride production is allocated. Noticing the distinctive of this work among the other previous works, by using SWS the objective functions are minimizing the cost of the fresh ammonia and waste due to reduce the duty of the waste treatment plant and to recover ammonia as much as possible. The process source means the process source that can be considered for reuse/ recycle, or waste discharged. The process sinks mean the process unit to accept the process source. Moreover, it also minimizes the hot and cold utilities considering HENS and the configurations of each heat exchanger afterwards. EMAT is precise at 35 °C. The TAC produced by this method is compared to the other literature at the same conditions. Based on Table 6.10, the results of this work successfully defeat the results of the other literatures using the same equations for OPEX, CAPEX, and TAC in eq. 167-169.

$$OPEX = h_{op} \left[ \sum_{j \in Fresh} C_{fresh} x F_{Fresh} + \sum_{i \in Waste} C_{waste} x F_{Waste} \right] + \sum_{hu \in HU} C_{HU} x Q_{HU} + \sum_{cu \in CU} C_{cU} x Q_{CU} \right] (167)$$

$$CAPEX = \sum_{i \in Hot} \sum_{j \in Cold} \left[ C_{HE}^{Cap} x N_{H1,H2} + C_{S}^{Cap} x S_{H1,H2} \right] (168)$$

$$Min. \ TAC = \frac{1}{N_{op}} x \left[ CAPEX + \sum_{n=1}^{Nop} \frac{OPEX}{(1+ra)^{n}} \right] (169)$$

The method in *(Ghazouani 2018)* has the fixed the temperature scale by using  $\Delta T_{min}$  step or shifting the temperature scale. Their method impacts to the computation time that increases when the  $\Delta T_{min}$  decreases. They locate the supply of the hot process stream at the interval where it is after the end on the cold process stream side. Different from their method, this work gives the fewest area because the supply of the hot streams is located at the first stage, and the target of the cold process streams are located at the first stage at the same interval with the supply hot process stream. Therefore, since *EMAT* decreased, the fewer the complexity is, the faster the computation time will be. At a year operational time  $(N_{op}=I)$  for EMAT 35°C, the total area 9 process heat exchangers, 7 hot utilities, and 2 cold utilities provided by this work are 123,603 m<sup>2</sup>, 35,126 m<sup>2</sup>, and 33,460 m<sup>2</sup>. Using SWS method, this thesis affords the *TAC* \$ 29,457,090  $a^{-1}$  which is 6 % higher than the current best result using Transshipment model. The total area is high impacting to higher CAPEX than their result. However, in this thesis the hot and cold utilities can be minimized so, it has lower OPEX than the current best result. Different from the other literature (Ghazouani 2018), the hot and the cold utilities are fixed at ( $N_{op}=I$  year), and not able to have the results fewer than their fixed number in Fig. 6.22. For further used, the units of each flowrate should be corrected to kg.h<sup>-1</sup>, and the fresh water which has the flowrate 350 kg.h<sup>-1</sup> should go to *Sink 1*. In the other words, *Source 1*, 350 kg.h<sup>-1</sup>, should be replaced to the fresh water.

Streams Flowrates		Composition in impurities	Temperatures
	(kg. h <sup>-1</sup> )	(ppm)	(°C)
Sink 1	350	0	30
Sink 2	677	0-40	187
Sink 3	126	0-75	55
Sink 4	202	0-100	98
Waste		0-500	40
Source 1	530	30	21
Source 2	68	150	43
Source 3	1130	300	130
Source 4	36	500	35
Fresh Ammonia	L	0	30

**Table 4.11** The stream data for CHAMENS's case study

Parameter								
Cfresh	0.5	\$.kg <sup>-1</sup>	$\mathbf{h}_{op}$	8000	Н			
Cwaste	0	\$.ton <sup>-1</sup>	N <sub>op</sub>	1	Year			
Chot	0.01	\$.kWh <sup>-1</sup>	Ra	0.05				
Ccold	0.0025	\$.kWh <sup>-1</sup>	EMAT	35	°C			
$C_{he}^{Cap}$	5291.9	\$	htc <sub>NH3</sub>	50	W.K <sup>-1</sup> m <sup>-2</sup>			
$C_S^{Cap}$	77.79	\$.m <sup>-2</sup>	htchot	1000	W.K <sup>-1</sup> m <sup>-2</sup>			
			htc <sub>cold</sub>	1000	W.K <sup>-1</sup> m <sup>-2</sup>			

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HENS is provided by *(Ghazouani 2018)* in CHAMENS at  $(N_{op}= 2 years)$  based on Figure 6.25. Even though their work provides HENS, they still calculate TAC based on eq. 167-169. To make the same comparison, the TAC is provided in the same way as them since HENS is also provided by them. Moreover, based on the Table 6.10, this work (SWS) produces 4 % higher TAC than the new transshipment method at  $(N_{op}=2 years)$  as the result of the heat exchanger matchings minimized in the initialization part Step 1 in Figure 6.25. Then, the heat exchanger matchings and the area of the heat exchangers are decreased twice in the next step. The minimum heat exchanger matchings from the initialization step are minimized

again in the next step to get the minimum area. The nonlinearities are avoided by using the initialization in Step 1, so the computation time is faster. Using many heat exchangers that have low area is preferred than using fewer heat exchangers with high area required.

Based on the comparison to the current best literature in Table 6.10 and Table 6.11, At the  $N_{op}=2$  years, the TAC (\$ 29,337,982) decreases about 0.40 % compared to the result at  $N_{op}=1$  year (\$ 29,457,090) using SWS. When the current best literature (*Ghazouani 2018*) is used, TAC is increased about 1.07% from their result at  $N_{op}=1$  year (\$ 27,861,601) compared to the TAC at  $N_{op}=2$  years (\$ 28,164,394). Based on Figure 6.20, EMAT 35°C is the optimum TAC among the other results at different EMAT. It shows that SWS is applicable for the long-term TAC. The results of the TAC in this thesis using SWS are higher than the current best result of the literatures because the concentrations of the Sink 3 (41.9 ppm for Nop 1 year and 43 ppm for Nop 2 years) are lower than the maximum requirement of the Sink 3 (75 ppm). The higher the freshwater usage is, the lower the concentration of Sink 3.

The TAC reduction of using SWS in this thesis compared to the floating pinch concept (Tan et al, 2014) is \$ 235,306  $a^{-1}$  for 1-year operational time. The TAC in SWS is lower than the floating pinch technology because the floating pinch technology only depends on the targeting and optimizing OPEX while the SWS uses the mathematical approach that can optimize both OPEX and CAPEX with the minimization the area of the heat exchanger.

Nop		1 year		
Parameters/ Methods	Energy recovery algorithm (Sahu et al. 2012)	The Floating Pinch Technology (Tan et. al, 2014)	New Transshipment (Ghazouani, 2018)	This Work (SWS)
LFresh (kg.h <sup>-1</sup> )	655	655	655	675
QH (kW)	132,925	132,927	145,594	135,136
QC (kW)	79,224	79,228	91,896	80,991
Q(kW)	-	-	-	130,993
NHE (Units)	12	12	10	18
Area HU (m <sup>2</sup> )	-	-	-	35,126
Area CU (m <sup>2</sup> )	-	-	-	33,460
Area Process Heat exchangers (m <sup>2</sup> )	-	-	-	123,603
Total Area (m <sup>2</sup> )	187,662	199,213	160,311	192,189
OPEX (\$)	14,838,480	14,838,720	16,104,994	15,132,039
CAPEX (\$)	14,661,730	15,560,282	12,523,512	15,045,625
TAC (\$)	28,793,615	29,692,396	27,861,601	29,457,090

**Table 4.13** The optimum result at EMAT 35°C using SWS in CHAMENS: Case 3 (Nop= 1 year)

\*OPEX, CAPEX and TAC are recalculated based on the same equations in eq. 163-165.

**Table 4.14** the comparisons of the SWS in this work among the other methods in the previous literatures

No.	Method		Dominance		Vice Versa
1	The Floating Pinch	•	Mostly gives the impact to the	•	Non-simultaneous.
	Technology (Tan et.		annual operating cost (Hot and		(Minimizing the fresh
	al, 2014)		Cold utility usages, and the		ammonia, waste, hot and
			fresh ammonia usage).		cold utility at the first step.
		•	Solved using Extended		Then, minimizing the
			LINGO v11.0 with Global		HENS sequentially by
			Solver, MINLP formulation		applying the Pinch
			based.		Technology at the second
		•	Direct recycle/ reuse system.		step).
				•	the shifted hot and cold
					composite curves.
				•	The sequential method for
					HENS using pinch
					technology.
				•	Isothermal.

1	Table 4.15 The com	parisons of the SWS in this work among the other method	ods in the
	previous literatures (	Continued)	

No.	Method		Dominance		Vice Versa
2	The New	•	Consider the temperature of	•	Difficult to find the search
	Transshipment		the fresh ammonia to reduce		space at low EMAT. They
	(Ghazouani et. al,		the TAC in HENS.		locate the supply of the hot
	2018)	•	Applicable for reducing the		process stream at the
			hot and cold utility demands.		interval where it is after the
		•	Non-isothermal condition for		end on the cold process
			HENS structure.		stream side.
		•	Using L <sub>fresh</sub> to satisfy the	•	Isothermal condition for
			utility demand.		MENS including the hot
		•	Using both		and cold utility demand.
		•	Simultaneous	•	Not applicable for long-
		•	Non-isothermal condition		term responsible use
					because it tends to decrease
					the OPEX more than the
					CAPEX.
				•	Using fixed temperatures
					limits
				•	Sometimes, it has less
					degree of freedom because
					it depends to a discrete set
					of temperatures.
				•	High computational time
				•	Minimizing the units of the
					heat exchangers more than
					the heat exchanger areas.
3	SWS in this work	•	Applicable for long-term	•	Non-simultaneous.
			responsible use because it	•	It satisfies all the constrains
			tends to decrease the CAPEX		but, it cannot maximize the
			more than the OPEX.		maximum concentration
		•	Suitable for both the low		requirement for Sink 3 in
			EMAT and high EMAT.		MENS impacting to the
		•	The low area of the heat		HENS configuration.
			exchanger because the	•	Isothermal condition.
			intermediate stream		
			temperature is the variable.		

**Table 4.16** The comparisons of the SWS in this work among the other methods in the previous literatures (Continued)

No.	Method	Dominance	Vice Versa
3	SWS in this work (Continued)	• It tends to minimize the heat exchanger area more than the	
		units of the heat exchangers.	
		• More accurate formulation for the area calculation.	

SWS is favorable to be used at the low EMAT due to the low computational time at low EMAT. The transshipment method has high computational time at low EMAT due to the complexity of transshipment model at low EMAT for finding the free space of the heat exchanger. In completion, the model is robust due to high TAC reduction at low EMAT, the low complexities and nonlinearities at the last step. Table 6.11 implies that SWS method is efficient to be applied for the long-term application. As the operational time increases, the TAC decreases. The longer the operational time is, the cheaper the CAPEX will be.

Nop	1 year		2 years	
Parameters/ Methods	The Floating Pinch Technology (Tan et. al, 2014)	This Work (SWS)	New Transhipment (Ghazouani, 2018)	This Work (SWS)
L <sub>Fresh</sub> (kg.h <sup>-1</sup> )	655	675	654.9	675
Q <sub>H</sub> (kW)	132,927	135,136	131,883	135,420
$Q_{C}(kW)$	79,228	80,991	78,185	81,290
Q <sub>HE</sub> (kW)	-	130,993	124,022	130,671
N <sub>HE</sub> (Units)	12	18	10	18
Area HU	-	35,126	34,570	35,157
Area CU	-	33,460	32,238	33,506
Area process Heat exchangers (m <sup>2</sup> )	-	123,603	114,182	121,644
Total Area (m <sup>2</sup> )	199,213	192,189	180,989	190,307
OPEX (\$)	14,838,720	15,132,039	14,733,940	15,160,709
CAPEX (\$)	15,560,282	15,045,625	14,132,070	14,899,212
TAC (\$)	29,692,396	29,457,090	28,164,394	29,337,982

Table 4.17 The comparison of the TAC among the other literatures for  $N_{op}{=}1$  and 2 years at EMAT 35°C

\*TAC is calculated in the same way as the literatures based on eq. 163-165.

\* Heat capacity = 2.19 kJ.  $kg^{-1}$ . $K^{-1}$ ; Temperature of cold utility = 5–5.1 °C; Temperature of hot utility = 230–229.9 °C.

32,579,047 34,348,857 34,348,856 32,488,676 29,991,817 30,968,774 29,337,982 TAC 22,569,685 22,569,685 20,175,159 17,981,646 14,899,212 14,291,886 16,314,832 CAPEX 12,368,130 19,201,520 12,368,130 12,929,192 14,360,834 15,160,709 13,636,484 OPEX **Unit HE** 15 16 18 4 15 15 15 Area HE 143,660 121,644 234,275 234,275 200,511 168,711 99,144 Nop= 2 years 152,986 145,913 138,669 90,263 158,596 158,596 130,671 0 Area CU 44,188 26,314 28,711 31,087 <u>33,506</u> 24,324 24,324 121,699 53,364 53,364 58,974 66,048 73,290 81.290 Qcu Area HU 39,440 30,517 30,517 31,509 32,714 33,895 35,157 175,828 107,494 113,105 120,177 107,494 127,421 135,420 Qhu EMAT 10 30 15 20 25 35 Ś

 Table 4.18 The optimum result on different EMAT using SWS in CHAMENS: Case 3 (Nop= 2 years)



Figure 4.19 The effect of EMAT to the TAC using SWS in CHAMENS: Case 3 (Nop= 2 years).

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c

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EMAT (°C)





Figure 4.20 The optimal CHAMENS for EMAT 35 °C using Transhipment model Nop= 1 year (Ghazouani 2018).





Waste 1084.3 kg/s Sink 3 126 kg/s (41.9 ppm) Sink 4 202 kg/s Source 1 120.4 kg/s (304.8 ppm) Fresh 325.3 kg/s (100 ppm) 252.6 kg/s Fresh 350 kg/s 68 kg/s Source 4 0.1 kg/s 157 kg/s 25.9 kg/s Source 1 Source 4 10 kg/s Source 4 Source 2 Source 3 31 kg/s Source 1 Qcu(j) 55°C 21°C 98°C 21°C 35°C 40°C 35°C 30°C C5 21°C 35°C Qhu(j) 30°C U 430 C1 3 C6 3 ව Q= 636 kW  $A = 182 \text{ m}^2$ Q= 80,354 kW 107 130 35 21 35 75 35 30 43 21 K10 86 21 Q=8,512 kW A= 8,431 m<sup>2</sup> STAGE Q= 284 kW A= 141 m<sup>2</sup>  $A = 33,278 \text{ m}^2$ 130 130 35 35 51 43 21 98 78 40 42 21 K0 Q= 6,512 kW  $A=5,723 m^2$ STAGE 8 130 130 46 4 43 35 35 40 98 21 21 18 K8 Q= 2,453 kW  $\mathbf{m}^2$ A= 1,558 STAGE 130 130 55 130 35 40 4 43 81 21 33 21 K7 STAGE STAGE STAGE STAGE 130 130 130 35 22 43 35 9 4 21 21 81 K6 130 130 55 130 43 35 K5 35 31 40 4 21 21 -130 130 130 55 43 35 35 18 4 40 21 21 K4 • 130 130 130 35 32 4 43 35 81 40 21 K 21 Q= 1,314 kW Q= 37,794 kW A= 40,792 m<sup>2</sup>  $A=1,304 \text{ m}^2$ Q= 25,443 kW Q=7,744 kW  $A=21,917 m^2$ A= 8,474 m<sup>2</sup> Q= 40,936 kW A= 35,263 m<sup>2</sup> STAGE 2  $A_6 = 13,200 \text{ m}^2$  $A_{s} = 16,999 \text{ m}^{2}$  $A_{a} = 1,195 m^{2}$  $A_{7} = 3.553 \text{ m}^{2}$ 161 m<sup>2</sup> , III  $A_3 = 10 \text{ m}^2$ Ao= A.= 130 130 130 130 56 35 55 35 35 56 35 40 K STAGE Qs= 3,870 kW Qa= 50,394 kW 0=13.701 kW Qs= 65,541 kW 130 130 130°C 130 1,031 kW 130 35 95 56 95 95 Qu= 33 kW 53 40 35 Q3= 66 kW KI H3 130°C 130°C 187°C 0,= 300C H2 Ξ CI 5 8 60 5 5 3 <u>0</u>% CS Source 3 1058.4 kg/s Source 3 5.6 kg/s Source 3 35 kg/s 677 kg/s (40 ppm) 350 kg/s (0 ppm) Sink I Sink 2

Figure 4.22 The CHAMENS result of the case study 3 at EMAT 35°C by using this work (Nop= 1 year).

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Figure 4.23 The optimal CHAMENS for EMAT 35 °C using Transhipment model Nop= 2 years (Ghazouani, 2018).

(0 ppm)         130°C           Source 3         H1         13           6.3 kg/s         5:         5:           6.3 kg/s         130°C         13           Source 3         H2         5:           35 kg/s         Q <sub>2</sub> =1,031         9:           A <sub>3</sub> = 10 m <sup>2</sup> Q <sub>3</sub> = 66	30 1											
Source 3 H1 13 6.3 kg/s 5: 5: 130°C 13 35 kg/s 0_11,031 A_3= 10 m <sup>2</sup> 0 <sub>3</sub> = 66	30 1							A	= 2641	11 <sub>7</sub>	2002	350 kg/s
6.3 kg/s 5: 5: 35 kg/s 0_1,031 0_1,031 0_1,031 0_1,031 0_2 0_6	305	30	130	130	130	130	130	130	130	130	2.00	Sink 3 126 kg/
130 <sup>0</sup> C 13 Source 3 130 <sup>0</sup> C 13 35 kg/s 0 <sub>2</sub> =1,03 A <sub>3</sub> = 10 m <sup>2</sup> 0 <sub>3</sub> = 66	50				Q= 2,4	53 kW		A= 1,557 m <sup>2</sup>				(43 ppm)
130 <sup>0</sup> C 13 Source 3 H2 35 kg/s Q <sub>2</sub> =1,03 A <sub>3</sub> = 10 m <sup>2</sup> Q <sub>3</sub> = 66	1 02	55	55	55	55	55	55	46	21	21	21 <sup>0</sup> C	Source 1
Source 3 H2 35 kg/s Q_= 1,031 A_= 10 m <sup>2</sup> Q_= 66	1 10	30 Q= 18,014 kW					) 				IJ	119.7 kg/s
$35 \text{ kg/s}$ $Q_2 = 1,031$ $A_3 = 10 \text{ m}^2$ $Q_3 = 66$		A= 19,743 m <sup>2</sup>	130	130	130	130	130	98	86	98	980C	Sink 4 202 kg/
$A_{3}=10 \text{ m}^{2}$ $Q_{3}=66$	1 kW	A <sub>2</sub> = 161 $m^2$					-0	6,460 kW A	= 5,919	) m <sup>2</sup>		(100 ppm)
$A_3 = 10 m^2$ $Q_3 = 66$	5 9	5	43	43	43	43	43	43 💦	21	21	21 <sup>0</sup> C	Source 1
	6 kW		35	F							C	157 kg/s
	T	Q= 1,	314 kV	35	35	35	35	35	35	35	35°C	Source 4
36	5 9	5 A=1,	311 m <sup>-</sup>						75	75	ខ	10 kg/s
130°C	30 1	30	81	81	81	81	81	81	A= 33,2	42 m		Waste 1083.6
Source 3									2 = 80,2	55 kV		kg/s
105/./ Kg/s A4= 31 m	m <sup>2</sup>	24= 284 kW						35			40°C	(304.8 ppm)
35	5	2	35	35	35	35	35	Q= 7,430 kW	35	35	35°C	Source 4
$A_{\rm S}=16.9$	)63 m	2 Q= 46,207 kW						$A = 5,402 \text{ m}^2$			C4	25.9 kg/s
$187^{0}C$ $Q_{5}^{=} 65,40$	00 KV	W A= 43,656 m <sup>2</sup>	30	30	30	30	30	30	30	30	30°C	Fresh
	35	95									C5	324.6 kg/s
Sink 2 Q6= 51,035	S kW	$A_6 = 13,237 \text{ m}^2$	21	21	21	21	21	21	21	21	21 <sup>0</sup> C	Source 1
(40 ppm)	5	5 Q=	41,050	KW m <sup>2</sup>							C6	253.3 kg/s
AT 10, 61 TY	2		43	43	43	43	43	43	43	43	43 <sup>0</sup> C	Source 2
Q8= 3,870 KW	6 9	5 Q= 7,744 kW									C7	68 kg/s
A <sub>8</sub> = 1,195 m <sup>2</sup> 13,	30 1.	30 A= 8,532 m <sup>2</sup>	130	130	130	130	130	130	130	130	130°C	Source 3
$Q_9 = 33 \text{ kW}$		$A_9 = 7 m^2$									C8	31 kg/s
35	5 3	5	35	35	35	35	35	35	35	35	35°C	Source 4
KI	K2	K	3 K	4	K5	K6 F	13	K8	-9	K10	0	0.1 kg/s
ST	AGE	STAGE	STAGE	STAGE	STAG	E STAG	ESTAC	GE STAGE	STAG	E	Ohnfö	Ocndi

**Figure 4.24** The CHAMENS result of the case study 3 by using this work at EMAT 35°C for Nop= 2 years.

Fresh	350 kg/s		Sink 3 126 kg/s	(43 ppm)	Source 1	119.7 kg/s	Sink 4 202 kg/s	(100 ppm)	Source 1	157 kg/s	Source 4	10 kg/s		Waste 1083.6 kg/s	(304.8 ppm)			Source 4	25.9 kg/s		Fresh	324.6 kg/s	Source 1	253.3 kg/s	Source 2	68 kg/s	Source 3	31 kg/s	Source 4	0.1 kg/s		Qcu(i)
300C	$263 \text{ m}^2$	,036 kW	55°C		21°C	IJ	980C		21°C	3	35°C	ខ		40°C	134 m <sup>2</sup>	10 kW	1 2012	35"C	3		300C	CS	21 <sup>0</sup> C	Š	430	C1	1300	C8	35°C	ව		Qha(j)
	A=	Q=1	130		21	= 473 m <sup>2</sup>	130		21		35			16	A= 43,4	Q= 118,2		35		-	30		21		43		130		35		K10	
			130		21	kW A	130		21		35			16				35			30		21		43		130		35		K9 1	STAGE
						Q=2,453																										STAGE
******			130		21		130	******	21		35			16				35			30		21		43		130		35		K8	6
			130		21		130		21		35			16				35			30		21		43		130		35		L	STAG
			130		21		130		21		35			16				35			30		21		43		130		35		K6 K	STAGE
			130		21		130		21		35			16				35			30		21		43		130		35		KS 1	STAGE
			130		21		130		21		35			16				35			30		21	a in bannan	43		130		35		K4	STAGE
			130		21		130		21		35			16				35			30		21		43		130		35		K3	STAGE
							AC 476 1 111	- 20,4/2 KW	A= 21,81 / m <sup>+</sup>	X	Q=10,983 kW	A= 16,279 m <sup>2</sup>	5 L	Ę	>						0- 53 605 LAV	Wy choire A	A= 61,049 m <sup>2</sup>	5	-0							
			130	$A_{1} = 970 \text{ m}^{2}$	21		130		- 86	$A_3 = 178 \text{ m}^2$	35			130				35		$A_5 = 22,791 \text{ m}^4$	30	$A_6 = 11,260 \text{ m}^2$	116	$A_7=3,008 \text{ m}^2$	116	As=1.195 m <sup>2</sup>	130	$A_{9}=7 m^{2}$	35		23	STAGE
30 <sup>0</sup> C			HI 130°C 130	Q1=8,913 kW	CI 21		H2 130°C 130		<mark>C2</mark> 98	Q3= 1,380 kW	C3 35		13005	H3 120'C 130	Ar= 284 m <sup>2</sup>	W112 -0	MATC -PA	C4 35		Qs= 111,607 kW	30	C5 Q6= 39,280 kW	1870C 116	C6 Q7=10,462 kW	116	C7 Q8= 3,870 kW	130	00=33 kW	35		K1 1	STAGE
Sink I	(0 ppm)	(	Source 3	CAN CO			Source 3	s/gx cc						Source 3	1057.7 kg/s								Sink 2	0 // kg/s (40 ppm)								

Figure 4.25 The CHAMENS result of the case study 3 by using this work at EMAT 5°C for Nop= 2 years.

Waste 1083.6 kg/s Sink 3 126 kg/s Sink 4 202 kg/s Fresh 324.6 kg/s (304.8 ppm) Source I 119.7 kg/s (100 ppm) 253.3 kg/s Source 4 10 kg/s (43 ppm) Source 2 0.1 kg/s Source 3 Fresh 350 kg/s Source I 157 kg/s Source 4 25.9 kg/s Source 1 31 kg/s Source 4 68 kg/s Qcu(j) 98°C 40°C 30<sup>0</sup>C C5 21<sup>0</sup>C 55<sup>0</sup>C 21<sup>0</sup>C 35°C C7 130<sup>0</sup> 30°C 21<sup>0</sup>C 35°C 35°C Qhu(j) Ce 430 CS Q= 1,035 kW 3  $A = 264 \text{ m}^2$ Q= 52,329 kW  $A = 24,060 \text{ m}^2$ 130 130 35 35 63 35 30 43 21 21 98 21 K10 STAGE 9 130 35 30 43 130 17 86 35 63 35 21 21 **K**0 Q= 6,460 kW A= 8,817 m<sup>2</sup> STAGE 8 130 46 30 43 130 35 35 65 35 98 21 21 A= 1,557 m<sup>2</sup> K8 STAGE 7 130 55 130 130 35 35 65 35 30 21 43 21 K6 K7 STAGE STAGE STAGE STAGE 3 4 5 6 130 Q=2,453 kW 130 130 35 55 30 35 35 43 21 65 21 130 12 130 65 130 35 K5 35 35 30 43 21 5 130 130 130 35 65 55 35 35 30 21 43 K4 21 130 130 22 59 130 35 35 35 30 21 43 K3 21 Q= 10,615 kW A= 22,522 m<sup>2</sup> Q= 59,712 kW Q= 26,475 kW A= 97,835 m<sup>2</sup> A= 73,795 m<sup>2</sup> A= 27,979 m<sup>2</sup> Q= 51,502 kW Q= 1,380 kW A= 1,770 m<sup>2</sup> A<sub>5</sub>=14,713 m<sup>2</sup> A6= 11,497 m A<sub>8</sub>=1,195 m<sup>2</sup>  $A_7 = 3.075 \text{ m}^2$ E STAGE STAGE 1 2 =6F 114 130 130 130 130 114 114 35 35 98 35 38 K2 C5 Q6= 40,583 kW Qs=51,895 kW Qs= 3,870 kW 0+=10,829 kW Qr= 284 kW 114 114 130 114 35 130 130°C 130 130 35 55 98 Q9= 33 LW  $A_4 = 31 \text{ m}^2$ 98 KI 130°C 130°C 9 187°C C4 300C H3 H H2 ຽ S IJ S C6 5 8 Source 3 1057.7 kg/s Source 3 6.3 kg/s Source 3 35 kg/s Sink 2 677 kg/s (40 ppm) Sink I 350 kg/s (0 ppm)

Figure 4.26 The CHAMENS result of the case study 3 by using this work at EMAT 10°C for Nop= 2 years.

Waste 1083.6 kg/s Sink 3 126 kg/s Sink 4 202 kg/s (304.8 ppm) Source I 119.7 kg/s Source 4 10 kg/s Source 4 25.9 kg/s 324.6 kg/s (100 ppm) 253.3 kg/s (43 ppm) 157 kg/s Source 4 0.1 kg/s Fresh 350 kg/s Source 1 Source 2 68 kg/s Source 3 31 kg/s Source 1 Fresh Qcu(j) 40°C 98°C 30°C C5 21°C 30°C 55<sup>0</sup>C 21<sup>0</sup>C 21<sup>0</sup>C 35°C C3 35°C 35°C Qhu(j) C6 430 C7 Q= 1,035 kW 300 CS 3 Q= 52,329 kW  $A = 264 \text{ m}^2$  $A = 24,060 \text{ m}^2$ 130 K10 STAGE 130 43 35 21 35 63 35 30 21 98 21 130 130 35 30 43 21 86 35 63 35 21 21 K0 Q= 6,460 kW  $A = 8,817 \text{ m}^2$ STAGE 130 130 35 30 43 46 35 59 98 35 21 21 K8 A= 1,557 m<sup>2</sup> STAGE 130 55 130 130 35 65 30 8 35 35 21 21 K3 K4 K5 K6 K7 stage stage stage 130 Q=2,453 kW 55 130 35 130 35 30 35 21 43 3 21 130 35 130 130 35 35 3 35 30 43 21 17 130 130 130 35 55 35 65 35 30 21 43 21 130 130 130 35 55 35 59 35 30 43 21 21 Q= 10,615 kW A= 22,522 m<sup>2</sup> Q= 59,712 kW Q= 26,475 kW A= 97,835 m<sup>2</sup> Q= 51,502 kW A= 73,795 m<sup>2</sup> A= 27,979 m<sup>2</sup> Q= 1,380 kW A= 1,770 m<sup>2</sup>  $A_5 = 14,713 \text{ m}^2$  $A_6 = 11,497 m^2$  $A_7 = 3.075 \text{ m}^2$  $A_8 = 1,195 \text{ m}^2$ E STAGE STAGE Ag= 130 130 114 114 130 130 114 35 55 35 86 98 R Q6= 40,583 kW Qs= 51,895 kW Qs= 3,870 kW KI Q7=10,829 kW Q4= 284 kW 114 114 114 HI 130°C 130 130 35 130 35 H3 130°C 130 Q9= 33 kW 55 98  $A_4 = 31 \text{ m}^2$ 98 130°C 187°C Î C4 H2 300C U C C3 60 S C6 5 C Source 3 1057.7 kg/s Source 3 6.3 kg/s Source 3 35 kg/s Sink 2 677 kg/s (40 ppm) Sink I 350 kg/s (0 ppm)



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Fresh	350 kg/s	Sink 3 126 ka/s	(43 ppm)	Source 1 119.7 kg/s	Sink 4 202 kg/s	(100 ppm)	157 kg/s	Source 4	10 kg/s Waste 1083.6 kg/s	(304.S ppm)	Source 4	202 kg/s	Fresh	324.6 kg/s	253.3 kg/s	Source 2	68 kg/s	Source 3 31 kg/s	Source 4	0.1 kg/s	
30 <sup>0</sup> C	= 264 m <sup>2</sup>	JOSS EW	2	21 <sup>0</sup> C	98°C	21°C	<u>C</u>	35°C	C3 40 <sup>0</sup> C	,051 m² 939 kW	35°C	3	300C	S	C S	430	C7	CS	35°C	ව	
	4	130		21	98	Į.	17	35	+ <u>†</u> /*	A= 26 Q= 57	35		30	ş	3	43		130	35	1710	NTN
		130		21	86	F	17	35	65		35		30		7	43		130	35	120	NA.
										= 0,400 kW = 8,117 m <sup>2</sup>											
		130	e.,	46	98	F	77	35	68		35		30	ş	17	43		T30	35		9
			1,557 m	0	-	)														*	
*******		130	=Y	8	130		i	35	68		35		30	5	:	43		Ret	35	K7	
		130	53 kW	85	130		ŧ	35	68		35		30	Ę	ŧ	43		NCT	35	K6	
		130	Q=2,4	22	130		I	35	68		35		30	Ţ	<b>i</b>	43		0CT	35	KK	
		130		22	130	10	1	35	68		35		30	F	1	43	061	nct	35	: K4	
		130		22	130		1	35	68		35		30		<b>.</b>	43		NCT	35	K3	
										0						-	78 kW	886 m²			
					W4 50	03 m <sup>2</sup>			j j j	Ŧ		870 kW	372 m²		10 mg 1		0,e=0	A= 17,			
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Waste 1083.6 kg/s Sink 3 126 kg/s Sink 4 202 kg/s Source 1 253.3 kg/s (304.S ppm) Source 1 119.7 kg/s (100 ppm) Source 4 25.9 kg/s Source 4 324.6 kg/s 68 kg/s Source 4 0.1 kg/s Fresh 350 kg/s (43 ppm) 10 kg/s 31 kg/s Source 1 157 kg/s Source 2 Source 3 Fresh Qcu(j) 30°C C5 21°C 300C 21°C 98°C 210C 35°C C3 40°C 35°C Qhu(j) 55°C 430 1300 35°C 3 C6 C8 ව Q= 751 kW  $A = 30,874 \text{ m}^2$ Q= 72,539 kW  $A = 2.12 \text{ m}^{-1}$ 109 130 E 35 21 35 35 30 43 21 98 21 K10 STAGE Q= 284 kW A= 138 m<sup>2</sup> +1/5 130 130 35 21 98 35 40 30 43 F 21 21 K0 STAGE 8 Q= 6,005 kW A= 6,116 m<sup>2</sup> 130 130 40 35 44 35 74 30 43 98 21 21 K8 A=1,515 m<sup>2</sup> STAGE 130 2 130 130 35 43 35 74 40 30 21 21 K6 K7 STAGE STAGE STAGE STAGE 9 130 Q= 2,453 kW 130 130 35 53 35 40 30 43 14 21 21 41 130 130 K5 53 74 30 43 130 35 35 40 21 21 130 130 130 53 35 74 40 30 43 35 21 21 K4 3 130 130 130 35 2 35 14 40 30 21 43 EM 21 Q= 8,488 kW  $A = 11,150 \text{ m}^2$ Q= 49,761 kW Q= 26,475 kW A= 54,517 m<sup>2</sup> Q= 43,823 kW A= 25,472 m<sup>2</sup> A= 43,424 m<sup>2</sup> Q= 1,380 kW A=1.327 m<sup>2</sup> A<sub>5</sub>= 16,403 m<sup>2</sup>  $A_6 = 12,800 \text{ m}^3$ A<sub>8</sub>=1,195 m<sup>2</sup>  $A_1 = 54 \text{ m}^2$  $A_7 = 3.436 \text{ m}^2$ Av= 7 m STAGE STAGE 100 100 130 130 130 130 001 35 3 86 40 98 KZ C5 Q6= 48,261 kW C6 Q7=12,956 kW Q5= 61,846 kW Q8= 3,870 kW Q1=455 kW 100 130 100 HI 130°C 130 130 100 O<sub>6</sub>= 33 kW 35 53 130 98 40 86 KI 130°C 130°C 9 187°C 300C H2 C4 3 G 3 HB 5 C 3 Source 3 1057.7 kg/s Source 3 6.3 kg/s Source 3 35 kg/s Sink 2 677 kg/s (40 ppm) Sink I 350 kg/s (0 ppm)



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### CHAPTER 5 CONCLUSION AND RECOMMENDATION

The three case studies MENS, HENS, and CHAMENS have been accomplished by adapting Stage-Wise Superstructure method using the LMCD and LMTD 2<sup>nd</sup> Chen's approximation which is different from the original SWS to prevent the underestimation areas of the heat exchangers giving the lowest error 0.53% (Shenoy and Fraser 2003) among the other approximations. The MENS case study decreases the TAC about \$ 21,538  $a^{-1}$  compared to the current best literature using IBMS method. The SWS has higher degree of freedom than IBMS method. The IBMS method only depends on the rich stream to solve the MENS. By using SWS, the process internal MSA usages can be maximized so, the external MSA usage is lower than IBMS method. In this thesis, the inter- and intra- plant HENS is solved. The TAC of HENS case study is 9.6% higher than the current best result using the new transshipment model. It has high TAC due to the piping and pumping costs not minimized in HENS. By applying the SWS in CHAMENS case study, the TAC reduction is achieved about \$ 235,306  $a^{-1}$  compared to the floating pinch method for a year operational time. The results for the literature case studies solved in this work demonstrate the applicability of SWS solving the MENS, HENS, and CHAMENS. The obtained solutions are capable in some cases better than those reported in recent publications. The SWS has high degree of freedom, less complexity, and efficient to reduce the TAC by lowering the heat exchanger process areas. Moreover, the minimization of the piping and pumping costs in HENS is needed to produce the low TAC.

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### **APPENDICES**

## Appendix A Case Study 1: MENS

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- The I are a second se	Description of the second sec	<pre>content of the second state of the second state of the second state of the second state of the second state of the second state of the second state of the second state of the second state of the second</pre>
Total To Total States	DATE: (i) DELET:	<pre>Dispersion constraints in relation from the set in relation constraints in relation for the set in relation constraints in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the set in relation in the set in relation of the relation in the set in relation of the relation in the relation in in relation of the relation in the relation in its in relation in the relation in the relation in its in relation of the relation in the relation in its in relation in the relation in the relation in its in relation in the relation in the relation in the relation in its in relation in the relation in</pre>
-com 1 -com 1	Description	<pre>composed () () () () () () () () () () () () ()</pre>
The second secon	DATE () DELETS () DE	<pre>content of a second secon</pre>
The second secon	DATE () DELETS () DE	<pre>compared.th interfaces.cl = 100 (2000 2000) Thermostation of memory and the state of the st</pre>
-com 1 Performance Special Spe	DATE () DELETS () DE	
- The I and	DATE () DELET (	<pre>table to the set of the set</pre>
- The second sec	Description Descr	Dispersion in conservation (1 and the latent is 1 and
Cong 1	Description Descr	<pre>THE () where the set of any set of a set of</pre>
I I I I I I I I I I I I I I I I I I I	Description Descr	<pre>sector = 1 + + + + + + + + + + + + + + + + + +</pre>
The second secon	International and a second sec	<pre>time is a second and it is a second at the second at</pre>
ngridatt to Tage 1 and	Description output to the provide sector of	<pre>Dispersion in conservation if a function is form if it is a second if it is a s</pre>

Figure A1 The result of case study 1 Mass Exchanger Network Synthesis (MENS).

Аррантиян Арранфба (1, 3) Epitempita (d., 7 ApTemp#315,5 (exepite (1, 2) twopite (1, 2) Appinepts (1, 2) DIATAN Manager and a state of the second dureal 100 0.010  $\begin{array}{l} \sum_{i=1}^{n} \operatorname{dip}(1, \hat{u}_i, \hat{v}(2)) \to d_{2^{n-1}}(-q_1(1, \hat{v}(2)) \to d_2(2, \hat{v}(2))) \to d_2(1, \hat{u}_i, \hat{v}_i, \hat{v}_i) \to d_2(1, \hat{u}_i, \hat{v}_i, \hat{v}_i) \to d_2(1, \hat{u}_i, \hat{v}_i, \hat{v}_i) \to d_2(1, \hat{v}_i, \hat{v}_i, \hat{v}_i) \to d$ AppTempH2(1,2) Distan (1.J.R) Distan (1.J.R) gi sua gi sua SUBSTICUTIONS. -100 44 pint2 104 - 10 - 11 104 - 104 - 11 2002 IV ey.10(1,7,8)+8947) 
$$\begin{split} & \mathbf{x}_{1}^{*}, \mathbf{L}_{1}^{*}(\mathbf{1}, \mathbf{1}') = \mathbf{i}_{1}, \mathbf{y}_{1}^{*}, \mathbf{X}_{2}^{*}, \mathbf{L}_{2}^{*}(\mathbf{1}, \mathbf{1}') = \mathbf{i}_{1}, \mathbf{i}_{2}^{*}, \\ & \mathbf{x}_{2}^{*}, \mathbf{X}_{2}^{*}(\mathbf{1}, \mathbf{1}') = \mathbf{i}_{2}, \mathbf{X}_{2}^{*}, \\ & \mathbf{x}_{2}^{*}, \mathbf{L}_{2}^{*}(\mathbf{1}, \mathbf{1}') = \mathbf{i}_{2}, \mathbf{X}_{2}^{*}, \mathbf{L}_{2}^{*}(\mathbf{1}, \mathbf{1}') \\ & \mathbf{x}_{2}^{*}, \mathbf{L}_{1}^{*}(\mathbf{1}, \mathbf{1}') = \mathbf{X}_{2}, \mathbf{X}_{2}^{*}, \mathbf{L}_{2}^{*}(\mathbf{1}, \mathbf{1}') \\ & \mathbf{x}_{2}^{*}, \mathbf{L}_{1}^{*}(\mathbf{1}, \mathbf{1}') = \mathbf{X}_{2}, \mathbf{X}_{2}^{*}, \mathbf{L}_{2}^{*}(\mathbf{1}, \mathbf{1}') = \mathbf{I}_{1} \end{split}$$
1,09(\*81\*,\*11\*,\*81\*,\*41 1,09(\*81\*,\*11\*,\*81\*)+41 1,09(\*81\*,\*11\*,\*81\*)+41 NAME TEL: ETA-0, 52/ VARIABLES VERTABLES LINCE (1.7, 8) ( HQUATIONS) Equation (1.7, 8) Equit (1.7, 8) Equit (1.7, 8) 4 POSITIVE VARIABLES 13 (1, 7, 8) 13 (1, 7, 8) L).L+(I,J,R) = BSAT++0.3275; L).L+(I,J,R) = BSAT++0.3275; LSCD.L+(I,J,R) = BSAT++0.3275; COMPTONS. Cost mostilisent for MDA is Cost montforient for MDA is Speckiscal time is decome Annual Factor Alian most mostilizent Cher mostilizent 102 10 12425 191225 19225 19247 CUAT2ONS ALL NO. option demine = 10900 option realize = 10000 monet Carternori (Arter) Casternori (optiles); Comento > diropt.opti Liffenbe

**Figure A2** The result of case study 1 Mass Exchanger Network Synthesis (MENS) (continued).

1		1.1.1.1
17.		340.41
Area.1	('R5','I2','K5')	+196.425;
me.1	('R5', 'L2', 'E5')	+0,0032
2.1	(*85*,*12*,*85*)	=1;
• si		
Arvs.1	(*#1', "13', "#5")	+571.429;
ne.1	('#1', 'L3', '#5')	=0.0001
2.1	(1211, 1231, 1251)	*17
1.0		
Area.1	(*#41, 1221, 1821)	+252.143/
ne.1	('88','12','82')	+0.003:
2.1	("R4", "12", "#2")	+17
n		
Area.1	(*R4*, *L1*, *R2*)	#303.571;
ne.1	('R4', 'L1', 'R2')	=0,0047
2.1	('#4', '11', '#2')	=1;
12.		
Area.l	('ES', 'LS', 'EE')	-1734.2867
mell	(*#3*, *13*, *#2*)	=0.024;
1.1	(1831, 1231, 1821)	*11
12		
Area.1	('EB', 'L1', 'EE')	=390.714/
ne.1	(*83*, *11*, *82*)	=0.005;
1.1	(*83*, *21*, *82*)	-11
1.0		
Area.1	1'82', '23', '82')	=714.286;
me.1	('E2', 'L3', 'E2')	-0.0101
z.1	(*#2*, *23*, *#2*)	*12

DISPLAY Areas1, FJ.L. z.L.me.L.qcu.L.qcs.L.qhu.L.qhs.L.TAC.L.dy.L.ddy.L.yi.L.xj.L.imod.L.Li.L.LJ.L.

**Figure A3** The result of case study 1 Mass Exchanger Network Synthesis (MENS) (continued).

### Appendix B The Result of The Case study 1 MENS (Searching for F('L3'))

```
**** REPORT SUMMARY :
                           0
                                 NONOPT
                           0 INFEASIBLE
                           0 UNBOUNDED
                                ERRORS ( ****)
                           0
DGAMS 24.2.1 r43572 Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 04/27/20 17:58:02
General Algebraic Modeling System
Execution
      352 VARIABLE Area.L
 ___
             K1
                        K2
                                    K5
Rl.L3
                                136.036
R2.L3
                    162.110
R3.Ll
          42.298
R3.L3
                    247.201
R4.L1
                     37.510
R4.L2
                     71.823
R5.L2
                                 33.019
----
       352 VARIABLE FJ.L
Ll 1.800,
            L2 1.000,
                         L3 24.871
                                                  I
       352 VARIABLE z.L Exchanger matching between rich I and lean J at stage k
____
              K1
                         K2
                                    K5
R1.L3
                                  1.000
R2.L3
                      1.000
R3.L1
           1.000
R3.L3
                      1.000
R4.L1
                      1.000
R4.L2
                      1.000
R5.L2
                                  1.000
____
       352 VARIABLE me.L mass exchanged between rich I and lean J
              K1
                         K2
                                     K5
R1.L3
                                  0.008
R2.L3
                      0.010
R3.L1
           0.005
R3.L3
                      0.024
R4.L1
                      0.004
R4.L2
                      0.003
R5.L2
                                  0.003
```

Figure B1 The result of case study 1 MENS (searching for F('L3')).

	352 VARIA	BLE qcu.L u	nused			
		( 51.1.	0 000 \			
		( ADD	0.000 )			
	352 VARIA	BLE qcs.L		= 0	.000 Total	cold utility
	352 VARIA	BLE qhu.L u	nused			
		/ 711	0 000 \			
		( ALL	0.000 )			
	352 VARIA	BLE qhs.L		= 0	.000 Total 1	hot utility
	VARIA	BLE TAC.L		= 451760	.488 Total A	Annual Cost
			-			
	352 VARIA	BLE dy.L App	proach compos	sition		
	121	¥2	K3	¥4	125	Ke
	n1	itis	no	11.1	1.0	110
R1.L1	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R1.L2	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R1.L3	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R2.L1	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R2.L2	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R2.L3	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R3.L1	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R3.L2	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R3.L3	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4	7.00000E-4
R4.L1	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4
K9.LZ	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4
25 T.1	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4
R5.L2	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4
R5.L3	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4	7.000000E-4
	352 VARIA	BLE ddy.L Re	eal Approach	Composition		
	KI	K2	K3	K4	K5	Kb
R1 . T.1	-0.002	9.388889E-4	0.003	0.003	0.003	-7.00000E-4
R1.L2	-0.004	-0.004	-2.50000E-4	-2.50000E-4	-2.50000E-4	-0.001
R1.L3	0.003	0.003	0.005	0.005	0.005	0.001
R2.L1	-0.002	9.388889E-4	8.00000E-4	8.00000E-4	8.00000E-4	8.00000E-4
R2.L2	-0.004	-0.004	-0.003	-0.003	-0.003	
R2.L3	0.003	0.003	0.002	0.002	0.002	0.002
R3.Ll	0.004	0.005	8.00000E-4	8.00000E-4	8.00000E-4	8.00000E-4
R3.L2	0.002	9.371429E-4	-0.003	-0.003	-0.003	8.67362E-19
R3.L3	0.009	0.008	0.002	0.002	0.002	0.003
R4.L1	0.003	0.006	0.003	0.003	0.003	0.003
R4.L2	0.001	0.001	-2.50000E-4	-2.50000E-4	-2.50000E-4	0.002
K4.L3	0.008	0.008	0.005	0.005	0.005	0.005
K5.L1	9.00000E-4	U.U04	0.006	0.006	0.006	5.00000E-4
K3.12	-5.000004-4	-5.000002-4	0.003	0.003	0.003	0 002
CO - 113	0.006	0.000	0.000	0.000	0.000	0.002

**Figure B2** The result of case study 1 Mass Exchanger Network Synthesis (MENS) (searching for F('L3')) (continued).

	352 VARIA	BLE yi.L C	Composition	of	rich stre	am i	at stage	k
	Kl	K2	K3		K4		K5	K6
Rl	0.005	0.005	0.005		0.005		0.005	0.001
R2	0.005	0.005	0.002		0.002		0.002	0.002
R3	0.011	0.009	0.003		0.003		0.003	0.003
R4	0.010	0.010	0.005		0.005		0.005	0.005
R5	0.008	0.008	0.008		0.008		0.008	0.002
	01000	01000	01000		01000		01000	01002
	352 VARIA	BLE xj.L C	Composition	of	lean stre	am j	at stage 1	k
	Kl	K2	K3		K4		K5	K6
L1	0.007	0.004	0.002		0.002		0.002	0.002
T.2	0.009	0.009	0.005		0.005		0.005	0.002
1.3	0.002	0.002 3	216651E-4	3.2	16651E-4	3.216	651E-4	01000
	352 VARIAN	BLE LMCD.L	12	KЗ		K4	K5	K6
KI.LI	0.003	0.00	4 7.0000000	9-2	7.000000	-4 7.	000000E-4	0.002
RI.LZ	7.00000E-4	7.00000E-	4 7.000000	5-4	7.00000E	-4 7.	000000E-4	0.003
RI.L3	7.00000E-4	7.00000E-	4 7.000000	2-4	7.00000E	-4	0.003	7.00000E-4
RZ.LI	7.00000E-4	7.00000E-	4 7.000000	5-4	7.00000E	-4 7.	000000E-4	0.002
R2.L2	7.00000E-4	7.00000E-	4 7.000000	2-4	7.00000E	-4 7.	000000E-4	0.002
RZ.L3	7.00000E-4	0.00	3 7.000000	5-4	7.000000E	-4 7.	000000E-4	7.00000E-4
R3.LI	0.006	7.00000E-	4 7.000000	9-2	7.000000E	-4 7.	000000E-4	0.002
R3.L2	7.00000E-4	7.00000E-	4 7.000000	5-4	7.000000E	-4 7.	000000E-4	0.002
R3.L3	7.00000E-4	0.00	5 7.000000	9-2	7.000000E	-4 7.	000000E-4	7.00000E-4
R4.LI	7.00000E-4	0.00	6 7.000000	5-4	7.00000E	-4 7.	000000E-4	0.001
R4.L2	7.00000E-4	0.00	2 7.000000	2-4	7.000000	-4 7.	000000E-4	0.002
R4.L3	7.00000E-4	7.00000E-	4 7.000000	5-4	7.00000E	-4 7.	000000E-4	7.00000E-4
R5.L1	7.000000E-4	7.00000E-	4 7.000001	2-4	7.00000E	-4 7.	000000E-4	0.002
R5.L2	7 00000000-4	7.00000E-	4 7.000000	<u>c-4</u>	7.00000E	-4	0.004	0.002
	7.0000002-4							
R5.L3	7.000000E-4	7.000000E-	4 7.000001	2-4	7.00000E	-4 7.	000000E-4	7.00000E-4

**Figure B3** The result case study 1 Mass Exchanger Network Synthesis (MENS) (searching for F('L3')) (continued).

	352 VARIABLE	Ll.L				
	Kl	K2	K3	K4	K5	Ke
R1.L1	0.114	0.197	0.093	0.093	0.093	0.093
R1.L2	0.093	0.093	0.093	0.093	0.093	0.093
R1.L3	0.093	0.093	0.093	0.093	0.173	0.093
R2.L1	0.093	0.093	0.093	0.093	0.093	0.093
R2.L2	0.093	0.093	0.093	0.093	0.093	0.093
R2.L3	0.093	0.154	0.093	0.093	0.093	0.093
R3.L1	0.163	0.093	0.093	0.093	0.093	0.093
R3.L2	0.093	0.093	0.093	0.093	0.093	0.093
R3.L3	0.093	0.203	0.093	0.093	0.093	0.093
R4.Ll	0.093	0.187	0.093	0.093	0.093	0.093
R4.L2	0.093	0.119	0.093	0.093	0.093	0.093
R4.L3	0.093	0.093	0.093	0.093	0.093	0.093
R5.L1	0.093	0.093	0.093	0.093	0.093	0.093
R5.L2	0.093	0.093	0.093	0.093	0.145	0.093
R5.L3	0.093	0.093	0.093	0.093	0.093	0.093
	352 VARIABLE	L2.L				
	Kl	K2	K3	K4	K5	K6
R1.L1	0.197	0.174	0.093	0.093	0.093	0.188
R1.L2	0.093	0.093	0.093	0.093	0.093	0.201
R1.L3	0.093	0.093	0.093	0.093	0.124	0.093
R2.L1	0.093	0.093	0.093	0.093	0.093	0.172
R2.L2	0.093	0.093	0.093	0.093	0.093	0.187
R2.L3	0.093	0.147	0.093	0.093	0.093	0.093
R3.L1	0.221	0.093	0.093	0.093	0.093	0.172
R3.L2	0.093	0.093	0.093	0.093	0.093	0.187
R3.L3	0.093	0.147	0.093	0.093	0.093	0.093
R4.Ll	0.093	0.181	0.093	0.093	0.093	0.133
R4.L2	0.093	0.153	0.093	0.093	0.093	0.157
R4.L3	0.093	0.093	0.093	0.093	0.093	0.093
R5.L1	0.093	0.093	0.093	0.093	0.093	0.172
R5.L2	0.093	0.093	0.093	0.093	0.187	0.187
R5.L3	0.093	0.093	0.093	0.093	0.093	0.093
EXECUTI	LON TIME	=	0.047 SECON	US 3 MB	24.2.1 r43572	WEX-WEI

**Figure B4** The result of the case study 1 Mass Exchanger Network Synthesis (MENS) (searching for F('L3')) (continued).

# Appendix C Result: Case Study 1 MENS (Searching for yi and xj to Calculate The Area by Using The Value of The F('L3') from Step 1)

**** RE	PORT SUMMARY	: 0 NONOPT 0 INFEASIBLE 0 UNBOUNDED	
DGAMS 2 Gene Exec	4.2.1 r43572 ral Al( ution	Released Dec 9, 2013 WEX-WEI x86_64/MS Windows 05/25/20 09:16:08 Page gebraic Modeling System	2 7
	352 VARIABLE	z.L. Exchanger matching between hot I and cold J at stage $k$	
	K2	K3 K4 K7	
R1.L3 R2.L3 R3.L1	1.000000	1.000000	
R3.L3 R4.L1 R4.L2	1.000000	1.000000	
R5.L1		1.000000	
	352 VARIABLE	me.L Heat exchanged between hot I and cold J	
	K2	K3 K4 K7	
R1.L3		0.008000	
R2.L3 R3.L1	0.005470	0.010000	
R3.L3 R4.L1 R4.L2	0.001500	0.024280	
R5.L1		0.002750	
	352 VARIABLE	qcu.L Heat exchanged between cold utility and hot I	
		(ALL 0.000)	
	352 VARIABLE	qcs.L = 0.000 Total cold utility	
	352 VARIABLE	ghu.L Heat exchanged between hot utility and cold ${\tt J}$	
		(ALL 0.000)	
	326 VARIABLE VARIABLE	qhs.L         =         0.000000         Total hot utility           TAC.L         =         2032.800000         Total Annual Cost	

**Figure C1** The result of the case study 1 MENS (searching for yi and xj to calculate the area by using the value of the F('L3') from Step 1).

 352	VARIABLE	dy.L	Approach	temperature

	Kl	K2	KЗ	K4	K5	K6
R1.L1	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R1.L2	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R1.L3	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R2.L1	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R2.L2	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R2.L3	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R3.L1	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R3.L2	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R3.L3	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R4.L1	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R4.L2	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R4.L3	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R5.Ll	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R5.L2	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
R5.L3	0.000700	0.000700	0.000700	0.000700	0.000700	0.000700
	20	7/0				
÷	K /	Kö				
R1.L1	0.000700	0.000700				
R1.L2	0.000700	0.000700				
R1.L3	0.000700	0.000700				
R2.L1	0.000700	0.000700				
R2.L2	0.000700	0.000700				
R2.L3	0.000700	0.000700				
R3.L1	0.000700	0.000700				
R3.L2	0.000700	0.000700				
R3.L3	0.000700	0.000700				
R4.Ll	0.000700	0.000700				
R4.L2	0.000700	0.000700				
R4.L3	0.000700	0.000700				
R5.L1	0.000700	0.000700				
R5.L2	0.000700	0.000700				
R5.L3	0.000700	0.000700				
	352 VARIABI	LE ddy.L Real	Approach	Temperature		
R1.T.1	-0.002100	-0.002100	0.001772	0.001772	0.003300	0.003300
R1.12	-0.003500	-0.003500	0.002500	0.002500	0.002500	0.002500
R1 T.3	0.003300	0.003300	0.003300	0.004678	0.004678	0.004678
R2 T.1	-0.002100	-0.002100	0 001772	-0.000728	0.000800	0.000800
R2 T.2	-0.003500	-0.003500	0.002500	-4 3368F-19	-4 3368F-19	-4 3368F-19
R2 T.3	0.003300	0.003300	0.003300	0 002178	0 002178	0 002178
23 T.1	0.003900	0.003900	0.005300	-0.000728	0.0002170	0.0002170
D3 T2	0.002500	0.002500	0.006203	_5 71420F_0	_5 71420F_0	_5 71420F_0
D3 T2	0.002300	0.002300	0 007727	0 002170	0 002170	0 002178
D4 T1	0.003300	0.003500	0.001772	0.0021/0	0.0021/0	0.002170
R4 T.2	0.001500	0.001500	0 002500	0.001//2	0.003500	0.003500
R4 T.3	0.008300	0.008300	0.003300	0.004679	0.004678	0.004678
R5 T.1	0 000900	0 000900	0 004772	0 004772	0.000800	0 000800
R5 T2	-0.000500	-0.000500	0.005500	0.005500	0.000000	0.000000
DE TO	0.006300	0.006200	0.005300	0.003500	0 002179	0 002170
NO.TO	0.000300	0.000300	0.000300	0.00/0/0	0.0021/0	0.0021/0

**Figure C2** The result of the case study 1 MENS (searching for yi and xj to calculate the area by using the value of the F('L3') from Step 1) (continued).

R1.L1	0.003300	-0.0007	00									
R1.L2	0.002500	-0.0015	00									
R1.L3	0.004678	0.0010	00									
R2.L1	0.000800	0.0008	00									
R2.L2	-4.3368E-19											
R2.L3	0.002178	0.0025	00									
R3.L1	0.000800	0.0008	00									
R3.L2	-5.71429E-9											
R3.L3	0.002178	0.0025	00									
R4.Ll	0.003300	0.0033	00									
R4.L2	0.002500	0.0025	00									
R4.L3	0.004678	0.0050	00									
R5.Ll	0.000800	0.0008	00									
R5.L3	0.002178	0.0025	00							-		
	352 VARIA	BLE VI.L	Iemperature	or	not	stream	1 at	not	ena	OI	stage	к
						** 4						
	KI	5.2	K.3			K4		K.	0		Ko	
<b>D</b> 1	0.005000	0.005000	0.005000		0.00	5000	~ ~	05000		~ /		
KI N2	0.005000	0.005000	0.005000		0.00	2500	0.0	03000	,	0.1	03000	
D-2	0.003000	0.003000	0.000437		0.00	2500	0.0	02500	,		02500	
R.3 D.4	0.011000	0.011000	0.005437		0.00	5000	0.0	02300	,	0.1	02300	
DE	0.0020000	0.010000	0.000000		0.00	2000	0.0	02500	,	0.1	02500	
R.J	0.000000	0.000000	0.000000		0.00	0000	0.0	02300	,	0.1	02300	
+	87	Ke										
+	15.7	100										
R1	0.005000	0.001000										
R2	0.002500	0.002500										
R3	0.002500	0.002500										
R4	0.005000	0.005000										
R5	0.002500	0.002500										
1.1.0												
	352 VARIA	BLE xj.L	Temperature	of	cold	l stream	ıja	t hot	; end	d of	stage	e k
	Kl	K2	K3			K4		K5	5		K6	
Ll	0.007100	0.007100	0.003228		0.00	3228	0.0	01700	)	0.0	01700	
L2	0.008500	0.008500	0.002500		0.00	2500	0.0	02500	)	0.0	02500	
L3	0.001700	0.001700	0.001700		0.00	0322	0.0	00322	2	0.0	000322	
+	K7	KS										
Ll	0.001700	0.001700										
L2	0.002500	0.002500										
L3	0.000322											
EXECU	IION TIME	-	0.109 SE(	LON	DS	3 ME	5 24	.2.1	143	572	WEX-W	51
ITEPD -	The Detrole	um and Dor	rochamical	201	1000		G1 93	216.2	2220	19-1	TN .	
USEK:	Chulalongko	uni and ret	ity	UUI.	reĝe		9131	21917	10222	n.3=1 n.c.4 :	120	
	License for	teaching	and research		t des	Tee ar.	ntin	a in-		0070 07.1-1	000	
	NYACTING TOT	0.00.0000000	and scotures		- wey	www.Ave		A	1.0.00	a wat i	1110	

K8

K7

+

**Figure C3** The result of the case study 1 MENS (searching for yi and xj to calculate the area by using the value of the F('L3') from step 1) (continued).

**Table D1** The result of the case study 1 MENS (calculating the exact area of the mass exchangers)

			ME	NS Case st	udy 2				
EMCD	Stream matching	yik	yik+1	xjk	xjk+1	LMCD	Me	Kya	Area
0.0001	R3.L1.K1	0.011	0.0073	0.0071	0.0017	0.005	0.0097	0.020	103.226
	R3.L2.K1	0.011	0.0073	0.0085	0.0053	0.002	0.0033	0.020	73.640
	R4.L3.K1	0.01	0.005	0.0017	0.0014	0.006	0.0075	0.020	66.677
	R2.L3.K2	0.005	0.0025	0.0014	0.0003	0.003	0.01	0.020	175.914
	R3.L3.K2	0.0073	0.0025	0.0014	0.0003	0.004	0.0168	0.020	224.086
	R5.L2.K2	0.008	0.0025	0.0053	0.0025	0.000	0.0028	0.020	430.467
	R1.L3.K5	0.005	0.001	0.0003	0	0.002	0.008	0.020	167.448
EMCD	Stream matching	yik	yik+1	xjk	xjk+1	LMCD	Me	Kya	Area
0.0003	H3.C1.K1	0.011	0.009	0.007	0.003	0.005	0.005	0.020	50.689
	H4.C1.K1	0.01	0.009	0.007	0.003	0.004	0.001	0.020	11.556
	H2.C3.K4	0.005	0.002	0.002	0.001	0.002	0.01	0.020	274.831
	H3.C3.K5	0.009	0.002	0.001	0.00032	0.004	0.024	0.020	296.690
	H4.C2.K6	0.009	0.005	0.009	0.003	0.000	0.006	0.020	1245.279
	H1.C3.K7	0.005	0.001	0.003	0	0.001	0.008	0.020	277.346
	H5.C1.K7	0.008	0.002	0.003	0.002	0.001	0.003	0.020	249.056
EMCD	Stream matching	yik	yik+1	xjk	xjk+1	LMCD	Me	Kya	Area
0.0005	H3.C1.K1	0.011	0.009	0.007	0.002	0.005	0.005	0.02	46.645
	H4.C1.K1	0.01	0.005	0.007	0.002	0.003	0.001	0.02	16.667
	H4.C2.K1	0.01	0.005	0.009	0.003	0.001	0.006	0.02	208.009
	H5.C1.K1	0.008	0.003	0.007	0.002	0.001	0.003	0.02	150.000
	H3.C3.K2	0.009	0.002	0.002	0.00072	0.003	0.024	0.02	357.121
	H2.C3.K3	0.005	0.002	0.00072	0.00032	0.003	0.01	0.02	180.097
	H1.C3.K4	0.005	0.001	0.00032	0	0.002	0.008	0.02	167.931

EMCD	Stream matching	yik	yik+1	xjk	xjk+1	LMCD	Me	Kya	Area
0.0007	H3.C1.K2	0.011	0.009	0.007	0.003	0.005	0.005	0.02	50.689
	H4.C1.K2	0.01	0.005	0.007	0.003	0.002	0.001	0.02	20.276
	H4.C2.K2	0.01	0.005	0.009	0.003	0.001	0.006	0.02	208.009
	H2.C3.K3	0.005	0.002	0.002	0.00032	0.002	0.01	0.02	219.777
	H3.C3.K3	0.009	0.002	0.002	0.00032	0.004	0.024	0.02	322.299
	H5.C1.K4	0.008	0.003	0.003	0.002	0.002	0.003	0.02	60.406
	H1.C3.K7	0.005	0.001	0.00032	0	0.002	0.008	0.02	167.931

Table D2 The result of the case study 1 MENS (case)	alculating the exact area of the mass
exchangers) (continued)	

EMCD	Stream matching	yik	yik+1	xjk	xjk+1	LMCD	Me	Kya	Area
0.0009	H2.C3.K1	0.005	0.0025	0.0017	0.00113	0.002	0.01	0.02	227.644
	H4.C2.K1	0.01	0.005	0.0085	0.0025	0.002	0.006	0.02	153.275
	H4.C3.K1	0.01	0.005	0.0017	0.00113	0.006	0.0015	0.02	12.918
	H5.C3.K1	0.008	0.0025	0.0017	0.00113	0.003	0.00275	0.02	42.555
	H3.C1.K6	0.011	0.0082	0.0071	0.0017	0.005	0.00972	0.02	95.321
	H1.C3.K7	0.005	0.001	0.00113	0	0.002	0.008	0.02	188.671
	H3.C3.K7	0.00822	0.0025	0.00113	0	0.004	0.02003	0.02	227.470

## Appendix E Case Study 2: HENS (Step 2)

SETS		
1	bot atteams	785,82,83,84/
-3	cold streams	/c1,c2,c3,c4,c8 /
×.	Stage no.	/RL, R2, R3, X4, R5, R4, R7, R5/2
· ALTERNATION	57.63	
		and had not any day that had need
CARAGE TER	TANK (A)	We the the the the till the sol
	1001111)	/HI- 100/HI- 100/HI- 110/HI- 10/
	TOTTTICT	Vote 200, cie 500, cie 200, cie 100, cie 100, cie
	RT(T)	/#3= 100 NT= 280 #3=7400 Wes 100/
	ET (3)	FTIE \$50,578 (50,538 150,548 350,548 350,5585)
	EHAT	/16/1
Q	contra .	Protocol .
÷	T2.4	110000/ #
ARIABLES		and the second se
da	(I, J, K)	Approach temperature
de	cu(1)	Approach temperature between cold utility and not atream
de	約回(学)	Approach temperature between hot utility and cold stream
41	I.J.K)	Heat exchanged between not I and cold J
de	#(1)	Best exchanged between culd utility and hot 1
qh	u(J)	Reat exchanged between hot utility and cold J
21	12.87	resperature of hot stream 1 at not end of stage R
23	1 . T . M.	Property and the second stream of an over the second stream a
= (	A+V=Fil (1)	Cold willing manufacture with par 7
20	41.73	Est ortility matching with cald J
10		Total Annual Cost
10		Total cold utility
oth		Total hot utility
dd	t(I, J, R)	Real Approach Temperature;
		and a second
POSITIVE	VARIABLE dt (1,	R, dtcu(I), dtbu(J), q(I, J, K), gcu(I), qbu(J), ti(I, R),
and the second	23 19.3	11
AINARY VA	RIABLES T(1, J,	K), Brow(I), Bhow(G) (
		Committee and white
Parameter		ODM NO IN
Dein T (T)	Overall	heat transfer at hot streams
DebJiJi	Overall	heat transfer at cold streams
DECEMBER 1.7 (1	JI Decer 1	ound set to the smallest heat content of the two streams involved in the mate
CHEGAT (T)	- In terms	THE DE OF THE DESCRIPTION OF THE OF T
DEEGAJ(J)		
TAL(L,J)	Magimum t	emperature difference for each exchanger:
UpbI(I)	- 71	I) * (IIIII(I) - TOUTI(I));
OpbJ(J)	- 13	3) * (TOUT3(3) - TIN3(3)):
*TAL (1.7)	- 1011	(1)-TOUT2(2)) - / TIN2())-DOCUT(0) (0
TAL(I,J)	- TOUT:	(J) -TOUTI(I) +NAX (TINI(I) -TINJ(J), ENAT);
CHEVEAT /	$T_{i}\sigma i = M_{i}$	H (Ilphy7) Jy , (Iph I (I)) )
*285/25/23	- 7027	(7) (7) - TOTTT (7) + MAR. (TTTT (7) - TTTT (7) (TMAR)
CREGALJ(I.	.J) = max	min(FI(I)*(TINI(I)-TOUTI(I))+
	82 (2	)*(TINI(I)-(TINJ(J)+EMAT)).
	136	) * (TOUT3 (J) -TIN3 (J) 1,
	73 (3	)*((TINI(I)-EMAT)-TINT(J))),(0);
OMEGAI (I)	<ul> <li>H13</li> </ul>	(UpbI(I), UpbI(I));
CHEGGET (3)	- 313	(Ope2(3), Ope3(2));
CURDINY C	APPLIE T	
CHEIGATJ. T	hL.	
	Part .	THE DISTRICT PALANCE
EQUATIONS		the set of
	ALLEDI (I)	Overall heat balance of hot streams I
	ALLHBJ(J)	Overall heat balance of cold streams 3;
	ALLHBI(I)	<pre> (IIBI(I)-TOUTI(I))*FI(I)*E* SUM((2,X),q(I,J,X))+qcu(I);</pre>
19	ALLHBJ(J)	(TOULD(d) = TIND(D)) * FJ(D) *E* SUM((1,K), q(1, J, K)) + qhu(D))
		and africants be show only
COATLONS.	18E	and sharping it fides that
a section day	HEIKI (I)-	Heat belance of hot stream 1 at state #1
	BIE2 (I)	Heat balance of hot stream 1 at state W2
	HBIE3(I)	Heat balance of hot stream 1 at stage #3
	HBIK4(I)	Heat balance of hot stream 1 at stage He
	RBIKS(I)	Seat balance of hot stream 1 at store #5
	HBIRG(I)	Heat balance of hot stream 1 at stage 25
	HBIR7(I)	Heat balance of hot stream 1 at stope Kh
	WELTS AT/	Best belance of mir proven 1 at stage #3
÷	RETAR (T)	Hast balance of hot proves 1 at stars 20
	N#INIA42(	Star Dallacts of hot offening a at stage 25
¥	BUTTUL (1)	livel balance of hall success a us prope II

Figure E1 Case study 2 HENS (step 2).

	(IBJK2 (-7)	Nest balance of cold stream 1 at stage #2
	HE-783 (-7)	Heat balance of cold stream 1 at stage K3
	HB-7K4 (-7)	Heat balance of cold stream ; at stage R4
	HB.7E6 (2)	Heat balance of cold stream 5 at store 25
	885287 (2)	Neat balance of cold stream ; at stage KA
6	APR. 2010. 571	deat balance of midd evening of an every An
5		Erst balance of cold stream   at sigge th
100	MERITAL (J)	Most maintim of vold starsm ; at stage with
1.1		
5		the second se
	(th1K1(7)	(t1(1,'R1')-t1(1,'R1'))*F1(1)*E* \$00((J,q(1,J,'R1')));
	HBIH2(1)	<pre> (t1(1,')(2')-t1(1,')(3'))'F1(1)*E* \$00(0,q(1,0,')(2'));</pre>
	HEIKS (I)	(t1(T, 'E3')-t1(T, 'E3'))*F1(T)*E* 500(J,q(T,J, 'E1'));
	101105(1)	<pre>/ti(1, 'K1')-ti(1, 'K1'))*FI(1)*E* 500 (0, 0(1, 0, 'K1'));</pre>
	H8IK6(1)	<pre> (11(I,'K6')-11(I,'K7'))'FI(I)=E= SOM(J,Q(I,J,'K6')))</pre>
	115 IK7 (I)	<pre> (t1(1, 'K7')-t1(1, 'K2')) *F1(1)=E= \$10(J,q(1,J,'K7'));</pre>
2	1002302(2)	(±) (2, (10) (1-±+(2, (10))) = (± (2) (2) (0) (0) (2, (2, 2) (2) (1)))
2	antikirorf/	12:17. 10:01-1-2:11. 10:01 (10:01) (10:01) = 10:01.0.01.0.000(10)
8.	WAIRLIT!	(1) (1) (1, (0)) (1) (1) (1) (1) (0) (1) (0) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1
		Including the second second second second second second second
	100001 (0) 100002 (0)	(1)(3, (1))-1)(3, (1)) +13(3)=0= 500(1, 2(1, 3, (1))))
	85783(7)	(13(J, 'K3')-13(J, 'K4'))-FJ(J)=E= MIN(I, g(T, J, 'K3'));
	RB284(2)	<pre> (t2((J, 'KA')-t2((J, 'K1')) *FJ(J) =E= \$00*(I,q(I,J, 'R4')))</pre>
	HBJRS (J)	<pre>1. (13(J, '#5')-15(J, '#6'))*FJ(J)*E* SOM(I,q(I,J,'#5'));</pre>
	85/207 (2)	1010, 1011, 1011, 1010, 1011, 1010, 101, 1010, 1000, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1010, 1000
÷	223,7777 (.21	1. 10.15. 98 11-10.15. 900 (1.187) (1.42) (1.42) (1.187) (1.187) (1.187)
2	10.753 (-7)	$(1_{1}, 1_{1}^{-1}, 1_{1}^{-1}) + z_{2}(J_{1}^{-1}) + Z_{2}(J_{1$
2	100,20110(3)	(TSTAL AGAI) - TSTAL AGAIN (TTATA) = INACL 971.3, OR 07.07
	International Party	1. It Just that 1-12 by the 11 dividual million of the million of the
	TINK .	larse conservations respectively at this this
EQUAT	IONS	Townships and an and the state of the state of the
	PE182(1)	Temperature superstructure feasibility of hot stream at #2
	FEIRS (1)	Temperature superstructure feasibility of hot stream at W3
	PEIKs(I)	Temperature superstructure feasibility of hit stream at K4
	FEIS((I)	Temperature superstructure feasibility of Not stream at KA
	FE1X7(1)	Temperature superstructure feasibility of hot stream at K4
5	F#159(2)	Desperative superstructure feasibility of not stream at 64
2	RETERATION (1)	Temperature superstructure teaching of and street at the
1.	FERRISIA	Temperation superstructure fearibility of his strengt at his
	FEJEL(J)	Temperature superstructure feasibility of cold stream at SI
	FEJES (J)	Temperature superstructure feasibility of cold stream at K3
	FEJE4 (J)	Temperature superstructure feasibility of cold stream at K4
	FEJKS (J)	Temperature superstructure feasibility of cold stream at K4
	PEGER (3)	Temperature superstructure feasibility of cold stream at Re
÷.	200387121	Imperative expectations feasibility of sale strong at the
4	120.701(2)	Depriture aperitruinate Charibility of mill States at Na
5.	1001011100	Pengeoslavy superstructory Jeasthility of cold strees at Bo
2	12-18-111	tenestations embettications conversition of onto account as he
		Contraction and the second
	FEIK1(1)	t1(I,'#1') =0= t1(I,'#2');
	FE183(1)	51(1, 1031) -D= 51(1, 1041).
	FEIR4(I)	11(I, 'K(') =D= 11(I, 'KI')/
	FEIRS(I)	11(1,'85') =0= 11(1,'80'))
	FEIGG(1)	., t1(I,'K0') =G= t1(I,'K1'); ., t1(I,'K1') =G= t((I,'K0');
èl I	(2113) (2)	1. £1/7,*80% will be (1,*80%)
÷	00200/23	11, 41/1, 000/1 -D= 41/1, 000/1/
5	P(1020(2)	1. 81(2, 010) wile er(2, 011(0))
	10,000 (7)	and and second second second
	FEJEL(J)	23(3,'H1') =0= 23(3,'H2');
	EX.282 (2)	t2((J, '#2') =9+ t2((J, '#3')))
	FEJE4 (J)	1. 13(0, 18) =0 - 13(0, 18);
	FEJKS (J)	., 13(J, 35') -0- 13(J, K6');
	EE JK6 (J)	t3(J,'X6') =G= t3(J,'X7');
5	FEJE7 (J)	" ZZ(2', M3, ) =0= ZZ(2', MH, ))
2	10.000 (3)	LA TRACTORIA HER BERGEREN
2.1	ETE-ME N(Z)	(1) (2) (0) (1) (0) (0) (0) (0) (0) (0) (0) (0) (0) (0
2.1	120221-0.0	(1) 17, 4111 (1) (40) (1) (7, 5112 (1))
		ANALY VALCE TI AND TJ
61.1	(*#2*,*#1*)	*500.0001
11.1	478314 TRL*3	=125.000;
11.1	(+H0+*+HT+)	=200,000;
11.1	CHILD MERCH	-200,0001
11.1	(*)#2*,*#2*)	-340.0001
1.1	(*83*,*82*)	-125.0003
12.2	STREET, STREET,	*200.000 <i>t</i>

Figure E2 Case study 2 HENS (step 2) (continued).

1.12	(*831, *831)	+200.000;
51.1	(+H3+,+H3+)	=360.000;
51.1	('H3', 'K3')	=125.090;
51.1	1.81, 84,1	=195/
\$1.1	(*#2*, *R4*)	=360;
11.13	(*#3*, *K+*)	=125;
t1,1	(1841,1841)	=195;
t1,1	('H1', 'RE')	=1957
51.1 	( H1 , HD )	=175
51.1	("H4", "NE")	=195;
11.1	(1811, 1861)	=195;
51,1	("H2", "K6")	=1497
51.1	(,出3,*,我6,)	=1257
t1.1	(.H4.', R0.)	-195;
t1.1	11811, TR712	=1952
t1.1	('B2', 'R7')	=149;
1,12	('H3', 'N7')	=1257
11.1	(1841, 1831)	-132.51
1.13	("H1", "K0")	=155.333;
61.1	(1821, 1801)	-1492
ti.1	("H4", "HD")	=132,57
13.1	1'G1', "E1')	-220.000;
t1.1	(.C3.', .KT.)	-403.333;
tj.1	(, C3.', , MT.)	-250,0002
tj,1	1'C4', 'SL')	-140,000;
cj.1	('C5', 'K1')	+205,000;
21.1	(*C34, *M34)	=250/
51.1	11031-12011	+250.000
53.2	(1041,1201)	-140.000;
tj.1	(1081,180.)	-205.000;
**.1	11731. 18311	-190.0001
11.1	1.021, 1831	=250;
tj:1.	('C1', 'E1')	-250,000;
tj,1	('04', '25')	-100,000;
tj.1	(.CP., (KJ.)	+205.000;
	Desir Seas	
51.1	(1021, 1201)	+250/
1.13	(1031, 1841)	-250.000:
cj.1	('C4', 'X4')	+160.0001
03.1	(.cs.*.84.)	-205.000;
	Same Sector	
c].1	('GI', 'K5')	-165.000;
e].1	( tot , RD )	-150 000-
11.1	(1041, 1851)	-160.000
53.1	1.02. *. 82.1	=195.000;
23.1	(1011, 1861)	-185.0902
63.1	(.cz., .ke.)	-1397
03.1	('53', '86')	=139.0001
1111	("CS1, 1941)	#195.000;
	in the second	-7010000
cj.1	(*C1*,*R7*)	=185.000;
\$3.1	(*C2*,*X7*)	=139;
62.1	(*C3*, *K7*)	=139.000;
52.1	(1041, 1871)	=110.000;
P. 7. 7	("55', '至7')	=195.000;
-312		
11.1	TARLA MENT	#185.000+
11.1	('C1', 'R8')	-165.000:
tj.1 tj.1	('G1','R8') ('G1','R8') ('G1','R8')	=185.060; =139; =20.000;
tj.1 tj.1 tj.1 tj.1	(*61', *88') (*61', *88') (*61', *88') (*64', *88')	=105.000; =139; =20.000; =110.000;

Figure E3 Case study 2 HENS (step 2) (Continued).

BURAT	2CMV	montes as real total we as	and applications	
	1914T1 (1) 0714T1(1) 0714T2(2) 0714T2(2) 0714T2(2) 0714T1(1) 1914T2(2) 0714T1(2) 0714T1(2) 0714T3(2)	Trapprisitive homotonics of an Trapprisitions constraints of an Trapprisitions constraints of our trapprisitions of our $\tau$ - THM (1) === 1(1)(1)(1)(1)(1)(1)(1)(1)(1)(1)(1)(1)(1)	et temperature 1 let remperature 1 et temperature 2 let temperature 2:	
	A DECK	is by investigation by	ANTIF DC DCCTI-AF ANTI-	and the second s
	Logic 1282 (1, 2) Logic 1282 (1, 2) Logic 1283 (1, 2) Logic 1284 (1, 2) Logic 1284 (1, 2) Logic 1284 (1, 2) Logic 1284 (1, 2) Logic 1287 (1, 2) Logic 1287 (1, 2) Logic 1287 (1, 2)	Southed completions to at the Southed constraints of at the Southed constraints of at the Logical constraints of at the Logical constraint of at the		
	1011120120120120120120120120120120120120	to depict contract at a state	64494p	
*	Legiori (1) Legioli (1, 4) Legioli (1, 4)	$\begin{array}{c} \begin{array}{c} x_{2}(1,2,2,2) \\ = & (1,2,2,2) \\ =$	$\begin{split} & \text{if}(X_i, \{0, 0\}) = (1 + 2i) \\ & $	
	0-q+0 m12/1.	<ul> <li>a) an intervention of the second sector of the sector of the second sector of the second sector of th</li></ul>	5 (2)(2)(2)(2)(2)(4)(4)(4)(4)(4)(4)(4)(4)(4)(4)(4)(4)(4)	
	LogidUT3 (3) LogidUT1 (3)		-1- 0) -1- 1)	
BUGAT	ICMS	the sectory tool	ATTY ADDRESS	
	COLDET (2)	Cold smillby Load:	the stree services	
	COLDER (2)	(1 (10013 (1) -07 (2' (87.)) - 82 (	2) -8- (201(2))	
RUNAT	CONTR.	ANT DECEMBER 1810251 DECEMBER 1	S-11111	
	AppTemp#1 (1, 7) AdpTemp#1 (1, 7) AdpTemp#2 (1, 7) AdpTemp#2 (1, 7)	Approxim temperature by at at The Aller approxim temperatur Approxim temperature 1) at at The scher approxim respectator	ege Ki a 13 An atage Ki age Ki a 13 ez atage Wi	
	3057emp23(1,3) Abp7emp23(1,3) App7emp23(1,3) App7emp24(1,3) Abp7emp24(1,3)	Applicath temperature 12 at at the other appliant tempelatur Appriant temperature 15 at et The other approxim temperatur	nge RL n by an orage RI nge R2 n b) at orage RI	
	AppTempRh(1, 2) AApTempRh(1, 2) AppTempRh(1, 2)	Approach competitions 12 st at the state approach temperature Approach competitions 12 st et	age WL W 13 at stage W1 age H2	
	AbgTongAS (1, 3) AggTongAT (1, 3) AbgTongAT (1, 3) AbgTongAT (1, 3)	The other approach tamperature Approach temperature 12 et at Die tiller approach temperature Charmach temperature et at	v Al al atige Ni age N2 v 15 at atage N1 atre N2	
	And Second Control of	22 - 22 - 22 - 22 - 22 - 22 - 22 -	en al an prain (a tape to a part atape to minut to minut to result of a prain (b) result of result of a prain (b)	
Į.	1947-01 (1, J, R) 01 (wal (1, J, R) 90 Fill 01 Am	Dist insettation		
	AppTrop#1+1,2) AApTrop#1+1,2) AppTrop#2+(1,2) AApTrop#2+(1,2)	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{split} & \stackrel{(+)}{\to} = \left\{ \left\{ \begin{array}{c} 2_{+} + \left\{ X_{+} \right\} \right\} \right\} + \left\{ \left\{ X_{+} \right\} \right\} \\ & \stackrel{(+)}{\to} = \left\{ \left\{ 2_{+} + \left\{ X_{+} \right\} \right\} + \left\{ X_{+} \right\} \right\} \\ & \stackrel{(+)}{\to} = \left\{ \left\{ 2_{+} + \left\{ X_{+} \right\} \right\} + \left\{ X_{+} \right\} + \left\{ X_{+} \right\} \right\} \\ & \stackrel{(+)}{\to} = \left\{ \left\{ 2_{+} + \left\{ X_{+} \right\} \right\} + \left\{ X_{+} \right\} + \left\{ X_{+} \right\} + \left\{ X_{+} \right\} \right\} \\ & \stackrel{(+)}{\to} = \left\{ 2_{+} + \left\{ X_{+} \right\} + \left\{ X_{+}$	$\begin{array}{l} \{2^{-\frac{1}{2}}\{\Sigma_{1},Z_{2}, {}^{+\frac{1}{2}}\Sigma_{1}^{+\frac{1}{2}}\}\} \\ \{2^{-\frac{1}{2}}\{\Sigma_{2},Z_{2}, {}^{+\frac{1}{2}}\Sigma_{1}^{+\frac{1}{2}}\}\} \\ \{2^{-\frac{1}{2}}\{\Sigma_{2},Z_{2}, {}^{+\frac{1}{2}}\Sigma_{1}^{+\frac{1}{2}}\}\} \\ \{2^{-\frac{1}{2}}\{\Sigma_{2},Z_{2}, {}^{+\frac{1}{2}}\Sigma_{1}^{+\frac{1}{2}}\}\} \end{array}$
	ApgTemp#3(1,3) AAgTemp#3(1,3) ApgTemp#4(1,3) AAgTemp#4(1,3)	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{split} & \stackrel{(1)}{\to} = & \stackrel{(2)}{\to} \left\{ \left( 2, \left( \frac{3}{2} \right)^{2} \right) \left( + \frac{1}{2} \right) \left( \frac{1}{2} \right) \left( \frac{3}{2} \right) \left( \frac{3}{2} \right)^{2} \right) \left( \frac{3}{2} \right) \left( $	$\{1, -\alpha(\Sigma, J_1, \pi(\Sigma^+))\}$ $\{1, -\alpha(\Sigma, J_1, \pi(\Sigma^+))\}$ $\{1, -\alpha(\Sigma, J_1, \pi(\Sigma^+))\}$ $\{1, -\alpha(\Sigma, J_1, \pi(\Sigma^+))\}$ $\{1, -\alpha(\Sigma, J_1, \pi(\Sigma^+))\}$
	λφρ2 emp(1:1,1,3)           λλα στουρ 25:17,7)           λα στουρ 25:17,7)           λα στουρ 25:17,7)           λα στουρ 27:17,7)	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\label{eq:second} \begin{split} & (-1) +$	$\begin{split} & \left( L \left( \pm 1, Z_{1}, Z_{2} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( \pm 1, Z_{2}, Z_{1} + 1 \right) \right) \\ & \left( L \left( -1 \right) \right) \\ & \left( L \left( L \right) \right) \\ &$
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	der ander	11 BUR -AL BOR (2*BUH1231)		

Figure E4 Case study 2 HENS (step 2) (continued).

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*1/
            gms.1(*M1*)=10400.000;
gms.1(*M1*)=T250.000;
gms.1(*M1*)=T250.000;
gms.2(*M1*)=T2500.000;
gms.2(*M1*)=T2500.000;
gnu.10/02/142400.000:
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0.1.111(1.12.1.1MTD, 1.Aves.1)
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Figure E5 Case study 2 HENS (step 2) (continued).

## Appendix F Case Study HENS: The Piping and Pumping Cost as The Parameter

SETS I	hot streams	/H1, H2, H5, H4/	
3	cold streams Stage no.	/C1,C3,C3,C4,C5 / /W1,K3,K3,K4,K5,KK,MT,K5/;	
ARAMETER			
	TINI (I)	the inlet temperature of the hot stre	am 1007
	TOUTI(I)	the outlet temperature of the hot str	ndm (0C)
	T1H2(2)	the inlet temperature of the cold str	mam. 10C1
	100727.21	/01= 185,02= 139,03= 20,04= 110,05=	165/
	Avereter	/C1+ 220, C2+ 500, C3+ 250, C4+ 140, C5+	208/
	PCF1(1)	the flowrate of the hot stream (kW p /H1+ 900, H2= 360, H3=2500, H4= 200/	er (00)
	FI(I)	the flowrate of the hot stream (kg pe	2 2001
	FCP2(2)	the flowrate of the cold stream (EM	per 001
	PJ (J)	<pre>/Cl= 500,Cl= 150,Cl= 100,C4= 250,CS=25 the flowrate of the cold stream (kg p</pre>	41 30C)
	DOLT	/C1=42.0,C2=50,C3=25,C4=50,C5=50/ /10/:	
HI(I)	the heat transf	fer coefficient of the hot stream 1 in	the source plant (MW per OC.m2)
15.75	/R1=1, 82=1.1, the heat transf	mini.1, mini.3/	the sink plant (M per OC.st)
	/01-1.4, 02-5.3	, C3+1.1, C4+1.1, C5+1.8/	and the second s
CAL(I)	/H1=10, H2=10,	seperity of the hot process stream (kJ ) H2=50, H4=10/	bat octabl
CF3 (3)	(C1+0, C2+3, C1	depectty of the cold process streamind : 0+4, C4+5, C5+50/	per oc.ko)
rho5(1)	density of the	hot process stream (by per m3)	
rhoT(J)	density of the	cold process stream (kg per mil)	
etus (T)	/ci=640, cz=680,	- C1=760, C4=780, C1=810/	bell side (Pa. set)
	/HL-0.000343.8	12-0.0002721,H3-0.0002875,H4-0.0002421/	
#14T(J)	/c1=0.0002754,0	to the process stream flowing through 12=0.0002432,C3=0.0002722,C4=0.0002831,	tube #1de (Fa.aec) C5=0.0003785/
k3(1)	thermal conduct	Hyper of the fluid hot process stream	flowing through shell side (N per m.
KT (J)	thermal conduct	livity of the fluid cold process stream	flowing through sube side (8 per m.
Le	/Cl=0.6,C2=0.6, The tube pitch	(C3=0.6,C4=0.6,C5=0.6/	
	/0.0254/		
1	(25. 4)		
*DEIN	The internet of	LARASSE OF SUDE (MR)	
DEIN	The internal di /0.0154/	ianeter of tube (m)	
* [] m	The equipalant i	Listater of flips (as)	
De	The equialent of	Lineser of Supe (m)	
	/0.02391/		
miur	/0.0002634/	Lecosity for water (Fe. sec)	
	The exponent fo	or investment pumping cost	
b	The exponent fo	is investment pumping cost	
e	The exponent fo	ar investment pumping ocst	
De cont	/0.2/	anatas of sube (a)	
	/0.019084021/	and the same fur.	
*Devez	/19.degozi/	siameter of these (pm)	
AI	The parameters	of schedule 50 steel pipes parameters	79.02/
E.A.	The parameters	of schedule 00 steel pipes parameters	74,47
A4 AE	the parameters the annual fact	of schedule 30 steel pipes parameters for of the capital investment	/295/ /0.284/
Fe	the electric pr	thes (S per MMh)	/0.14
effpump	The efficiency	of the pump	/0.70/
2			
Parameter		is repully of the case of	
g(1, 2, K)	the heat exchan	oder matchings (NP);	
	4(*82*,*C2*,*83	'!=35000.000j	
	d(,87,,c2,,k)	1.1=12000.0001	
	4(*81*,*C1*,*X	()=1500.0001	
	THE PART & Loss & Mar	1-10-04/4/4/	
	4(*#2*, *C3+, *#3	5")=11100.000r	
	4(*#2*,*03*,*#3 4(*#4*,*01*,*#3 4(*#4*,*04*,*#4	*'=11100.000; *'=1000.000; *'=12500.000;	

Figure F1 The piping and pumping cost as the parameter of case study 2 HENS.

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        Construct
        Construction

        V12(1)
        All end +21/2(1)
        All the bit without in per sec.)

        (H1-42, H2-2)
        H1-2 (H1-2)
        H1-2 (H1-2)

        (H1-42, H2-2)
        H1-2 (H1-2)
        H1-2 (H1-2)

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           Added Table

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Thus The file that (paufor mefficient of the sole sizes to be saledisted
                    \begin{split} & \text{State}\left(t\right) = \\ & \left((t, 223^{+} + (t, 5, 1)) + (243^{+} + (t, 5))^{+} \right) \\ & \text{max}\left(t, 21^{+} + (1, 4)\right) + (21^{+} + (22^{+} + 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (23^{+} + (1, 2))^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23^{+} + (23
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(10-045(10)*(10*200(1)*(03(1)*3,3)*(102(1)*3,7)))
*((0000(1))/0000(1*(-0,14))*3,2)
*((0000(1))/0000(1*(-0,14))*3,2)
                   TAXAGETERS 
 M_{2}^{1}(\Sigma, Z, N) The presence doup in shall such caused by M2 (for 
 M_{2}^{1}(\Sigma, Z, N) The presence doup in tube side masked by M2 (for
                          D-EP1
D-EP1c
                    \begin{array}{l} (1)_{1} (1)_{2} (1)_{2} (1)_{2} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{1} (1)_{1} (1)_{1} (1)_{2} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3} (1)_{3
                \begin{array}{c} (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (12) + (
```

**Figure F2** The piping and pumping cost as the parameter of case study 2 HENS (continued).

```
Sdpi = sum ((I, J, K), dPi(I, J, K));
SdFj = sum ( (I, J, K) , dFj (I, J, K) ) ;
PARAMETERS
vi(I), vj(J), Rei(I), Rej(J),
fri(I) the fanning friction factor of the hot stream
          the fanning friction factor of the cold stream
fri(J)
          the pressure drop caused by the pipeline for the hot stream to one plant Lp= 83 m (Fa)
dPip(I)
dPjP(J)
          the pressure drop caused by the pipeline for the cold stream to one plant Lp= 33 m (Pa)
dPipp(I) the pressure drop caused by the pipeline for the hot stream among three plants L=167 m (Pa)
dP_jPP(J) the pressure drop caused by the pipeline for the cold stream among three plants L=167 m (Pa)
dPippp(J) the pressure drop caused by the pipeline for the hot stream among three plants L=250 m (Fa)
dPippp(J) the pressure drop caused by the pipeline for the cold stream among three plants L=250 m (Fa)
v1(I) = (4*FCPI(I)) / (CPI(I)*(22/7)*rhoS(I)*(Dini(I)**2));
vj(J) = (4*FCFJ(J)) / (CFJ(J)*(22/7)*rhoT(J)*(Dinj(J)**2));
Re1(I) = (rhoS(I)*Din1(I)*v1(I))/miuS(I);
Rej(J)= (rhoT(J)*Dinj(J)*vj(J))/miuT(J);
fri(I)= 0.046/(Rei(I)=*0.2);
fr1(J)= 0.046/(Re1(J)**0.2);
dPip(I) = (4*fri(I)*Lp*rhoS(I)*(Vi(I)**2))/(2*Dini(I)) ;
dPjp(J) = (4*frj(J)*Lp*rhoT(J)*(vj(J)**2))/(2*Dinj(J)) ;
dPipp(I) = (4*fri(I)*Lpp*rhoS(I)*(vi(I)**2))/(2*Dini(I)) 7
dFjpp(J) = (4*frj(J)*Lpp*rhoT(J)*(vj(J)**2))/(2*Dinj(J)) :
dPippp(I) = (4*fri(I)*L*rhoS(I)*(vi(I)**2))/(2*Dini(I)) ;
dPjppp(J) = (4*frj(J)*L*rhoT(J)*(vj(J)**2))/(2*Dinj(J)) :
PARAMETERS
Q1 (I, J, K)
                     the power required to drive the pump for the hot process stream
Qj(I,J,K)
PC(I,J,K)
                     the power required to drive the pump for the hot process stream
Q1('H2','C2','K1') =
                           ( (0.001*FCPI('H2'))/(CPI('H2')*zho5('H2')*effpump) )
                           (dP1('H2','C2','R1')+dP1p('H2'));
O1('H1','C1','K3') =
                           ( (0.001*FCPI('H1'))/(CPI('H1')*rho5('H1')*effpump) )
                           *(dPi('H1','C1','K3')+dPip('H1'));
Q1('H2','C5','K4') =
                           ( (0.001*FCPI('H2'))/(CPI('H2')*rho5('H2')*effpump) )
                           *(dF1('H2','C5','K4')+dF1pp('H2'));
                           ( (0.001*FCPI('H1'))/(CPI('H1')*rhoS('H1')*effpump) )
Q1('H1', 'C1', 'K5') =
                          * [dP1('H1', 'C1', 'K5')+dPip('H1'));
Q1 ('H2', 'C2', 'K5') =
                           ( (0.001*FCPI('H2'))/(CPI('H2')*rhoS('H2')*effpump) )
                           *(dPi('H2','C2','K5')+dPip('H2'));
Q1('H2','C3','K5') =
                           ( (0.001*FCPI('H2'))/(CPI('H2')*rho5('H2')*effpump) )
                           '(dP1('H2','C3','K5')+dPipp('H2'));
                           ( (0.001*FCPI(*H4*))/(CPI(*H4*)*rhoS(*H4*)*effpump) )
Q1('H4','C1','K5') =
                           *(dPi('H4','Cl','K5')+dPippp('H4'));
Q1('H4','C4','K6') =
                             (0.001*FCPI('H4'))/(CPI('H4')*rhoS('H4')*effpump) )
                          * (dPi('H4','C4','K6')+dPip('H4'));
Q1('HI','C3','R7') =
                           ( (0.001*FCPI('H1'))/(CPI('H1')*rho5('H1')*effpump) )
                          *(dP1('H1','C3','N7')+dP1pp('H1'));
01('H2','C2','K1') =
                          { (0,001*FJ('C2'))/(CPJ('C2')*rhoT('C2')*effpump) )
                           '(dPj('H2', 'C2', 'K1')+dPjp('C2'));
                           ( (0.001*FJ('C1'))/(CFJ('C1')*rhoT('C1')*effpump) )
Oj('H1','C1','K3') =
                           * (dPj('H1','C1','K3')+dPjp('C1'));
                           ( (0.001*FJ('C5'))/(CPJ('C5')*rhoT('C5')*effpump) )
Q1('H2','C5','K4') =
                           *(dPJ('H2','C5','E4')+dPJpp('C5'));
Qj('H1','C1','K5') =
                             (0.001*FJ('C1'))/(CPJ('C1')*rhoT('C1')*effpump) )
                          *(dPJ('H1', 'C1', 'K5')+dPJp('C1'));
Q1('H2', 'C2', 'K5') =
                          ( (0.001*FJ('C2'))/(CPJ('C2')*rhoT('C2')*effpunp) )
```

**Figure F3** The piping and pumping cost as the parameter of case study 2 HENS (continued).

\* (dPJ('H2','C2','K5')+dPJp('C2')):

```
( (0,001*F3(*C3*))/(CF3(*C3*)*zhoT(*C3*)*effpump) )
*(dF3(*F3*,*C3*,*K3*)*dF3pp(*C3*));
( (0,001*F3(*C3*))/(CF3(*C3*)*zhoT(*C3*)*effpump) )
( (0,001*F3(*C3*))/(CF3(*C3*)*zhoT(*C3*)*effpump) )
*(dF3(*F3*,*C3*,*E5*)*dF3pp(*C3*));
( (0,001*F3(*C3*)*(CF3(*C3*)*zhoT(*C3*)*effpump) )
*(dF3(*F3*,*C3*,*E5*)*dF3pp(*C3*));
) %(dF3(*F3*,*C3*,*E5*)*dF3pp(*C3*));
02(182,1,03,1,081) =
$2("##","CI","#5") *
Q3 (*84*, *04*, *88*) +
23 (*N1*, *C3*, *NT*) =
                                   THE WEIGHT SOFT
PARAMETERS
CostPump1(1,J,K)
CostPumpJ(T, J, H)
TotalFumpCost;
CostPump1('H2','C2','H1')=
(Fe'Hy'Q1('H2','C2','H1'))+
125* 10+
(P.(((LCbI(.HD,),(Ub7(.HD,'.CD,'.HT,)+Qb1b(.HD,)))/(CbI(.HD,),TWOP(.HD,))).
111
CostPumpI('82','C5','84')=
(PerBy*Q1('82','C5','84'))+
(AF'(a+
(b*( ((FCFI('HD')*(dFi('HD'),'CD','K*')+dFipp('HD'))))(CFI('HD')*Exe5('HD')))*+d)))
CostPump1('R1','C1','R5')=
(Pm*Hy*Q1('R1','C1','R5'))+
(Af'(A+
(b*) (((FCFI(*H1*)*(dP1(*H1*,*CI*,*R5*)*dP1p(*H1*)))/(CFI(*H1*)*cmod(*H1*)))+*c)))
112
CostPumpT(<sup>1</sup>H2<sup>+</sup>, <sup>1</sup>C2<sup>+</sup>, <sup>1</sup>(S<sup>+</sup>)=
(Fe<sup>+</sup>Sy<sup>+</sup>Q4(<sup>1</sup>H2<sup>+</sup>, <sup>1</sup>C2<sup>+</sup>, <sup>1</sup>H5<sup>+</sup>))+
(&f*(*+
(b*((1(FCFI(*H2*)*(dF1(*H2*,*CI*,*K5*)+dF1p(*H2*()))/(CFI(*H2*)*inch(*H2*)))**c)))
))/
CostPumpI('82','03','85')=
(Pe'8y*Q1('82','03','85'))*
(A2*(s+
(b,( (((FCFI('H2')'(GFI('H2','CB','R5')+dFipp('H2')))/(CFI('H2')'(fFCFI('H2')))))))
612
CostPumpI('N4','C1','M5')=
(Fw'Hy'O1('R4','C1','K5'))+
TAT: IAS
 (b*( ((*C#I('N4')*(dPI('N4','CI','N5')*dFippp('N4')))/(CFI('N4')*thol('N4')))**** ))
1.1.2
CostPump1('H4','C4','R4')=

1Pm*Hy*C1/'84','C4','R6')+

(Af'(a+
(b*( (((FCF2((184*)*(MF1,*C4*,*C4*,*N(*)+dE1p((184*)))))(CF2((84*)*Ebu8((184*)))*****)))))
())
CostPumpI('H1','C3','K7')=
(Pe'Hy+Q1('H1','C3','K7'))+
122-10-
 (b*( (((TCRE('H1')*(dRE('H1'+'CB',*B7')*dRIDD('HT,))))(CRE('HT,)*EPOP(HT,)))**d) ))
111
CostPump3('EI','CI','EI')=
(Fe'Ey*Q3('EI','CI','EI')+
(Af'(a+
 (b+1 (((FCP3(*C2*)+(dP3(*H2*,*C1*,*E1*)+dP3p(*C2*)))/(CP2(*C2*)+EBoT(*C2*)))++o) ))
112
CostFumpJ('E1','C1','E3')=
(Fe'H2'QJ('H1','C1','E3'))+
(Af'(e+
 (b+( (((FCB3(*CL*)*(dP)(*EL*,*CL*,*N3*)*dP)p(*CL*)))/(CP3(*CL*)*ENoT(*CL*)))**e) ))
152
CostPump3('824, *C5*, *R4*)=
($e*87*03(.HI.'.C2.'.K*.))+
(AT*(A*
(b*((1)CP2(*CS*)*(B*)(*CS*,*CS*,*K*)*(B))pp(*CS*)))/(CB*(*CS*)*2b(at*(*CS*)))**(a*)))
CostPumpJ('H1','C1','E5')=
(Fe'Hy+Oj('H1','C1','E5'))+
(Af'(N+
(p_*(-(((\texttt{LCDS}(,\texttt{CT}_*),\texttt{(qb3}(,\texttt{HT}_*,\texttt{CT}_*,\texttt{HT}_*),\texttt{qb3}(,\texttt{CT}_*)))))(\texttt{CB3}(,\texttt{CT}_*),\texttt{true1}(,\texttt{CT}_*))(,\texttt{e}())))
CostPumpJ('82','C2','85')=
(Pe'8y*Q5('82','C2','85'))+
(A5'(e*
(b*( (((PCBJ(*CD*)*(dPj(*N2*,*CD*,*N5*)*dPjp(*CD*)))/(CPJ(*(CD*)*REST(*CD*)))**e) ))
111
```

**Figure F4** The piping and pumping cost as the parameter of case study 2 HENS (continued).

```
CostPumpJ('H2','C3','K5')=
(Pe*Hy*Qj('H2','C3','K5'))+
(Af* (a+
(b*( (((FCPJ('C3')*(dPj('H2','C3','E5')+dPjpp('C3')))/(CPJ('C3')*rhoT('C3')))**d) ))
)):
CostPumpJ('H4','C1','K5')=
(Pe*Hy*Qj('H4','Cl','K5'))+
(Af* (a+
(b*( (((FCPJ('Cl')*(dPj('H*','Cl','N5')+dPjppp('Cl')))/(CPJ('Cl')*rhoT('Cl')))**o) i)
)):
CostFumpJ('H4','C4','K6')=
(Pe*Hy*Qj('H4','C4','K6'))+
(Af * (a+
(b*( (((FCPJ('C4')*(dPj('H4','C4','H6')+dPjp('C4')))/(CPJ('C4')*zhoT('C4'))))))))
));
CostPumpJ('81','C3','K7')=
(Fe*Hy*Qj('H1','C3','K7'))+
(Af* (a+
(b*( (((FCPJ('C3')*(dPj('H1','C3','K7')+dPjpp('C3')))/(CPJ('C3')*rhoT('C3')))**d) ))
332
TotalFumpCost=( SUM((I,J,K),CostFumpI(I,J,K)))+ ( SUM((I,J,K),CostFumpJ(I,J,K)));
                         ---- THE TOTAL PRESSURE DROF AT EACH MATCHING --
PARAMETERS
PD(I,J,K) Total pressure drop at each HE matching 1 (Pa)
PD('H2', 'C2', 'K1')=dPi('H2', 'C2', 'K1')+dPip('H2')+dPj('H2', 'C2', 'K1')+dPjp('C2');
FD('H1','C1','K3')=dP1('H1','C1','K3')+dPip('H1')+dPj('H1','C1','K3')+dPjp('C1');
FD('H2','C5','K4')=dP1('H2','C5','K4')+dPipp('H2')+dPj('H2','C5','K4')+dPjpp('C5');
PD('H1','C1','K5')=dP1('H1','C1','K5')+dP1p('H1')+dPj('H1','C1','K5')+dP1p('C1');
PD('H2','C2','K5')=dP1('H2','C2','K5')+dP1p('H2')+dPj('H2','C2','K5')+dP1p('C2');
PD('H2','C3','K5')=dP1('H2','C3','K5')+dPipp('H2')+dPj('H2','C3','K5')+dPjpp('C3');
PD('H4','C1','K5')=dPi('H4','C1','K5')+dPippp('H4')+dPj('H4','C1','K5')+dPjppp('C1');
PD('H4','C4','K6')=dPi('H4','C4','K6')+dPip('H4')+dPj('H4','C4','K6')+dPjp('C4');
PD('H1','C3','K7')=dPi('H1','C3','K7')+dPipp('H1')+dPj('H1','C3','K7')+dPjpp('C3');
DISPLAY
Dini
Dinj
Douti
Doutt
81
103
P11
£1j
PICI
PICS
PIPINGCOST
DISPLAY
vi, vj, Rei, Rej, fri, frj, dPip, dPjP, dPipp, dPjPp, dPjppp, dPjppp
Q1,Q1, dp1, dp3, kshell, ktube
Sdp1, Sdpj
CostPumpI, CostPumpJ
TotalPumpCost;
DISPLAY
PD:
```

**Figure F5** The piping and pumping cost as the parameter of case study 2 HENS (continued).

#### Appendix G Case Study 2 (HENS)

512 VARIABLE z.L Exchanger matching between hot I and cold J at stage \_\_\_\_ K1 КЗ K4 K6 K7 K5 H1.C1 1.000 1.000 H1.C3 1.000 H2.C2 1.000 1.000 H2.C3 1.000 H2.C5 1.000 H4.C1 1.000 H4.C4 1.000 512 VARIABLE q.L Heat exchanged between hot I and cold J \_\_\_\_ K1 K3 K4 K5 K6 K7 H1.C1 15000.000 1500.000 H1.C3 11900.000 H2.C2 35000.000 16650.000 H2.C3 11100.000 H2.C5 25000.000 H4.C1 1000.000 H4.C4 12500.000 \_\_\_\_ 512 VARIABLE qcu.L Heat exchanged between cold utility and hot I H1 10600.000, H2 7250.000, H3 15000.000, H4 20500.000 512 VARIABLE gcs.L 53350.000 Total cold utility = ----512 VARIABLE ghu.L Heat exchanged between hot utility and cold J \_\_\_\_ C2 2500.000 512 VARIABLE ghs.L 2500.000 Total hot utility \_\_\_\_ = 1091166.769 Total Annual Cost VARIABLE TAC.L 512 VARIABLE dt.L Approach temperature ----Kl K2 KЗ K4 K5 K6 H1.C1 10.000 10.000 10.000 10.000 10.000 10.000 H1.C2 10.000 10.000 10.000 10.000 10.000 10.000 H1.C3 10.000 10.000 10.000 10.000 10.000 10.000 H1.C4 10.000 10.000 10.000 10.000 10.000 10.000 H1.C5 10.000 10.000 10.000 10.000 10.000 10.000 10.000 H2.C1 10.000 10.000 10.000 10.000 10.000 H2.C2 10.000 10.000 10.000 10.000 10.000 10.000 H2.C3 10.000 10.000 10.000 10.000 10.000 10.000

Figure G1 The result of case study 2 HENS for the step 2.

10.000

10.000

10.000

10.000

10.000

10.000

10.000

10.000

10.000

10.000

10.000

10.000

10.000

10.000

10.000

H2.C4

H2.C5

H3.C1

10.000

10.000

10.000

H3 C2	10 000	10 000	10 000	10 000	10 000	10 000
up Cp	10.000	10.000	10.000	10.000	10.000	10.000
H3.C3	10.000	10.000	10.000	10.000	10.000	10.000
H3.C4	10.000	10.000	10.000	10.000	10.000	10.000
пэ.сэ на ст	10.000	10.000	10.000	10.000	10.000	10.000
H4.CI	10.000	10.000	10.000	10.000	10.000	10.000
H4.C2	10.000	10.000	10.000	10.000	10.000	10.000
H4.C3	10.000	10.000	10.000	10.000	10.000	10.000
H4.C4	10.000	10.000	10.000	10.000	10.000	10.000
H4.C5	10.000	10.000	10.000	10.000	10.000	10.000
+	K7	K8				
H1.C1	10.000	10.000				
H1.C2	10.000	10.000				
H1.C3	10.000	10.000				
H1.C4	10.000	10.000				
H1.C5	10.000	10.000				
H2.C1	10.000	10.000				
H2.C2	10.000	10.000				
H2.C3	10.000	10.000				
H2.C4	10.000	10.000				
H2.C5	10.000	10.000				
H3.C1	10.000	10.000				
H3.C2	10.000	10.000				
H3.C3	10.000	10.000				
H3 C4	10,000	10.000				
H3 C5	10.000	10.000				
H4 C1	10.000	10.000				
H4.C2	10.000	10.000				
H4.C2	10.000	10.000				
H4.C3	10.000	10.000				
14.C4	10.000	10.000				
H4.C5	10.000	10.000				
	512 VARIABL	E ddt.L Re	al Approach	Temperature		
	LT.	K2	K3	14	N9	10
HI CI	30,000	30 000	30 000	10 000	10 000	10 000
H1 C2	-233 333		-2 8422F-14	-50,000	-50,000	56,000
H1 C3	200.000		-2 8422F-14	-50.000	-50.000	56.000
H1 C4	90,000	<u>60</u> 000	90 000	40.000	40.000	35.000
H1 C5	45 000	45 000	45 000	-5.000	5 000	33.000
H1.05	40.000	140.000	140.000	170.000	70.000	-26 000
H2.C1	16 667	110.000	110.000	110.000	10.000	-30.000
H2.C2	250.000	110.000	110.000	110.000	10.000	10.000
H2.C3	230.000	200.000	200.000	200.000	10.000	10.000
H2.04	340.000	200.000	200.000	200.000	100.000	-11.000
n2.05	295.000	155.000	155.000	155.000	65.000	-46.000
H3.CI	-95.000	-95.000	-95.000	-65.000	-65.000	-60.000
H3.C2	-358.333	-125.000	-125.000	-125.000	-125.000	-14.000
H3.C3	-125.000	-125.000	-125.000	-125.000	-125.000	-14.000
n3.04	-35.000	-35.000	-35.000	-35.000	-35.000	-35.000
H3.C5	-80.000	-80.000	-80.000	-80.000	-70.000	-70.000
H4.CI	-20.000	-20.000	-20.000	10.000	10.000	10.000
H4.C2	-283.333	-50.000	-50.000	-50.000	-50.000	56.000
H4.C3	-50.000	-50.000	-50.000	-50.000	-50.000	56.000
H4.C4	40 000	40.000	40.000	40.000	40.000	35.000
	40.000					33.000

Figure G2 The result of case study 2 HENS for the step 2 (continued).

H1.C1	10.000	-29.6	67									
H1.C2	56.000	16.3	33									
H1.C3	56.000	135.3	33									
H1.C4	85.000	45.3	33									
H1.C5		-39.6	67									
H2.Cl	-36.000	-36.0	000									
H2.C2	10.000	10.0	000									
H2.C3	10.000	129.0	00									
H2.C4	39.000	39.0	000									
H2.C5	-46.000	-46.0	000									
H3.Cl	-60.000	-60.0	00									
H3.C2	-14.000	-14.0	000									
H3.C3	-14.000	105.0	000									
H3.C4	15.000	15.0	000									
H3.C5	-70.000	-70.0	00									
H4.Cl	-52.500	-52.5	00									
H4.C2	-6.500	-6.5	00									
H4.C3	-6.500	112.5	00									
H4.C4	22.500	22.5	00									
H4.C5	-62.500	-62.5	00									
	512 VARIAB	BLE ti.L	Temperature	of	hot :	stream	i at	hot	end	of	stage	k
			• • • • • • • • • • • • • • • • • • • •									
	Kl	K2	K3			K4		K	5		K6	
Hl	250.000	250.000	250.000		200	.000	20	0.000	D	19	95.000	
H2	500.000	360.000	360.000		360	.000	26	0.000	0	1.	49.000	
H3	125.000	125.000	125.000		125	.000	12	5.000	0	12	25.000	
H4	200.000	200.000	200.000		200	.000	20	0.000	0	19	95.000	
+	K7	KS										
Hl	195.000	155.333										
H2	149.000	149.000										
H3	125.000	125.000										
H4	132.500	132.500										
	512 VARIAB	BLE tj.L	Temperature	of	cold	strear	nja	t hot	t en	d of	f stag	e)
	Kl	K2	K3			K4		K	5		K6	
								_				
Cl	220.000	220.000	220.000		190	.000	19	0.000	D	18	35.000	
C2	483.333	250.000	250.000		250	.000	25	0.000	0	13	39.000	
C3	250.000	250.000	250.000		250	.000	25	0.000	0	13	39.000	
C4	160.000	160.000	160.000		160	.000	16	0.000	D	10	50.000	
C5	205.000	205.000	205.000		205	.000	19	5.000	0	19	95.000	
+	K7	K8										
C1	185.000	185.000										
C2	139.000	139.000										
C3	139.000	20.000										
C4	110.000	110.000										
C5	195.000	195.000										

K7

+

K8

Figure G3 The result of case study 2 HENS for the step 2 (continued).

k

---- 514 VARIABLE q.L Heat exchanged between hot I and cold J

	Kl	K3	K4	K5	K6	K7		
H1.C1		15000.000		1500.000		11900 000		
H2.C2	35000.000			16650.000		11900.000		
H2.C3				11100.000				
H2.C5			25000.000					
H4.Cl				1000.000				
H4.C4					12500.000			
	514 VARIABI	E Area.L						
	Kl	K3	K4	K5	K6	K7		
H1.C1		313.004		44.468				
H1.C3						112.741		
H2.C2	270.493			157.857				
H2.C3				128.243				
H2.C5			143.904					
H4.C1				22.096				
H4.C4					195.825			
EXECUTION TIME = 0.031 SECONDS 3 MB 24.2.1 r43572 WEX-WEI C O N O P T 3 version 3.15M Copyright (C) ARKI Consulting and Development A/S								
		DK-2880 Ba	gsvaerd, Denn	ark				
			,,					
The model has 1373 variables and 1574 constraints with 5493 Jacobian elements, 1700 of which are nonlinear. The Hessian of the Lagrangian has 872 elements on the diagonal, 800 elements below the diagonal, and 1032 nonlinear variables.								
** Opt	imal solutio	on. Reduced	gradient less	than toler	ance.			
CONOPT	time Total			0.008 se	conds			
of w	hich: Functi	on evaluati	ons	0.001 =	12.5%			
	lst De	rivative ev	aluations	0.000 =	0.0%			
DIC	OPT: Stopped	i on NLP wor	sening					

The search was stopped because the objective function of the NLP subproblems started to deteriorate.

--- DICOPT: Best integer solution found: 1091166.768659

Figure G4 The result of case study 2 HENS for the step 2 (continued).

### Appendix H Result Case Study 2: HENS (The Piping and Pumping Cost)

```
COMPLIATION TIME = 0,000 SECONDS 3 HS 24,2,1 s43573 WEX-WEI
NAMES 24,2,1 s43572 WEX-WEI
RAMES 24,2,1 s43572 WEXENES Dec 9, 2013 WEX-WEI x36 64/HS Windows 05/25/20 LONIS157
Reneral Algebraic Neceling System
Execution
---- 91 PARAMETER ( the heat exchanges matchings (MW)
                                    2.8
                                              .85
             81
                         10
                                                              56
                                                                           87
           15000.000
12.48
                                             1500.000
                                                                    S00.00911
10.13
12.52
      35000.000
                                           26680.000
H2.03
                             25000.000
1000.000
H2.C5
10.14
                                                         12500.000
84.04
---- 435 FARAMETER Dimi. The inner diameter of the pipeline dor the hot proce 
as stream (m)
RE 0.175. HE 0.141. NO 0.196. NO 0.192
  -- 935 FARADETER Dinj The inner diameter of the pipeline for the cold proc
                             and birthe isl
CE 0.249, C3 0.336, C3 0.145, D4 0.202, C5 0.198
All FARAMETER Doull The opter diameter of the pipelike for the bot proc sing stream (m)
MI 011994 MI 0.161, MR 01727, MA 01153
---- 43% FARAMETER Dout; The Outer diameter of the pipeline for the cold pro
                             dean stream (m)
CI 0.201, CI 0.245, CN 0.166, C4 0.239, C8 0.238
```

iss FARAMETER #1 The weight per unit length of the pipeline for the hot process stream (ky per m)

BI 54.396, BZ 37.898, B3 46.432, 34 54.236

---- 435 FARAMETER W) The weight per unit length of the pipeline for the oul u process stream (by per m)

CI 105.321, C2 79.422, E3 59.645, C4 70.365, C5 65.675

----- 485 WARANETER F11 the pipe capital cost por init length for hot stream (f per m)

CL 274.101, CZ 238.149, CS 166.228, C4 223.097, CS 219.191

HL 25576-406, H2 21460-954, B¥ 30638-322

---- 415 FARAMETER PLC3 The pupping cost

C1 542721071, C3 31941.667, C5 28633.264

HL 3.000. HZ 3.000, HS 3.000, H4 3.000

445 PARAPETER #3

EL 2.000, CJ 2.000, CS 2.000, C4 2.000; CS 2.000

Figure H1 The result case study 2 HENS for the piping and pumping cost in step 2.

```
..... 440 PARAMETER Rel
H1 921543.741, H2 030254.654, H3 1130495.590, H4 793545.594
**** *** PARAMETER Rej
CI 1147116.345, C2 1117728.259, C8 807925.349, C4 1112948.599
C5 1148436.409
       448 FARMETER for the family friction factor of the hot stream
M1 0.003, M2 0.005, M3 0.003, M4 0.003
       440 FARAMETER frj the famming friction factor of the cold stream
CI 0.003, CI 0.005, CS 0.003, C4 0.003, C5 0.003
  --- #40 FARAMETER dFip the pressure drop caused by the pipeline for the bot
stream to one plant 1p= 53 m (Fa)
M1 20898.102, M2 94307.134, M3 24011.180, M4 33244.935
---- #48 FARAMETER dF)F the pressure drop caused by the pipelite for the col 
it stream to one plant Lp= 83 m (Fm)
CL 14449.149, C2 17046.221, C3 31020.012, C4 21949.052, C5 23000.068
H1 41794.204, H2 60414.247, H3 43022.341, H4 64533.549
----- 445 FARAGETER dFyFp the pressure drop caused by the pipeline for the co-
id stream among three plants L=167 m (Pa)
C1 28108.258, C2 35402.442, C3 43441.428, C4 43886.104, C5 46016.114
---- 440 FARANCIES dFippp the pressure drop caused by the pipeline for the h
ot stream among three plants 1+200 m (Fm)
H1 42494.304, H2 102921.401, H3 72033.541, H4 99000.004
---- 440 FARADATTER dBjppp the pressure drop caused by the pipeline for the c
old stream among three plants L=250 m (Fm)
C1 43347.447, C2 53538.443, C3 98442.437, C4 68829.154, C5 49024.178
..... #40 FARAMETER Q1 the power required to drive the pump for the hot proce as stream
                           83 84
              RL.
                                                     215
                                                                   214
                                                                               87
H1.C1
H1.C3
H2.C2
H2.C3
H2.C5
H2.C5
H1.C5
H1.C1
H1.C4
                        1.642
                                                  1.442
                           1.442 1.442
1.528
3.055
                                                                              2.004
             1.528
                                   3.055
                                                   3,933
                                                                  1.911
       443 FARAMETER 02 the power required to drive the pump for the hot proce as stream
.....
             KL K3 214
                                                     85
                                                                   84
                                                                               87
           0.252
                                     0.252
H1.C1
                                                                              0.748
H1.C3
H2.C2
H2.C3
H2.C8
            0.425
                                                  0.425
                                     0.081
N4.C1
N4.C4
                                                    0.754
                                                                 0.402
---- ++S FAADETER dF1 The pressure drop in shell side caused by HE (Fs)
               RL K3 E4 H5
                                                                   2.6
                                                                               87
                      .001007E-5 3.27017E-10
8.340331E-5
6.146008E-9
H1.C1 1.001007E-9
H1.C1 1.
H1.C3
H2.C2 3.743245E-9
H2.C3
H2.C5
H4.C1
H4.C4
                                                                      9.21983E-10
                               €....
1.234094E-9
9.35524E-10
4.475039E-9
---- 448 PARAMETER dFj The pressure drop in tube side caused by HE (Pa)

        NI
        NS
        N6
        N6
        N6

        NI_C2
        1.2817682-5
        2.2773812-6
        N1.081028-6
        N1.081028-6

        NI_C2
        2.1685212-5
        3.0895012-5
        N1.089642-7
        N1.089642-7

        N4_C2
        2.1089642-7
        N1.3152732-6
        S.2228632-6
        S.2228632-6

                                                                   2.6
                                                                               87
                                                                       4.3214148-4
```

**Figure H2** The result case study 2 HENS for the piping and pumping cost in step 2 (continued).

18

---- 448 PARAMETER Kabell The film heat transfer coefficient of the hot stre am to be calculated H1 1.27412E-12, H2 1.25827E-12, H3 4.03571E-14, H4 1.65426E-12 ---- 448 PARAMETER Ktube The film heat transfer coefficient of the cold stre am to be calculated C1 2.726255E-9, C2 9.621458E-9, C3 1.281668E-8, C4 5.045706E-9 C5 3.20364E-10 ---- 448 PARAMETER 5dPl = 2.807401E-8 PARAMETER SdPj ■ 1.327973E-4 ---- 448 PARAMETER CostPumpI K5 K6 K7 K1 K3 K4 11121.675 B1.C1 11121,675 H1.C3 13420.072 H2.C2 11279.261 11279.261 H2.C3 13659.324 H2.C5 13659.324 H4.C1 14824.595 H4.C4 10871.215 ---- 448 PARAMETER CostPumpJ KT K3 R4 K5 K6 R7 81.01 10702.546 10702.546 H1.C3 11774.785 H2.C2 10882.198 10882.198 82.03 11774.785 11802,062 H2.C5 H4.C1 13128.208 84.04 10817.286 ---- \$48 PARAMETER TotalPumpCost = 213703.016 ---- 454 PARAMETER FD Total pressure drop at each HE matching 1 (Pa) K4 K3 R1 85 87 K6 35347.251 35347.251 H1.C1 105437.829 H1.C3 H2.C2 52153.355 52153,355 82.03 132255.892 H2.CS 114630.383 H4.C1 143148.251 55209,987 84.04 EXECUTION TIME = 0.016 SECONDS 4 MB 24.2.1 r43572 WEX-WEI USER: The Petroleum and Petrochemical College G131219:2228AS-WIN Chulalongkorn University DC4365 License for teaching and research at degree granting institutions

**Figure H3** The result case study 2 HENS for the piping and pumping cost in step 2 (continued).

HENS Case study 2										
EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area	
10	H2.C2.K1	500	360	483.333	250	49.426	35000	0.600	1180.224	
	H1.C1.K3	250	200	220	190	18.193	15000	0.583	1414.225	
	H2.C5.K4	360	260	205	195	103.515	25000	0.624	387.036	
	H1.C1.K5	200	195	190	185	10.000	1500	0.583	257.290	
	H2.C2.K5	260	149	250	139	10.000	16650	0.600	2775.000	
	H2.C3.K5	260	149	250	139	10.000	11100	0.574	1933.798	
	H4.C1.K5	200	195	190	185	10.000	1000	0.674	148.368	
	H4.C4.K6	195	132.5	160	110	28.287	12500	0.596	741.431	
	H1.C3.K7	195	155.333	139	20	89.865	11900	0.524	252.711	
Hot Utilities	Fuel.C2.K7	800	750	500	483.333	283.004	2500	0.811	10.893	
Cold Utilities	H1.Water.K3	155.333	120	20	18.327	117.695	10600	0.500	180.125	
	H2.Water.K3	149	120	20	18.327	114.790	7250	0.545	115.887	
	H3.Water.K8	125	119	16.406	15	106.280	15000	0.524	269.344	
	H4.Water.K6	132.5	30	18.327	16.406	47.249	20500	0.565	767.914	
EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area	
2	H1.C1.K1	250	191.667	220	185	15.500	17500	0.583	1936.538	
	H2.C2.K1	500	297	498	195	25.855	45450	0.600	2929.822	
	H2.C3.K1	500	297	250	197	163.622	5300	0.574	56.432	
	H1.C4.K5	191.667	150	160	110	35.670	12500	0.524	668.768	
	H2.C5.K6	297	197	205	195	23.853	25000	0.624	1679.603	
	H2.C2.K7	197	163.4	195	139	8.963	8400	0.600	1561.890	
	H4.C3.K7	200	111.5	197	20	26.117	17700	0.596	1137.094	
Hot Utilities	Fuel.C2.K6	800	750	500	498	275.297	300	0.811	1.344	
Cold Utilities	H1.Water.K6	150	120	20	15	117.052	9000	0.500	153.778	
	H2.Water.K6	163.4	119	20	15	122.638	10850	0.545	162.333	
	H3.Water.K6	125	119	20	15	104.499	15000	0.524	273.935	
	H4.Water.K6	111.5	30	20	15	42.273	16300	0.565	682.461	

 Table I1
 The exact area calculation of case study 2 HENS
EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
4	H1.C5.K1	250	247.333	205	204.68	43.816	800	0.565	32.315
	H1.C1.K2	247.333	189	220	185	12.133	17500	0.583	2473.937
	H2.C2.K4	500	199.008	496	195.008	4.000	45148.8	0.6	18811.989
	H2.C3.K4	500	199.008	250	190.804	71.375	5919.63	0.574	144.490
	H2.C5.K4	500	199.008	204.68	195.008	69.359	24179.6	0.624	558.677
	H4.C5.K5	200	199.898	195.008	195	4.945	20.449	0.65	6.362
	H4.C2.K6	199.898	157.892	195.008	139	10.352	8401.23	0.624	1300.619
	H1.C4.K7	189	147.333	160	110	32.990	12500	0.524	723.102
	H2.C3.K7	199.008	130.687	190.804	20	39.442	17080.4	0.574	754.434
Hot Utilities	Fuel.C2.K6	800	750	500	496	276.357	600	0.811	2.677
Cold Utilities	H1.Water.K2	147.333	120	20	18.943	113.685	8199.9	0.500	144.257
	H2.Water.K2	130.687	120	20	18.943	105.798	2671.75	0.545	46.336
	H3.Water.K5	125	119	18.943	17.486	103.769	15000	0.524	275.863
	H4.Water.K6	157.892	30	17.486	15	56.072	25578.4	0.565	807.380
EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
6	H1.C5.K1	250	247.5	205	195	48.653	750	0.565	27.284
	H2.C2.K1	500	201	494	194	6.487	45000	0.6	11561.50
	H2.C3.K1	500	201	250	195	66.277	5500	0.574	144.573
	H2.C5.K1	500	201	205	195	75.373	24250	0.624	515.596
	H4.C2.K2	200	193.25	194	185	7.065	1350	0.624	306.228
	H1.C1.K3	247.5	193.75	220	187.75	14.110	16125	0.583	1960.205
	H4.C4.K3	193.25	130.75	160	110	26.507	12500	0.596	791.244
	H1.C1.K5	193.75	191	187.75	185	6.000	825	0.583	235.849
	H2.C1.K5	201	191	187.75	185	9.148	550	0.646	93.072
	H2.C3.K5	201	191	195	175.5	10.004	1950	0.574	339.571
	H2.C2.K6	191	182.2	185	170.3	8.600	2200	0.6	426.357
	H1.C2.K7	191	175.3	170.3	139	27.761	4700	0.545	310.642
	H2.C3.K7	182.2	120	175.5	20	34.587	15550	0.574	783.269
Hot Utilities	Fuel.C2.K6	800	750	500	494	277.41	900	0.811	4.000
Cold Utilities	H1.Water.K1	175.33	120	20	18.396	126.55	16599	0.500	262.330
	H3.Water.K6	125	119	18.396	15	105.29	15000	0.524	271.860
	H4.Water.K6	130.75	30	18.396	15	48.323	20150	0.565	738.023

 Table I2
 The exact area calculation of case study 2 HENS (Continued)

	EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
	8	H1.C5.K1	250	247.4	205	195	48.626	766.667	0.565	27.905
		H2.C2.K1	500	203	491.77	195	8.110	44516.7	0.6	9147.962
		H2.C3.K1	500	203	250	195	70.935	5500	0.574	135.080
		H2.C5.K1	500	203	205	195	80.447	24233.3	0.624	482.744
		H1.C1.K3	247.4	198.83	220	190.833	15.762	14583.3	0.583	1587.029
		H2.C2.K3	203	198.83	195	190.833	8.000	625	0.6	130.208
		H2.C3.K3	203	198.83	195	190.833	8.000	416.667	0.574	90.738
		H1.C2.K4	198.8	194.94	190.83	186.167	8.382	700	0.545	153.225
		H1.C3.K4	198.8	194.94	190.83	186.167	8.382	466.667	0.524	106.244
		H2.C1.K4	198.8	194.16	190.83	186.167	8.000	1166.67	0.646	225.748
		H4.C1.K4	200	194.16	190.83	186.167	8.570	1166.67	0.674	201.976
		H1.C1.K5	194.9	193	186.16	185	8.382	583.333	0.583	119.365
		H2.C2.K5	194.1	193	186.16	185	8.000	175	0.6	36.458
		H2.C3.K5	194.1	193	186.16	185	8.000	116.667	0.574	25.407
		H4.C4.K5	194.1	131.66	160	110	27.440	12500	0.596	764.321
		H1.C2.K6	193	170	185	139	16.966	6900	0.545	746.226
		H2.C3.K6	193	127	185	20	38.228	16500	0.574	751.952
]	Hot Utilities	Fuel.C2.K6	800	750	500	491.778	278.585	1233.3	0.811	5.459
C	Cold Utilities	H1.Water.K6	170	120	20	15	126.154	15000	0.5	237.805
		H2.Water.K6	127	120	20	15	105.997	1750	0.545	30.293
		H3.Water.K6	125	119	20	15	104.499	15000	0.524	273.935
		H4.Water.K6	131.66	30	20	15	48.128	20333.4	0.565	747.756
	EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
	14	H1.C1.K2	250	204	217.6	190	21.919	13800	0.583	1079.929
		H2.C2.K3	500	333	468.333	190	73.786	41750	0.6	943.040
		H2.C3.K4	333	309	250	190	99.912	6000	0.574	104.621
		H1.C2.K5	204	201.333	190	187.333	14.000	400	0.545	52.425
		H1.C3.K5	204	201.333	190	186	14.656	400	0.524	52.084
		H1.C2.K6	201.33	177.167	187.333	139	24.083	7250	0.545	552.371
		H2.C5.K6	309	209	205	195	44.857	25000	0.624	893.158
		H4.C3.K6	200	117	186	20	42.853	16600	0.596	649.958
		H1.C4.K7	177.16	135.5	160	110	21.057	12500	0.524	1132.869
		H2.C1.K7	209	199	190	185	16.372	2500	0.646	236.379

 Table I3
 The exact area calculation of case study 2 HENS (continued)

Hot Utilities	HP.C1.K2	280	279	220	217.6	60.697	1200	0.787	25.121
	Fuel.C2.K1	800	750	500	468.333	290.736	4750.05	0.811	20.145
Cold Utilities	H1.Water.K6	135.5	120	20	15	110.166	4650	0.5	84.418
	H2.Water.K6	199	120	20	15	138.699	19750	0.545	261.274
	H3.Water.K6	125	119	20	15	104.499	15000	0.524	273.935
	H4.Water.K6	117	30	20	15	43.897	17400	0.565	701.554

 Table I4
 The exact area calculation of case study 2 HENS (continued)

VENCLASSIN, VENCLAS en more i sont reals i anno more i sont fore i -----1212 nMu(1,2,8), construct, click, se(1,1,8), t\_meen(1), t\_freehilt,fill,fi, filt,fi, c\_men(1), <freehilt,  $\begin{array}{l} \begin{array}{l} \label{eq:selection} & \mbox{selection} & \mbox{selection$ ALLINGT (T) ALLINGT (T) ALLINGT (T) ALLINGT (T) ALLIENTS (8) BLIEBOW (7) ALLIENTS (2) BLIEBOW (7)(2)  $\begin{array}{l} \begin{array}{l} \label{eq:product} \mbox{Product} & \mbox{With} & \mbox{Product} & \mbox{With} & \mbox{$ 村山村山 四日田田町 細胞の細胞の細胞の 18-201 (J) 18-201 (J) 18-201 (J) 18-201 (J) 18-201 (J) 100124014 200115,01 200105,01 HELIPS (1) \*\*\*\* 2 100 12. CINET.

Appendix J Case Study 3: CHAMENS (Step 1)

Figure J1 Case study 3 CHAMENS for step 1.

(BL20) (2) (B220) (2) (B220) (2) (B220) (2) (B220) (2) (B220) (2) (B220) (2) (B220) (2) (B220) (2)	$\begin{split} & (2\pi) (g_1^{-1} \pi (x_1 - CH^2(g_1^{-1} (x_1) + m + m + m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - T)))) \\ & CH^2(g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - T) + m + m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - T))))) \\ & CH^2(g_1^{-1} (\pi (x_1 - CH^2(g_1^{-1} (x_1 - T) + m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - T)))))) \\ & CH^2(g_1^{-1} (\pi (x_1 - CH^2(g_1^{-1} (x_1 - T) + m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - T))))))) \\ & CH^2(g_1^{-1} (\pi (x_1 - CH^2(g_1^{-1} (x_1 - T) + m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - T))))))) \\ & CH^2(g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - m + m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - T))))))))) \\ & CH^2(g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - m + m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - m + m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - m + g_1^{-1} (x_1 - CH^2(g_1^{-1} (x_1 - CH^2(g_1^{-1$
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76.2015 (-1) PE.2015 (-2) PE.2015 (-2) PE.2016 (-2) PE.2016 (-2) PE.2016 (-2) PE.2017 (-2) PE.2016 (-2) PE.2016 (-2)	$\begin{array}{c} p^{2}_{2}(z_{1}^{2}, \eta_{2}^{2}) := \eta_{1}^{2} - p^{2}_{2}(z_{1}^{2}, \eta_{2}^{2}, \eta_{2}^{2}) := p^{2}_{2}(z_{1}^{2}, \eta_{2}^{2}, $
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Figure J2 Case study 3 CHAMENS for step 1 (continued).

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                                                                                                                                                                                              \begin{array}{l} \texttt{Reliming}_{1}(\tau_{1}, \sigma_{1}(\tau_{1})) & = , \ \texttt{Li}_{1}(\tau_{1}, \sigma_{1}(\tau_{1})) + \texttt{Rel}_{1}(\tau_{1}, \sigma_{1}(\tau_{1})) + \texttt{Rel}_{1}(\tau_{1}, \sigma_{1}(\tau_{1})) + \texttt{Rel}_{1}(\sigma_{1}(\tau_{1})) + \texttt{Rel}_{1}(\sigma_{1}) + \texttt{Re}_{1}(\sigma_{1}) + \texttt{Rel}_{1}(\sigma_{1}) + \texttt{Rel}_{1}(\sigma_{1}) + \texttt{Rel}_{1}(\sigma_{1}) + \texttt{Rel}_{1}(\sigma_{1}) + \texttt{Re}_{1}(\sigma_{1}) + \texttt{Rel}_{1}(\sigma_{1}) + \texttt{Rel}_{1}(\sigma_{1}) + \texttt{Re}_{1}(\sigma_{1}) 
                                                                                                                                                                                         \begin{array}{l} \mathtt{EQL}(\mathtt{R}_{2}(T_{1}, T_{2}^{-1} \mathtt{R}_{2}^{-1}) \rightarrow \mathtt{L}_{2}(T_{1}, T_{2}^{-1} \mathtt{R}_{2}^{-1}) \rightarrow \mathtt{E}_{2}(T_{2}^{-1} \mathtt{R}_{2}^{-1}) \rightarrow \mathtt{R}_{2}(T_{2}^{-1} 
                                                                                                                                                                                              \begin{split} & \texttt{EQLIM}([1,d],(\mathbf{E}^{1})) \to (\texttt{Le}(1,d_{1},(\mathbf{E}^{1}))) \ast \texttt{E}^{*}(\texttt{ETR}([1,(\mathbf{E}^{1}))) \ast \texttt{E}([1,d_{1},(\mathbf{E}^{1})])) \to (\texttt{ETR}([1,(\mathbf{E}^{1})))) \to \texttt{E}(\texttt{ETR}([1,(\mathbf{E}^{1})))) \to \texttt{E}(\texttt{ETR}([1,(\mathbf{E}^{1}))))
                                                                                                                                                                                         \begin{array}{l} \sup_{z \in \mathcal{L}_{2}} \sup_{z \in \mathcal{L}_{2}} \left( 1, 2, 2 \in \mathcal{L}_{2} + 2, 2 \in \mathcalL_{2} + 2
                                                                                                                                                                                         \begin{array}{l} \text{EGLING}(1,2,2^{+0,0(1)}) \rightarrow \text{EL}(1,2^{+0,0(1)}) = \text{E-}(110(1,2^{+0,0(1)}) + \text{E-}(1,2^{+0,0(1)})) \rightarrow \text{E-}(120(2,2^{+0,0(1)})) \rightarrow \text{E-}(120(2,2^{+0,0(1)})) \rightarrow \text{E-}(120(2,2^{+0,0(1)}))) \rightarrow \text{E-}(120(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)}))) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)}))) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)}))) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)}))) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)}))) \rightarrow \text{E-}(12(2,2^{+0,0(1)})) \rightarrow \text{E-}(12(2,2^{+0,0(1)})
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Figure J3 Case study 3 CHAMENS for step 1 (continued).

	EQLICI (1.3.) EQLIST (1.3.) EQCIVER (1.3.)	2011) Li Li J, J, 2011) - E× (CLE) L, 1011) - SEE (L, J, 1011) + − (CLE) J, 1011) + 22 (J, 1011) + 1 1011 Li J, J, J, 1011) - E× (SLE) J, 1011 - 1012 (J, 1011) + − (CLE) J, 1011) + 1 2011 Li J, 1111 - E× - Li J, J, 1111 - (T + 1 - 1012) + (T + 1 - 1011) + (T
	EQLINA(1,2,) EQLINA(1,2,)	$\begin{array}{l} (0.1) & = 1 \\ (1.1, 2.1, (1.1, 1) + 0 + (CER(1, 1, 0.1)) + 0.0((1, 2, 0.0(1))) \\ (0.1, 1) \\ = 1 \\ (1.1, 2.1, (1.1, 1) + 0 + (CER(1, 2, 1, 0.0(1))) \\ (1.1, 1) \\ = 1 \\ (2.1, 1) \\ (2.$
	EQCAVORT (1.5	Z, 1987)(2004) Z, Z, 1987) → C+ 11 (I, Z, 1987) / (502) (0, 001) II (I, Z, 1987) (1) /
	EQLIPT(I,J,) EQLIPT(I,J,) EQCAVORS(I,J)	$\begin{array}{l} B(1) & = 1, 1 \leq 2, 3 \leq 10^{-1} + 10^{-1} + 10^{-1} \leq 10^{-1} + 10^{-1} \leq 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1} < 10^{-1$
	CONJEL CONJEL CONTEL CONTEL	<pre>i COM2(SING1*,FE(*)+ M4(SING1*,FE(*)+ E_freen(SALE(*)+c_freen(SALE(*)))(mex(0.001), M2(SINE1*,FE(*)+E_freen(SALE(*))))=0=0; c) COM2(SINE1*,FE(*)+ M4(SINE1*,FE(*)+E_freen(SALE(*)+c_freen(SALE(*)))(mex(0.001), F2(SINE1*,FE(*)+E_freen(SALE(*))))=0=0; c) COM2(SINE1*,FE(*)+ M4(SINE1*,FE(*)+E_freen(SALE(*)))(mex(0.001), F2(SINE1*,FE(*)+E_freen(SALE(*))))=0=0; c) COM2(SINE1*,FE(*)+ M4(SINE1*,FE(*)+E_freen(SALE(*)))(mex(0.001), F2(SINE1*,FE(*))))(mex(0.001), F2(SINE1*,FE(*))))=0=0; c) COM2(SINE1*,FE(*)+F4(SINE1*,FE(*)+E_freen(SALE(*)))(mex(0.001), F2(SINE1*,FE(*))))(mex(0.001), F2(SINE</pre>
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Figure J4 Case study 3 CHAMENS for step 1 (continued).

#### Appendix K Result: Case study 3 CHAMENS (Step 1)

425 VARIABLE me, 1 Reat exchanged between hot I and cold J K1 82 23 K4 K5 SOURCE1.SINK2 0.0224 2.123621E-5 250.1763 0.0011 16.4485 SOURCEL.SINK3 106.3585 0.0011 9.4202328-5 SOURCEL.SINK4 6.3697512-6 2.0298 0.0075 SOURCEZ.SINK2 67.9922 SOURCE2.SINK4 0.0075 SOURCE3.SINK2 31.0000 SOURCES.SINKS 3.1652 SOURCES.SINK4 35.0000 0.0002 SOURCE4.SINK2 0.005€ SOURCE4.SINK3 0.0055 10,0000 SOURCE4.SINK4 K€ ..... 87 109 SOURCE1.SINK4 66.8924 49.0486 39.0139 ---- 429 VARIABLE f\_waste.L SOURCE3 1060.8147, SOURCE4 25.9000 ---- 428 VARIABLE I fresh.L SINK1 350.0000; SINK2 327.8035 ---- 428 VARIABLE f waste.L SOURCE3 1060.8147, SOURCE4 25.9888 ---- 428 VARIABLE f\_fresh.L BINK1 350.0000; SINK2 327.8035 ---- 428 VARIABLE TAC.L 246.9407 Total Annual Cost . EXECUTION TIME - 0.016 SECONDS 3 MB 24.2.1 143572 WEX-WEI G131219:2228AS+WIN USER: The Petroleum and Petrochemical College Chulalongkorn University DC4365 License for teaching and research at degree granting institutions \*\*\*\* FILE SUNMARY C:\Users\Eleopora Amelia\Desktop\codel.gms Incut C:\Users\Eleonora Amelia\Documents\gamsdir\projdir\codel.ist Output

Figure K1 The result of case study 3 CHAMENS for step 1.

# Appendix L Case study 3: CHAMENS (Step 2: Process Heat Exchanger at EMAT 35 °C for $N_{op}=1$ year)

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I wild straws will B Brage BA. 1951	102 (C3
and and a second se	
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**Figure L1** Step 2 the process heat exchanger network at EMAT 35 °C for Nop= 1year case study 3 CHAMENS.

sunit:	085	AND ADDRESS PRODUCTION AT ANY TAXA -
	PETRI (T)	Temperature superstructure Feasibility of not erreas
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	PETROLEI	Temperature superentiation Teachtliby of his stress
	PEDRO (T)	Temperature superstructure feasibility of bit stream
	PE107(1)	Temperature superstructure Insalitability of the stress
	PEIRS(I)	Temperature experiences feasibility of but stream
	PE-2011-0-21	Temperature superstanture Testinitity of bit stand
	P8-282 (-7)	Temperature superstructure freshelling of only stress
	38-383 (2)	Temperature experiences Taxaibility of mill ences
	PE-2014 (-2)	Temperature superstructure feasibility of only stream
	#16-290-8 (-2-y	Temperature superstructure feasibility of only worked
	P2.287 (2)	Temperature superstructure feasibility of mild stream
	FE.265 (2)	Temperature augerationships fraanstiling of mild arread
ř .		
	PERSONAL (E)	AL(1, (1)) -D* EL(1, (17))
	FEIR3(I)	TA(I, 'KI') -0- TA(I, '#1'))
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	TRIDE (T)	- Boot (Bot)
	FE287(2)	HA(1, 'HT') -OF HA(1, 'HU') (
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	That Pills	
	75-763 (2)	x2(4)(1011) -00 x2(4)(101)
	TE.003 (2)	#1(4,+0)+) +5# #1(4,+Ex+))
	12/2010 (21)	#312, *#811 -Ge #312, *#8*117
	75,000,101	1 11 10, 10, 10 1 -0 11 10, 10 11, 10 11, 10
	191.097 1-71	MINT, MINT -Ge 1217, MINT
	PE-288 (-7)	x1(2)(401) -0.0 x2(2)(401))
-	and a second	ALL
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R.1.1	11021,10211	- 1 2017 
14/3	1"83", "83"	43301
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11.1	1.821	*20,886)
		107
81.1	ALBERT THEY	41.000
84.2	ATMET, THEFT	-50.554
21-1	THE TREE	*1801 *1801
11.1	ATRA- PRI-1	+00.4041
C-3	STRATATED A	-1291 
14.1	1"RX-, *B4"+	+80.400
1.5	Table Trade	
and a	COMPANY OFFICE	-2004
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1.1	Association in the second	
AL.1	ATRAC, SHALL	whet point
14-1	1.81	~00,50U
Sec.5	THERE MADE	*13//
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12.3	(	
1.13	ATTAC PROPERTY.	-1(0.000)
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22.4	(*09*,*819*)	- 84 Jan 27
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83.I	1"CA", "K15"1	=11.00W
52.3	1,000,000,000,000	-43,9997
12-3	STORY TRADES	*L10.3003
1213	Contra Males	4441444
\$2.1	11011-1100-1	*#1,000;
22	(1021,1048)	**£2.0871
51.1	(*CA1 - 195-1	- Hall - Childy -
12-4	1101, 1811	-88,0004
12-1	11001-1001	+21-000
22.1	faller's (RSa)	+£2, 955;
14	1128-1128-1	-35,000
214	(***********	~#5.6431
10.1	11231 1881	*23.040/
1.1	August and a second	~40,000)
12.4	ATTAL SECTO	-21,000
37-1	1.221. 180.1	+4.1.0001
82.4	1.Ch.*	*239,000,
12.4	Association of	-25,0001
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12-4	Talifa Mout	-62.8977
12-1	ALCONT, SPECIAL	-47, 0004
82.3	1128- 1891	+30,000y
17.1	1-281, 1877)	*E1.0004
12.1	Typical Aller	-88.0007
and the second se		

**Figure L2** Step 2 the process heat exchanger network at EMAT 35 °C for Nop= 1year case study 3 CHAMENS (continued).

83-5	17517, "BRIT	#88,8000 #42,8875
83-3	1.25	-21,000
\$3.3	11081218813	=10,000, +00,000
31+4	("CHT_TRATE	=E1.000/
83.3	11271, 18874	-41,0004
53.3	1.234 * ME.1	-11-1000
	112-11.00011	
11.1	11521-18171	*\$2,8973
\$1.5	11231-18313	=12, 25hy
83-8	("120", "#8")	*89,0990, *84,0004
\$2.4	F+C#+*+K2+3	=Z1, U9W/
12.1	11201-11211	-\$8,000s
\$2.4	ALCON	*98.090 <i>3</i>
in the	distanti -	+41, 100 V
13-4	17221-478874	+62,007/
12.4	1.23.******	*28,000/
53+4 53+4	1*05***#8**	+24,7997
27.1	(10K1+1841)	=21,0597
11.1	42057, 18871	-128, 3000/
\$3.5	11281, 18811	-28.9997
62.3	TAPLE, SPECI	-ts. 505.
83.1	1-11 HEAL	*42,897).
\$2-4	(.c. +.e.)	*24.0400 #80.7000
33.4	11011, 183-1	=20,000/
45+3	11082-1851	=25,000/
82.5	11231 1231	+L30,806/
87.18	C-29+2-81+1	-34,000j
1.00	VICE AND A	with June .
\$3.5	("23"+"82")	-55,0001
11.1	11231, 0211	-91.0007
13.5	101-1021	=82,000/
NJ-A	11007 18211	*85.8004
83.3	1101-11010	-98,0201 +130,0001
13.1	11081-10011	-31,000J
		with limits
83+L	(101-,-101-)	-98,0001
\$3.2	PARTY ARTA	-68,0004
83.5	175512 18311	- 80,0007 #68,0004
\$3.3	1-01-151-1	-94,000/
24	11011-11011	=50,0002
\$1.1	(*08*,*007)	-21,048)
		ministry has not had an only manifest
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NUCATI	LegistJR111, LegistJR111, Mattri (1) Mattri (1) Mattri (2) ReflyT (2) Mattri (2)	<pre>20 q01.2. V0.0')-0000A13(1.2)'0(1.0, V0.0') +(* 0)  q00(1)-0p0(1)'1'000(1) +(* 0)  q00(1)-0p0(1)'1'000(1) +(* 0)  q00(1)-0p0(1)'1'000(1) +(* 0)  q00(1)-0p0(1)'1'000(1) +(* 0)  q00(1)'0(1)-000(1) +(* 0)  q00(1)'1'000(1) +(* 0)*(* 0)  q00(1)'1'000(1) +(* 0)*(*</pre>
RUCATO	LegistJR11(1) LegisTJ2(2) MettyT(1) MettyT(1) MettyT(2) MettyT(2) MettyT(2) MettyT(2)	<pre>21 q17.2. '02.0')-OBEAD312.2.1'017.0.4'010') +(* 0)  gmail-Ope3/2)'100007</pre>
NUCATI NUCATI	LegistJMIN(2) LegistJJ (2) LegistJJ (2) MULTI (1) MULTI (1) MULTI (2) MULTI (2) M	<pre>21 q(1, 2, '0.0')-OBENII(1, 2)'s(1, 3, '0.0') + &lt;= 0;  que(1)-Que(1)'s(0.0') + &lt;&lt; 0;  que(1)-Que(1)'s(0.0') + &lt;&lt; 0;  que(1)-Que(1)'s(0.0') + </pre>
RUCATO	Logistoria) Logistoria (2) Logistoria (2) million million (2) million (2) Mil	21 q17.2. "Via":-CHEMEATICL.2:"4(1, 8, "Kid": +<** 0) questi -Cparit/1*100017 via": 4-* 0) questi -Cparit/1*100017 via": 4-* 0) questi -Cparit/1*1000000 via": 4-* 0) questi -Cparit/1*100000000000000000000000000000000000
RUGATO	Legislari, (J) Legislari, (T) Legislari, (T) Martin (T) Martin (T) Martin (T) Martin (T) AppTempH1 (T, 4 AppTempH1 (T, 4 AppTempH2 (T, 4) AppTempH2 (T, 4)	<pre>20qt1.2. 'Via''-OBSAUDIL2(1,2)'E(1,3, 'Via''-OSE AU quall-Oparit/1'Ean(1)</pre>
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RUCATO	Legislari, (J) Legislari, (J) Legislari, (J) Martin, (	21 qtf.2. (%2.*)OBSENDIG.2(1.2)*GTT.8. %2.*) queid)-Operit/1*Instif. queid)-Operit/1*Instif. queifir-Operit-Operit/1*Instif. queifir-Operit/1*Instif. queifir-Ope

**Figure L3** Step 2 the process heat exchanger network at EMAT 35 °C for Nop= 1year case study 3 CHAMENS (continued).

	AppTempH1(1,7) AApTempH1(1,7) AppTempH1(1,7)	Approach temperature 12 at state K1 The other explosit temperature 12 at Approach temperature 15 at state K2	a prage Mi	
	MapTempH (1, 3) AppTempH (1, 3) MapTempH (1, 3) AppTempH (1, 3) AppTempH (1, 3) AppTempH (1, 3) AppTempH (1, 3)	The other represent temperature is an approach temperature is an energy $k_{\rm Z}$ . The other approach temperature is a target $k_{\rm Z}$ and there approach temperature is a target for the approach temperature is an approach temperature is at any $k_{\rm Z}$ .	i Filipi Ri 1 Jilipi Ri 1 Jilipi Ri Manje Ri	1
	beatin (1,4,8) Horasi(1,3,8) Units	DSI melejzajel		
-	АррТинця́ (1,.1) МарТинця́ (1,.1) АррТинця́ (1,.1) МарТинця́ (1,.1) МарТинця́ (1,.1)	$\begin{array}{llllllllllllllllllllllllllllllllllll$	$\begin{split} & \xi_{1} = (2\xi_{1}, \tau_{1}) + e E(\xi_{1}, \xi_{1}) + e \xi_{2} - e + (T_{1}, T_{2}, -\eta_{2}) + (1) \\ & \xi_{2} = (2\xi_{1}, \tau_{1}) + e E(\xi_{2}, \xi_{2}, \tau_{1}) + (1) + e + (T_{2}, -\eta_{2}) + (1) + (1) \\ & \xi_{2} = (2\xi_{1}, \tau_{2}) + (2\xi_{2}, \tau_{2}) + (\xi_{2}, \tau_{2}) + (1) + (1) + (1) \\ & \xi_{2} = (2\xi_{2}, \tau_{2}) + (2\xi_{2}, \tau_{2}) + (\xi_{2}, \tau_{2}) + (2\xi_{2}, \tau_{2}) + $	1
	AppTroupE3 (1, 2) AbpTroupE3 (1, 2) AppTroupE4 (1, 2) AbpTroupE4 (1, 2)	$\begin{array}{llllllllllllllllllllllllllllllllllll$	$\begin{split} & \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + 1 \right) + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \\ = \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \left( \frac{\pi (1)}{2} + \mathcal{I}_{2} \right) \right) \right) \right) \\ = \mathcal{I}_{2} \left( \pi ($	
	AppTeepE3 (1, 4) AdpTeepE3 (1, 4)	$\begin{array}{rcl} &=& (1,1,1,1) & (1,1)$	$\begin{split} \mathbf{f}_{1} &= (\mathbf{T}_{11}, \mathbf{f}_{11}) + (\mathbf{T}_{11}, \mathbf{f}_{12}) + (\mathbf{T}_{11}, \mathbf{f}_{12}, \mathbf{T}_{12}) + (\mathbf{T}_{11}, \mathbf{f}_{12}, \mathbf{T}_{12}) + (\mathbf{T}_{12}, \mathbf{T}_{12}, \mathbf{T}_{12}) + (\mathbf{T}_{12}, \mathbf{T}_{12}) + (\mathbf$	
	1085 et (1.7,8)	m(1,7,8) -> max;		
	$dtrack(\Sigma, \mathcal{Z}, \theta)$	ans (1, 2, 8)		
	gan.			
84(4) 84(4) 84(4)	the last that (1)=0.13, 22- the last fact (1)=0.12, 22- the model b at (1)(2)=00	the coefficient of the hos science ( 1.5. (200-10) offse medicated of the said street ( 1.5. (200-10) (200-10) (1.5.) (201-10) (200-10) (200-10) (1.5.) (201-10)	in the sharp glant in the same glant (The data cost of costs of costs) sector(s)	
MARIANIA LINTO (1, ) Right (1, ) Right (1, ) Right (1, ) Right (1, ) Li (2, ), 1	1, 8) 5 1, 8, 8 1, 8, 8 1, 8 1, 8 1, 8 1, 8 1,			
EqLi (L, ) EqLi (L, )	C (, ), , , , , , , , , , , , , , , , , ,	$\begin{array}{l} & = 1 + (1_{11}, (1_{11}, 0_{11}) + (1_{12}, 0_{11}) + 23\Delta_{11}^{2} (1_{12}, 0_{11}) + (1_{12}, 0_{12}) \\ & = 42 + (1_{12}, (1_{12}, 0_{12})) + (1_{12}, 0_{12}) + (1_{12}, 0_{12$	(1, 2, 20) 1 * * 8(, 3278) 1 * 4 (2, 4, 5 + 2) * * 4, 3278) (1 / 8 - 3273) (	ł
11.10(T. 12.10(T. 12(T).10)	$(d_1 R) = ESERT(+),$ $(d_2 R) = ESERT(+),$ $(T_1 J_2 R) = ESERT(-),$	12757 12757		
Nariatio As j Roberton Astactor Astactor		*** ****(11,7,8),33854(1,7,8)//		
BAUAUMETTS	ALPES COLOR	ors metficient for mild stilling any institutes for mild stilling any institutes for bod utiling any metficient process according any metficient for using any metficient for using any metficient for balance processed according (pent)	2 200 2 200 2 200 2 200 2 200 200	
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11,12706		(\$,\$,\$),\$(\$,\$,\$))		
(1/90#)*	(C#+### ( (X, #, #)	(0000.017, 0, 0()))		1

**Figure L4** Step 2 the process heat exchanger network at EMAT 35 °C for Nop= 1year case study 3 CHAMENS (continued).

Roffecha Rres.1	1 2000 · · · ·			
Ar**.1				
Ar**.1		4.00		
Ar**.1 q.1				
4.1	4*85*, *25*, *85*¥	-0604.8702		
0.0	(7831,1221,1251)	-7828.9111		
and a second	("BAT, "GET, "BATA	=1/		
9	Construction of the local division of	Cast Cast		
Arenit	Viel', cearlings,	-328-1291		
94	ATRL'STORT, TRATE	-263.405f		
HAL.	durit contrast.	-11 ·		
1.0				
Aces.1	31831,1011,18813	+1382.9297		
q.1	6-121-1-121-, -WA-1	-4440,0421		
4.4	("BAT, "CLT, "MAT)	411		
4.00				
Ares:1	11027-1221-1011	+0653.300 A		
1.1	11021-1011-10211	*0452.8001		
1,1	19821, 1021, 18771	+1/		
Sec		THE R. LANS.		
Aces. 1	("HI", "ET", "HZ")	-5680.1091		
1.1	(-101-, -CL-, -102-)	*7743,9402		
	ton for a deal	745		
Aces.1	11031-1041-10211	+44914,0552		
4.1	4"H3", "C#", "#271	+41048,7881		
z.1	11831,1067,18211	-11		
	delete alter slater	antidia anti-		
0.1	distant sizes against			
1.1	(1983). 1081. 10811	*17		
	a construction of the second			
14				
Ares.1	(Helm, ream, rise)	+280217241		
404	1.4834.44234.48244	~1314,000)		
#+1-	(100), 100, 100, 100, 11	*11		
Sees.T	1100 - 1200, 100 M	*20473.7241		
t.).	11831,1031,1031	-17814,8052		
6-5	(1801,1001,1801)	~1r		
BEN-1/18	1'1+781.6193 3'1+80264,7403			
m	3*}=1031,480;			
Q011-311-2	3 1 1 - 6 5 - 7 0 0 2			
A 10.00	STLEED 0.4951			
abell, Law	Traw13700.680 -			
1011-24+0	3*3=32848.730/			
gtm.1(*2	31)=33,280;			
ACLVE ICA	SERTUDY: USING MIN	F REPERTING T	E)	

**Figure L5** Step 2 the process heat exchanger network at EMAT 35 °C for Nop= 1year case study 3 CHAMENS (continued).

#### Appendix M Case Study 3: CHAMENS (Step 2: Process Heat Exchanger)

DIFFEASURE 0 THROSHED 0 EREGS GAUS 34.2.1 r4372 Released Dec 9, 2013 WEE-WEI #14\_64/HS Windows 04/15/20 07:31:40 Rege 7 0 # N = F # 1 A 1 g = 3 F # 1 C N = 6 = 1 A g 3 F # 5 = 8 E # + 6 = 5 1 C N ---- 540 VRAIABLE pro.L Cold utility matching with hot I M1 1.000, M3 1.000 140 TREIREE shull Bet utility matching with cold 2 Ci 1.000, Ci 1.000, Ci 1.000, C4 1.000, C8 1.000, C8 1.000 C7 1.000, C8 1.000, C9 1.000 140 PARAMETER 0 the overall heat transfer coefficient of each heat each anget c2 01 03 040 C1 0.06 0.025 0.028 0.028 0.028 0.029 0.028 0.028 0.025 0.025 0.025 0.025 0.025 0.025 0.025 0.028 8.025 N1 N2 N3 -C8 .09 . 0.028 0.028 0.025 0.025 0.025 0.025 0.025 N1 和 約 540 VERIABLE w.L. Eschanger matching between hot I and cold J at stage & 87 10 N2.C1 N3.C1 N3.C3 N3.C3 N3.C3 N3.C3 N3.C3 N3.C3 N3.C3 1.099 1.000 1.000 1.000 1.000 1.000 1.000 1.000 540 WARRANE g.L. Meat exchanged between hot I and cold J 83 87 89 82.61 83.61 83.63 83.63 83.63 83.63 83.65 2452,800 4440.042 7429.776 18013.444 1314.000 44204.710 41045.755 7743.840 545 VARIABLE gou.L. Reat exchanged between cold utility and bot 1 R1 1014.773. R3 80214.740 AND VARIABLE GOR.L. - #1209.818 Total cold utility ---- 540 VERIABLE gbu.1 Nest exchanged between hot utility and cold J C2 1031.490, C8 48.700, C4 258.405, C5 65400.408, C6 81034.884 C7 13700.440, C8 3849.730, C9 33.288 NATABLE Ghr.L VARIABLE TAC.L IS\$419.745 Total hot utility
 7437527.436 Total Annual Cost 540 VARIABLE St.L. Approach temperature 81 82 83 104 N1-01 N1-03 24,000 25,000 25,000 35,000 35,000 35,000 35,000 35,000 10.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 38.000 36,000 38,000 38,000 38,000 38,000 38,000 38,000 38,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 N1.08 N1.09 N2.01 N2.02 N2.03 38,000 35,000 25,000 38,000 38,000 38,000 38,000 38,000 38,000 38,000 38,000 28,000 28,000 28,000 28,000 28,000 28,000 28,000 39,000 39,000 39,000 39,000 N2.03 N2.04 N2.03 N2.03 N2.03 N2.03 N2.03 N2.03 N2.03 38,000 38,000 35,000 38,000 38,000 35,000 35,000 35,000 38,000 82.01 35.000 33.000 38.000 25.00 NJ.C1 NJ.C3 NJ.C3 NJ.C4 NJ.C5 NJ.C5 NJ.C5 NJ.C3 NJ.C3 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 38,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 35,000 15.000 15.000 15.000 15.000 15.000 15.000 15.000 15.000 15.000 85,000 35,000 35,000 35,000 37,443 38,000 35,000 15.000 15.000 25.000 25.000 25.000 25.000 25.000 25.000

**Figure M1** The result case study 3 CHAMENS of the process heat exchanger for the step 2.

	87	63	89	610		
181.02	15,000	25,000	18.000	15,005		
10.03	\$5.000	35.000	35.000	30.000		
81.03	38,000	36.010	38,000	30.000		
83.64	38,000	38,900	35.000	38.000		
12.03	35,020	15,000	35,000	35.000		
81,67	35,000	85,000	35-000	38,000		
81.00	\$5,050	a5.000	38.000	38,000		
84.09	38.000	35.000	35.000	30.000		
36.01	18,000	391050	36,000	ME.000		
MI.CI	35,000	35,900	35,000	38.000		
82.08	25,000	25,000	38.000	38.000		
82.05	55,000	88,000	58.000	35.000		
H2.Ce	28.000	\$5,000	55.000	38.000		
RI,CT	25.000	10,1040	33.000	38.000		
RI.CH	88,990	88,020	88,000	88.000		
82.09	55,290	28,000	35,1990	321999		
83.05	85.000	86,000	86,000	85,000		
83.03	55,000	85.000	35.000	35,000		
185.04	35,000	35.000	35.000	38.000		
081.08	361040	35,010	30,000	38+000		
10.04	85,7000	36,000	38.000	30,400		
10.0.07	55,990	28,000	35.000	38.998		
101.07	15,000	85.000	38.000	15,000		
	140 YARIAN	AR SHELD BE	HAL REPORT	Tesporators		
	61	12	83	101	25	10
in an						
101-02	16.100	25,000	78,000	75,000	75,000	75.000
84.63	34,000	88,0000	81,000	88.004	80.000	63.040
81.09	88,000	#6,000	85,000	88.000	98.000	\$4.000
\$1.05	16,000	36,000	100.000	100.000	100,000	100.000
81-00	85.000	85.000	105.000	105.000	199,000	109.000
181.75	25.000	35,000	85.000	88,000	37.000	33,000
10.11	76.000	78,000	78.000	10.000	18,000	13.000
107.02	29,020	34,000	87,981	87.391	97.391	\$71.843
82.03	35,000	35,000	95.000	96.000	95,000	95,000
112.04	95,000	\$5,000	\$5.000	95.000	99.000	95.000
102.00	56,000	28.000	300.000	100.000	100.000	100.000
82.07	35.000	55.000	87.000	ET.000	87,800	\$7.000
10.09	85,000	99,000	85.000	88.000	99,000	98.000
REAL	Th. 200	TR.000	28.44%	28,448	21, 11)	23.443
#3.52	35,000	26,000	35,039	38.039	35.074	31.084
85.08	16.000	\$6.000	85.243	45.449	45.242	45.643
35.04	\$5.000	85.000	85.643	82.683	45.643	401643
101.04	38,000	84,000	20.042	10.445	30.443	10,001
33.07	35,000	38,000	27,643	27.642	37.693	37.641
183.02			-48.337	-98.387	-17.237	-49.087
183.59	86.000	96.000	85.843	39-40	45.643	45.80
	17		75	#10		
MILCH	10,000	84,987	309.000	1091000		
81.12	87.391	17,381	109.000	100.000		
William .	95,000	\$5,000	35,000	88,000		
183-25	100,000	100.000	300.000	300.008		
11.05	1691000	109.050	108.000	159.000		
TLICT	17.950	111000	87.020	87.009		
81.09	88,000	85-000	85,000	82,000		
ML CR	19,000	52,237	77,000	77.999		
12.13	95.000	85,000	88.000	82.900		
82-04	95.000	88.000	\$5.000	83.000		
182.05	100.000	85,000	80,000	88.000		
00.04	109.000	17,000	11.000	97.000		
182.05	617.000	- 32,400	-12.000	-32.000		
101.09	+4,000	63,000	\$2,000	63,070		
189.01	28.693	29.000	55.247	50.441		
83-53	82,029	88.038	52.447	50.447		
83.03	451442	83.643	55.447	191447		
#3.04	40.643	85.643	39.847	39.647		
RS.CO	50,043	00.043	85.647	83.847		
\$3.07	27.642	11,611	11.597	31,397		
83.28	-41.337	-46.337	-55.325	-45.832		
185.09	45.643	45,043	36.847	36,447		
	NYO VAREA	LE TALL THE	TH PAUTON PR		as jos and	
	35	72	23	21	10	
121	170.000	430.000	190.000	130.000	210,000	100,000
112	139.009	130,000	199.000	1,80,000	140,100	129,920
83	139.000	139.000	80.898	80,852	10.493	55.493
	191	25	23	121		
W.)	180,050	150,000	LAN, DOG	190.000		
Ha	199,000	98,000	\$H.000	89,000		
16.3	27.643	80.843	78.887	78,947		

**Figure M2** The result case study 3 CHAMENS of the process heat exchanger for the step 2 (continued).

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	540 TARIAS	SLE 13.1 Tes	to eroferrep	oold stream	3 at hot and	i of stage
	81	82	83	214	25	ze.
				** ***		** ***
CL.	\$5,000	55.000	\$5.000	55.000	\$5.000	\$5,000
	95,000	99.000	42,009	42.409	42,609	42.409
	95.000	99.000	35,000	39,000	35,000	35.000
04	35.000	35.000	35.000	35.000	35.000	35.000
C5	95.000	95.000	30,000	90,000	30,000	30.000
C6	95.000	95.000	21.000	21.000	21.000	21.000
29	95,000	95.000	\$3.000	43.000	43.000	43.000
0.0	130,000	130.005	130,000	130,000	130,000	130,000
0.9	35,000	35.000	35.000	35.000	35.000	35.000
	87	82	2.5	#10		
C1.	\$5,000	45.643	21.000	21.000		
	62.009	42.609	21,000	21.000		
2.8	35.000	35.000	35.000	35.000		
24	35.000	35.000	35.000	35,000		
CS .	30,000	30.000	30.000	\$0.000		
06	21,000	21.000	21,000	21.000		
C7	43.000	43.000	43.000	43.000		
20	130.000	230.000	130.000	130.000		
6.0	35.000	35.000	35.000	35.000		
	542 VARIA	LE q.L. Heat	exchanged b	etween bot I	and cold 2	
	82	87	11			
M2.C1		2492.000	9			
#3.01			6460.042			
43.02	10013.644		7829,776			
13.03	1318.000					
83.05	\$6206.810					
83.CE	\$1045.758					
83.CT	7743.040					
	542 VARIAN	LE LL.L				
	81	82	13	24	25	
#1.C1	3,294	3.204	3.204	3.204	3.204	3.2
#1.C2	3,204	3.204	3.204	3.204	9.204	3.2
81.03	3,204	3.204	3.204	3.204	3,204	3.2
10.15	3,204	3.204	3.204	3.204	3,204	3.2
81.05	3,204	3.204	5.204	3.204	3.204	3.2
11.04	3,204	3.204	3,204	3,204	9,204	3.2
11.07	3,204	3,204	3.204	3,204	3,204	3.3
1.08	3,204	3,204	3.204	3,204	5,204	3.2
41.74	3.354	3 304	8 2.04	5 204	5 204	1.1.1
Railly	31404	3.204	3.404	3.204	2.204	
Berne -	81205	31204	2.208	3.204	3.204	
ta cue		2.204	3.208	0.004		
12.03	31204	3,204	81494	3.299	31204	3.4
82.04	3.204	3.204	3.204	3,204	3,204	3.2
82.05	3,204	3.204	3.204	3,204	3,204	3.2
82.06	3,204	3.204	3.204	3.204	3.204	3.2
82.07	3.204	3.204	3.204	3.204	31204	3.2
82.CS	3.204	3.204	3.204	3.204	31204	3.2
12.09	3.204	3.204	3.204	3.204	3.204	3.2
10.69	3,204	3,204	3,204	8,204	3,204	8.3
13.02	4.770	3,204	3,204	8,204	3,204	
13.02	4.770	3.204	3.574	2.201		
13.03	3,204	3.204				
13.04				3,204	3,204	3.2
R3.C5	3.204	3,204	3.204	3,204 3,204	3,204	3.2
	6.345	3,204	3,204	9.204 9.204 5.204	3,204 3,204 3,204	3.1 3.1 3.2
13.06	5.204 6.345 6.411	3.204 3.204 3.204	3.204 3.204 3.204	9,204 3,204 3,204 3,204	3,204 3,204 3,204 3,204	3.1 3.1 3.2 3.3
83.CE	3.204 6.345 6.411 6.240	3.204 3.204 3.204 3.204	3.204 3.204 3.204 6.268	3.204 3.204 3.204 3.204 5.945	3,204 3,204 3,204 3,204 4,112	9.3 9.3 9.3 9.3 8.3
83.C6 83.C7 83.C8	3.204 6.345 6.411 6.248 3.204	3,204 3,204 3,204 3,204 3,204	3,204 3,204 3,204 4,268 3,204	3,204 3,204 3,204 5,204 5,945 3,204	3,204 3,204 3,204 3,204 4,112 3,204	3.3 3.3 3.3 6.3 3.2
83.06 83.07 83.08 83.09	3.204 6.345 6.411 6.248 3.204 3.204	3,204 3,204 3,204 3,204 3,204 3,204 3,204	3,204 3,204 4,248 3,204 4,248 3,204 3,204	5,204 3,204 3,204 5,945 3,204 3,204 3,204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.1 3.2 3.2 6.2 3.3 3.3
13.06 13.07 13.05 13.05	3.204 6.345 6.411 6.240 3.204 3.204 87	3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 4.248 3.204 3.204 3.204	5,204 3,204 3,204 5,204 5,204 3,204 3,204 3,204 8,204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.3 3.3 3.3 6.2 3.3 3.3
H3.C6 H3.C7 H3.C8 H3.C9 H3.C9 H3.C9 H3.C1 H1.C1 H1.C1	3.204 6.345 6.411 6.248 3.204 3.204 87 5.204 5.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 825 825 3.204	3.204 3.204 3.204 4.246 3.204 3.204 83 83 83 5.204	3,204 3,204 3,204 5,945 3,204 3,204 3,204 #10 5,204 3,204	3,204 3,204 3,204 6,112 3,204 3,204 3,204	3.3 3.2 3.2 6.2 3.2 3.2 3.2 3.2
H3.C6 H3.C7 H3.C5 H3.C5 H3.C5 H3.C5 H3.C5 H1.C1 H1.C2 H1.C3	3.204 6.345 6.411 6.240 3.204 87 3.204 87 3.204 3.204 3.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 82 82 3.204 3.204 3.204	3,204 3,204 4,246 3,204 3,204 3,204 83 83 3,204 83 3,204 3,204 3,204	3.204 3.204 3.204 3.945 3.204 3.204 3.204 8.204 8.204 3.204 3.204	3,204 3,204 3,204 4,112 3,204 4,112 3,204	3.3 3.3 6.2 3.3 6.2 3.3 3.3
13.06 13.07 13.08 13.09 14.01 14.02 14.02 14.03	3.204 6.411 6.248 3.204 3.204 87 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 4,264 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 3,204 4,122 3,204 4,122 3,204 3,204	5.3 5.3 5.2 6.3 8.2 3.2 3.2 3.2
13.06 13.07 13.05 13.05 13.05 14.05 14.05	3.204 6.345 6.411 6.249 3.204 87 3.204 87 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3,204 3,204 4,246 3,204 3,204 3,204 85 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 8.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	8.2 3.2 3.2 8.2 8.2 3.2 3.2 3.2
10.06 10.07 10.08 10.09 10.09 10.09 10.09 11.01 11.02 11.03	3.204 6.345 6.411 6.248 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3,204 3,204 4,266 3,204 3,204 3,204 85 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.2 3.2 3.2 6.2 3.2 3.2 3.2
11.01 11.02 11.02 11.02 11.02 11.02 11.02 11.02 11.03 11.04 11.05 11.05	3.204 6.345 6.411 6.240 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 4,246 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 4.112 3.204 3.204	3.3 3.3 3.3 8.3 8.3 3.3 3.3
11.01 11.03 11.03 11.03 11.03 11.03 11.04 11.04 11.04 11.05 11.05 11.05	3.204 6.345 6.411 6.248 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 4.246 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 4.204 4.122 3.204 3.204	3.1 3.1 3.2 3.2 4.2 3.2 3.2
H3.06 H3.07 H3.08 H3.05 H1.01 H1.02 H1.02 H1.04 H1.06 H1.06 H1.07 H1.06	3.204 6.345 6.431 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 4,246 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 4.112 3.204 3.204	3.1 3.1 3.2 3.2 6.2 3.2 3.2 3.2
H3.06 H3.07 H3.08 H3.09 H3.09 H1.01 H1.02 H1.03 H1.05 H1.06 H1.05 H1.05 H1.05 H1.05 H1.05 H1.05	3.204 6.345 6.411 6.249 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 3,204 4,246 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 4.112 3.204 3.204	3.1 3.1 3.1 3.2 6.1 3.2 3.2 3.2
H3.06 H3.07 H3.05 H3.05 H1.01 H1.02 H1.02 H1.03 H1.04 H1.05	3.204 6.345 6.411 6.249 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 4.112	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 4,268 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 4.112 3.204 3.204	3.1 3.1 3.2 3.2 8.1 3.1 3.1
H3.06 H3.07 H3.08 H3.05 H3.05 H1.01 H1.03 H1.03 H1.05	3.204 6.345 6.411 6.240 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 4,246 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.1 3.1 3.2 3.2 8.1 3.2 3.1
H1.01 H1.02 H1.03 H1.03 H1.03 H1.04 H1.05 H1.06 H1.05 H1.06 H1.05 H1.06 H1.05 H1.06 H1.05 H1.06 H1.05 H1.06 H1.05	3.204 6.345 6.411 8.248 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204 3.204	3.204 3.204	3,204 3,204 4,246 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.1 3.1 3.2 3.2 3.2 3.2 3.2 3.2 3.2
11.01 11.011	3,204 6,345 6,411 6,248 3,204	3,200 3,204	3,204 3,204 4,265 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.1 3.1 3.2 3.2 3.2 3.2 3.2 3.2
13.06 13.07 13.05 13.05 13.05 13.05 14.05	3,204 6,345 6,411 6,249 3,204	3,204 3,204	3,204 3,204 4,266 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.1 3.1 3.2 3.2 3.2 3.2 3.2 3.2 3.2
83.06 83.07 83.05 83.05 81.01 81.02 81.03 81.05	3,204 6,345 6,411 6,248 3,204	3,200 3,204	3,204 3,204 4,265 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.1 3.2 3.3 3.3 3.3 3.3 3.2 3.2
H1.C1 H1.C1 H1.C2 H1.C3	3,204 6,345 6,411 6,249 3,204	3.204 3.204	3,204 3,204 4,266 3,2043	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.1 3.1 3.2 3.2 3.2 3.2 3.2 3.2 3.2
83.06 83.05 83.05 83.05 83.05 83.05 83.05 83.05 84.056	3,204 6,345 6,411 6,248 3,204	3,200 3,200 3,204	3,204 3,204 4,265 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.1 3.1 3.3 3.3 3.3 3.3 3.3 3.3
85.06 85.05	3,204 6,345 6,411 6,249 3,204	3,204 3,204	3,204 3,204 4,266 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204	3.1 3.1 3.1 3.2 3.2 3.2 3.2 3.2
8.06 8.07 8.07 8.07 8.07 8.07 8.07 8.07 8.07	3,204 6,345 6,411 6,248 3,204,	3,204 3,204	3,204 3,204 4,265 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204 3,204	3.3 3.2 3.2 8.2 8.2 3.2 3.2 3.2
83.06 83.05 83.05 83.05 83.05 83.05 84.05	3,204 6,345 6,411 6,249 3,204	3,204 3,2043	3,204 3,204 4,266 3,2043	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204	3.1 3.1 3.1 3.2 3.2 3.2 3.2 3.2
8.06 8.07 8.07 8.07 8.07 8.07 8.07 8.07 8.07	3,204 6,345 6,411 6,248 3,204	3,200 3,2043	3,204 3,204 4,265 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204	3.3 3.2 3.2 8.2 8.2 3.2 3.2 3.2
	3,204 6,345 6,411 6,249 3,204	3,204 3,204	3,204 3,204 4,266 3,204,	3.204 3.204	3,204 3,204 3,204 6,112 3,204 3,204	3.1 3.1 3.1 3.2 3.2 3.2 3.2 3.2
	3,204 6,345 6,411 6,248 3,2043,204 3,204 3,204 3,2043,204 3,204	3,204 3,204	3,204 3,204 4,265 3,2043,204 3,204 3,204 3,204 3,204 3,2043,204 3,204 3,204 3,204 3,204 3,204 3,2043,204 3,204 3,204 3,204 3,2043,204 3,204 3,204 3,2043,204 3,204 3,204 3,204 3,2043,204 3,204 3,204 3,204 3,2043,204 3,204,	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204	3.3 3.2 3.2 8.2 8.2 3.2 3.2 3.2
	3,204 6,345 6,411 6,249 3,204,	3,204 3,204	3,204 3,204 4,266 3,204,	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204	3.1 3.1 3.1 3.2 3.2 3.2 3.2 3.2
	3,204 6,345 6,411 6,248 3,2043,204 3,204	3,200 3,200 3,2043,204 3,204 3,204 3,204 3,204 3,2043,204 3,204	3,204 3,204 4,265 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204	3.1 3.2 3.2 3.2 8.2 3.2 3.2 3.2 3.2
	3,204 6,345 6,411 6,249 3,204,	3.204 3.204	3,204 3,204,	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204	3.1 3.2 3.2 3.2 3.2 3.2 3.2 3.2
	3,204 6,345 6,411 6,248 3,204	3,204 3,204	3,204 3,204	3.204 3.204	3,204 3,204 3,204 4,112 3,204 3,204	3.2 3.2 3.2 6.2 3.2 3.2 3.2 3.2

Figure M3 The result case study 3 CHAMENS of the process heat exchanger for the step 2 (continued).

	THE PERSON NEWS					
	E1	82	85	24	. 85	E.c.
81.51	3.20%	3.294	21254	3.204	3,264	3.254
81.02	3.204	3.204	3,209	3,204	3,204	3,204
81.03	5,204	3.204	3,208	3.704	3.204	3.294
81.03	3.204	91294	37204	3.204	3.404	3,205
811CB	3.204	31294	3,208	3.204	3.204	3,254
82.58	3.208	3.254	3.298	3,209	2.275	3,204
11.61	3.204	5.274	3.204	3,204	3,204	3,294
NT1CS	3.204	3.234	3,204	3,204	3.204	3.204
M1-C9	3,204	3,204	3.204	3.204	3,204	1,204
10.01	3.204	3-208	3.305	3,204	3,204	3.204
10.02	3,204	3,204	3-204	3,204	11264	3,274
85.03	3.204	3.204	3,254	3.214	3,205	4.204
10.04	9.204	31204	3,204	11504	14204	1,204
12.08	3,294	3.209	3.204	3.204	3,204	8.204
H2.Ce	0,204	9.294	2,204	11204	31204	3/204
82.07	3.205	3,294	3.294	3.294	3+224	3,204
82.CF	31204	3,204	3,204	3,204	4,204	8,204
82.05	31204	3.208	3,204	31214	3.204	8-204
B3.C1	9,204	3,294	2,204	3,204	3*504	3,204
83.02	3.20%	5.716	2.204	9.294	3,204	3,254
B3.C3	3.204	5,657	8.209	4.204	3,204	3,204
85.04	3,20%	3.204	3,204	3.204	1.204	3.204
83.00	3,20%	6.859	2,204	3,204	3,204	8,294
#3.00	3.208	6.504	3.204	31204	3.204	3.204
83.57	3.204	4.263	3-204	3.204	3,204	3.204
83.08	3,208	3.208	3.204	3.204	3.204	4.204
Harra	31204	A1404	1100	31204	- 1. A. M.	2.2.00
	107	KL.	K3	MTO		
10.01	5.264	8.204	3.208	3,204		
10.02	3.204	3.224	3.204	3,204		
14.05	3.204	31204	3,204	3,204		
81.08	3.204	3.278	1.296	3.294		
RILCH	3,204	3,204	3-204	3,204		
83.08	3.204	3.204	3.204	3.204		
M4.01	3.204	31208	3,204	8,204		
10.00	3.254	3.204	3.204.	3.294		
H1.C9	8,298	8,294	0,204	31204		
82.01	8.275	3,294	3,294	3,204		
HI.CI	9,204	8.204	8,204	3,204		
82.03	31204	3,204	3,204	3.204		
H2.C4	9,204	9.294	2,204	3,204		
82.05	3.20%	5,294	2.2.94	31204		
Hz.ce	3.204	3.204	3.204	3.204		
82107	3.20%	3,204	3.204	3.204		
82.09	3,20%	3-204	3,204	3,204		
82.09	3,204	3,294	3.204	31204		
81.01	3.204	2.929	3-204	3.204		
H01C2	31204	5.055	3.206	3.204		
83.03	3.20%	3.294	31296	3.204		
10.08	31204	31204	3.208	3.204		
101.01	31204	3.204	3.201	3,208		
113.1.8	8.204	3.404	3.204	9.204		
13.67	3.209	3.574	31294	3,294		
10.09	3.204	3,204	3-204	3,204		
	142 VARIABLE	C CHITD.L.				
	25-	10	83	84	25	24
	10.000					
81.01	35,200	35,200	35,000	31,000	35,900	88,000
81.02	15.000	851.000	527000	35,400	38,000	49,009
81.03	35.000	35.000	35,009	35, 999	35,000	35,000
81108	33.000	35.999	25,000	35,000	35,000	35.000
81.08	33.000	25.12958	20,900	35.000	331000	391029
BALCE.	23-2072	431444	221000	35,000	35,000	35.000
Ma con	33.000	34	35.000	48,000	35.000	44
81.00	11.000	42.490	88.000	35.000	38,000	33-545
Marcal Marcal	23.000	351900	221000	30,000	35.000	3319200
82.01	23.000	22.000	35.000	22.000	33,000	15,000
83.00	35.000	38	32.000	49.000	35.000	44.444
82.03	35,000	33.370	33.000	23.000	38,000	35.000
An es	35.000	22.000	44.400	48.000	44,590	
10.04	1.2	The second	35 000	35,000	35.000	35 000
Marce.	35-000	28.000	48.990	40.000	39,099	14.890
No. Cor	33.000	38.000	31.000	34.000	34.000	15.000
82.02	35,000	38.990	34×050	36.000	38.000	18,000
10.00	15,000	15. 000	55,000	35,000	35,000	36 0.00
83.03	85 335	86.100	35.000	35.000	38, 200	35,000
HT CT	10.000	24 174	55,000	45.000	35.000	13
83.08	35,500	35.020	35.000	25,000	25,000	38,000
10.0	110,002	122.447	45.000	35.000	35.000	45,000 r
RX.CR	120,833	127,583.	35,000.	35,000	35,000	\$6,007
10.07	124.400	335-652	115.432	103.014	109,740.	1.19.433
10.01 H3.02	114-600	315.000	111.432	103.011	109.740	119.433

**Figure M4** The result case study 3 CHAMENS of the process heat exchanger for the step 2 (continued).

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                              35.000
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H1.C3
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81.04
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HI.CS
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81.09
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H2.C7
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H2.C8
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H3.C6
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            K2
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HZ.Cl
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                               2945.176
H3.C1
83.02
        7497,391
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**** FILE SUMMARY
Input
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          EMAT 35 -- Area heat exchanger minimization.gms
Output
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         at exchanger minimization.1st
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**Figure M5** The result case study 3 CHAMENS of the process heat exchanger for the step 2 (continued).

Appendix N Case study 3: CHAMENS (Cold Utility Without Minimizing Area at EMAT 35 °C for *N<sub>op</sub>=1 year*)

2 and service	M (TL-92, TD)
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**Figure N1** The cold utility without minimizing area at EMAT 35 °C for Nop=1 year Case study 3 CHAMENS.

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	18,783 (2)	Temperature superstructure teasurility of init erress
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11.1	11827, 483 F	=110,0007 =10,0007
11-3	(1884*1874)	-14,841;
11.5	1 84 . 84 7	-server and
1.12	(1821, 1821) (1831, 1821)	-00,000/ 
	ALMER AND	
54-2	11827, 18873	-94,0000
64.73	S180+ (83+)	*87,9207
2.49	31411-120811	HEF, DOWN
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1.47	11831, 1851)	-88, 5551
5.17	Toni-Policy.	+49,0001
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53.18	10021-00011	-87,000/
4.17	110.6.0011	+58,000
14.47	(1821, 1877)	-99,000.
51.1	Carlo dant	+11 (1251)
1.17	ATRAC, TRACK	-44, 0207
14-4	11001, 1001	749,0001
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54.3	11011-11010	-98.0001
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**Figure N2** The cold utility without minimizing area at EMAT 35 °C for Nop=1 year Case study 3 CHAMENS (continued).

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App:TempR1 (2, 2) 5ApTempR1 (2, 2) App:TempR4 (2, 2) 5ApTempR4 (2, 7) 5ApTempR4 (2, 7)	Approach Despectation 12 at stary The other approach temperature of Approach temperature 12 at they The other approach temperature of	HI 3 as stage Ri 45 3 at stage RI	
AppTempR7 (1, 7) AApTempR7 (1, 7) AppTempR3 (1, 7) AppTempR3 (1, 7) AApTempR3 (1, 7)	Approxim respective 12 at stars Die other approxim temperature 1 Approxim temperature 13 at stars The other approxim temperature 1	NI 3 AL PLAGE RI 41 3 AL ALAGE RI	
AppTrop(D)(1, 2) AbgTrop(D)(1, 2) b2027at(1, 2, 4) (trows(1), 2, 7) prov. prov. prov. prov. prov.	Approach tempetation (2 st stap The solide approach temperature ) BOAT constraint	its C vi magi Al	
) AggTrogR1 (1, 3) AggTrogR1 (1, 3) AggTrogR2 (1, 3) AggTrogR2 (1, 3)	$\begin{array}{l} \ldots = (1, 1, (0))  \text{so}  (\pi_1(1, (0))) \\ \ldots = (1, 1, (0))  \text{so}  (\pi_1(1, (0))) \\ \ldots = (1, 1, (0))  \text{so}  (\pi_1(1, (0))) \\ \ldots = (1, 1, (0))  \text{so}  (\pi_1(1, (0))) \\ \ldots = (1, 1, (0))  \text{so}  (\pi_1(1, (0))) \end{array}$	45 (7, 18, 1) + 785 (3, 7) + 14 45 (7, 18, 1) + 785 (3, 7) + 14 45 (7, 18, 1) + 785 (1, 7) + 14 43 (7, 18, 18, 1) + 785 (1, 7) + 14 43 (7, 18, 18) + 145 (1, 7) + 14	$= (T_{+}T_{+}^{-1}\pi(L^{+})))$ $\pi (T_{+}J_{+}^{-1}\pi(L^{+}))) +$ $\pi (T_{+}J_{+}^{-1}\pi(L^{+}))) +$ $\pi (T_{+}J_{+}^{-1}\pi(L^{+}))) +$
AppTmgR3(1,7,7) AApTmgR3(1,7,7) AppTmgR3(1,7,7) AppTmgR3(1,7,7) AppTmgR3(1,7,7)	$\begin{array}{llllllllllllllllllllllllllllllllllll$	$\begin{array}{l} (1, 2, 2, 3, 3, 2) \mapsto TAL((1, 2) + (1, 3, 3)) \\ (2, 3, 3, 3, 3) \mapsto TAL((1, 2) + (1, 3, 3)) \\ (3, 3, 3, 3) \mapsto TAL((1, 2) + (1, 3, 3)) \\ (4, 3, 3, 3) \mapsto TAL((1, 2) + (1, 3, 3)) \\ (3, 3, 3) \mapsto TAL((1, 2) + (1, 3, 3)) \\ \end{array}$	8 (2, 2, 183*))) 8 (2, 2, 183*)) 8 (2, 2, 183*) 8 (2, 2, 183*)) 8 (2, 2, 183*))
AppTexp85(1,7) MapTexp85(2,7) AppTexp85(2,7) AppTexp86(2,7)	$\begin{array}{c} & de\left(1, J_{1}^{-1}(0, 1)\right) \rightarrow d_{2}^{-1}\left(e_{1} \left(1, \frac{1}{2} \left(1\right)\right)\right) \\ & de\left(1, J_{1}^{-1}(0, 1)\right) \rightarrow d_{2}^{-1}\left(e_{2} \left(1, \frac{1}{2} \left(0, 1\right)\right)\right) \\ & de\left(1, J_{1}^{-1}(0, 1)\right) \rightarrow d_{2}^{-1}\left(e_{1} \left(J_{1}^{-1}(0, 1)\right) \\ & de\left(J_{1}, J_{1}^{-1}(0, 1)\right) \rightarrow d_{2}^{-1}\left(1, \frac{1}{2} \left(J_{1}^{-1}(0, 1)\right)\right) \end{array}$	$\begin{array}{l} T_{2}^{1}\left(\vec{x}_{1}^{-1}\left(25\right)^{2}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) + \left(1+\frac{1}{2}\right) \\ T_{2}^{2}\left(\vec{x}_{1}^{-1}\left(25\right)^{2}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) \\ T_{2}^{2}\left(\vec{x}_{1}^{-1}\left(25\right)^{2}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) \\ T_{2}^{2}\left(\vec{x}_{1}^{-1}\left(25\right)^{2}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) \\ T_{2}^{2}\left(\vec{x}_{1}^{-1}\left(25\right)^{2}\right) + TRL\left(\vec{x}_{1},\vec{x}_{2}^{-1}\right) + TRL\left(\vec{x}_{2},\vec{x}_{2}^{-1}\right) + TRL$	n ( 12, 2, 4 ( 10, 5 ) ) ) n ( 12, 2, 4 ( 10, 5 ) ) ) n ( 12, 2, 7 ( 10, 5 ) ) ) n ( 12, 2, 7 ( 10, 5 ) ) ) n ( 12, 2, 7 ( 10, 5 ) ) )
- App:Temp877 (1,-1)	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \pm j \left( \mathcal{I}_{n}^{-1} \left( 1 \right)^{n} \right) + \Sigma \delta \mathcal{I}_{n}^{-1} \left( \mathcal{I}_{n}^{-1} \left( 1 \right)^{n} \right) \\ \pm j \left( \mathcal{I}_{n}^{-1} \left( 1 \right)^{n} \right) + \Sigma \delta \mathcal{I}_{n}^{-1} \left( \mathcal{I}_{n}^{-1} \left( 1 \right)^{n} \right) \right) \\ \pm j \left( \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \right) + \Sigma \delta \mathcal{I}_{n}^{-1} \left( \mathcal{I}_{n}^{-1} \left( 1 \right)^{n} \right) \\ \pm j \left( \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \right) + \Sigma \delta \mathcal{I}_{n}^{-1} \left( \mathcal{I}_{n}^{-1} \left( 1 \right)^{n} \right) \\ \pm j \left( \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \right) + \Sigma \delta \mathcal{I}_{n}^{-1} \left( \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \right) \\ \pm j \left( \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \right) + \Sigma \delta \mathcal{I}_{n}^{-1} \left( \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \right) \\ \pm j \left( \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \right) + \Sigma \delta \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \left( 2 \right)^{n} \left( 2 \right)^{n} \right) \\ + \Sigma \delta \mathcal{I}_{n}^{-1} \left( 2 \right)^{n} \left( 2 \right)^{n}$	#12,2,1871999 012,2,1871917 #12,2,21891933 #12,2,789333
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**Figure N3** The cold utility without minimizing area at EMAT 35 °C for Nop=1 year Case study 3 CHAMENS (continued).



**Figure N4** The cold utility without minimizing area at EMAT 35 °C for Nop=1 year Case study 3 CHAMENS (continued).

### Appendix O Result Case Study 3: CHAMENS (Cold Utility Without Minimizing Area at EMAT 35 °C for $N_{op}=1$ year)

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**Figure O1** The result cold utility without minimizing area at EMAT 35 °C for Nop= 1 year Case Study 3 CHAMENS.

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**Figure O2** The result cold utility without minimizing area at EMAT 35 °C for Nop= 1-year Case Study 3 CHAMENS (continued).

# Appendix P Case Study 3: CHAMENS (Hot Utility Without Minimizing Area at EMAT 35 °C for *N<sub>op</sub>=1 year*)

SZTS	
I hot streams	(1.1)
2 cold streams	YEL, C2, C3, C4, C4, C5, C7, C8, C3 /
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ARTABLES	A set a second s
F1(2)	LF HF HF FUEL flow same
ATT 17. 3. 81	Second temperature
-dt cu (T)	Approach temperature between cold utility and hot stress
dama (2)	Approach temperature between bot utility and cold stream
11(7, 7, 8)	Seat exchanged between not I and cold J
qcu(1)	Been exchanged between cold unility and not I
april (3)	Seat exchanged between hot utility and cold 2
51(I.H)	Temperature of hot stream 1 at hot end of stage k
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# 11. (7, M)	Exchanged matching between bot I and cold J at stage #
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415882(0)	Overall heat balance of hot streams 1
&11.HBJ (7)	Overall heat Balance of cold streams J:
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ALLHBJ (7)	(TOUTS(3)-TINS(3))-FS(3)+CB-E- SCH((1,K),g(1,3,K))+chu/
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HDIN3(I)	Heat balance of not stream i at stage #3
HBINA(I)	Heat balance of not stream 1 at stage N4
新建工程店 (II)	Heat balance of hot stream 1 at stage #5
REIN((I))	Heat balance of hot stream 1 at stage N6
#BIN7(I)	Reat balance of hot stream 1 at stage 27
(I) CHIER	Best Balance of hot stream 1 at stage #8
88109(1)	Seat balance of hot stream 1 at stage R5
am2MT (2)	near neismoe of cold stream 1 at stage El
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12181200	(51(1, 'F4')-51(1, 'R5')) *F1(1)*SP-D- SDB(2, 4(1, J, 'K4')))
HBIES(I)	(11(1, 'E5')-11(1, 'E6'))*E1(1)*CP+E+ NDH(2, Q(1, J, 'E5'));
MBIR#(T)	(ta(1,'84')-ta(1,'87'))*FI(1)+CP-E- 518(3,q(1,3,'84'));
MBIN7(1)	(51(1, "K"")-51(1, "K"")) "FI(1) "CP-D- NUM(2, g(1, 3, "K""));
(I) 0MI(I)	(E1(I, 'KD')-E1(I, 'KD')) *FI(I) *CP+E= NDM(d, q(I, 3, 'K(')))
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#15-39(1 (J)	(53(0, 'KL')+53(0, 'KL'))*#2(0)*CP+E+ 508(0, 0(0, 0, 1KL'));
(19-7)(2 (-7)	(13)(3, "#2")+13(4, "#3")) *#3(3)*CP+E= \$15(1, q(1, 3, "#3")))
825783 (3)	(1)(2, "E1")-1)(2, "E0")) *F2(2)+D+E= \$18(1,4(1,2,"E3"));
HB-78(4 (3)	(t2(J, 'X4')-t5(J, 'K5'))*TJ(J)*CP+E= SIM(1,q(1,J,'X4'));
(03.78.9 (.7)	<pre>(+ (+2(d,*Kh*)++)(d,*Kh*))*FJ(d)*CP=E= \$(M(1,q(1,d,*K5*)))</pre>
HB-2H-6(-3)	(1313, 1861)-13(2, 1831)+183(3)+CP-8- \$15(1, q(1, 3, 1861))
HE-3767 (-3)	(05)(J, 'N'')-53(J, 'N'')) 'EJ(J) 'CP-E- 600(1, 0(1, J, 'N''));
HE-JKE (-5)	(t513, '#5')+t5(3, '#9'))*T3(3)*CP=E= 500(1, g(1, 3, '#5'));
00% 70/10 L 71	INTELLEVIS AND AND ADDRESS AND ADDRESS

**Figure P1** The hot utility without minimizing area at EMAT 35 °C for Nop=1-year of the case study 3 CHAMENS.

EQUATIONS	subsection panetotation in and states	
FEIRL (I)	Temperature superstructure feasibility of hot stream	at H1
FEIRZ (I)	Temperature superstructure feasihility of hot stream	at MI
FEIR3(I)	Temperature superstructure feasibility of hot stream	at KB
FEIR4(I)	Temperature superstructure feasibility of not stream	at Ki
FEIRS(I)	Temperature superstructure feasibility of not stream	at KS
FEIR4(I)	Temperature superstructure feasibility of not stream	at Ké
YE1X7(1)	Temperature superstructure feasibility of not stream	at K7
AKING(I)	Temperature superstructure feasibility of not stream	#t K0
PEIN+(I)	Temperature superstructure feasibility of hot stream	at N9
FEJKI (J)	Temperature superstructure feasibility of cold stream	at RL
FEJH2 (J)	Temperature superstructure feasibility of cold stream	at M2
FE-3K3 (-3)	Temperature superstructure feasibility of cold stream	st RS
FE-784 (-7)	Temperature superstructure feasibility of cold stream	at K4
FE-785 (-7)	Temperature superstructure feasibility of cold stream	at HS
FEJR6(J)	Temperature superstructure feasibility of cold stream	at K6.
FEJR7 (J)	Temperature superstructure feasibility of cold stream	at K7
FEJKS (J)	Temperature superstructure feasibility of cold stream	at Kö
PEJKk(J)	Temperature superstructure feasibility of cold stream	at K9
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	and the second	
FEIRL(I)	<pre>., t1(I,'K1') =G= t1(I,'K2'))</pre>	
FEIR2 (I)	E1(I,'E1') =G= E1(I,'E3');	
PEIR3(I)	., 51(1, 1831) =0= 11(1, 1841);	
FEIK4(I)	t1(I,'X4') =0= t1(I,'K5');	
FEIRS (1)	·· 11(1, 'N5') =0= 11(1, 'K6');	
FLIKE(I)	+* ET(1, (0,) =0= ET(1', 01,))	
FEIR7(I)	<pre>r* ET(I', %i, ) =0= ET(I', %i, );</pre>	
FRING(L)	51(1, 'KB') =0= 51(1, 'K9')/	
CLERP (A)	the setter by 7 -o- setter here fr	
	The second se	
FEDRI(J)	-' c3(g', c1,) =0= c3(g', k1,):	
FEJIC2 (J)	·· 23(2, (ET.) =0= 23(2, (K3,));	
FE383 (J)	+3 (3, 1031) =0= +3 (3, 1041);	
FEJE4 (J)	** 23(2', K#+,) =0= 23(2', KE+)1	
FEJES (J)	** £3(0, (KP.) =0= £3(0, (Ke.))	
FEJKe (J)	- 23(0'.K0.) =0= 23(0'.K1.);	
FEGR.7 (G)	** 23(2*, 10, 1) =0= 23(2*, 102, 1);	
FEURO (J)	< 23(0, 10)   =0= 23(0, 10)   1	
FROMMAN	·· e) (e) eb.1 -e- e) (e) ere ()	
TOURRATIVE CONCT	TALIN'S THE BACK CHART AND OUTLAN TOGERANIZES	
EQUATIONS		
INLETI (I)	Temperature constraint of inlet temperature 1	
OUTLETI(I)	Temperature constraint of outlet temperature 1	
INLETJ (J)	Tesperature constraint of inlet tesperature j	
OUTLETJ (J)	Temperature constraint of dutlet temperature 1/	
INLETI (1)	TINI (1) "E" ti(1,'K14);	
OUTLETI(I)	<pre>+, TOUTI(I) =L= t1(I,'H10');</pre>	
INLETJ (J)	TINJ (J) =E= t3(J, NIO));	
COLFEL2 (2)	., TOUTJ(J) =G= tj(J, 'K1'))	
*THE LOUIDAL COMPTRAINTS	TO CONTENT THE EXESTANCE OF BATCH 24 DESIGN AT BACE OF	- 100
EQUATIONS		
LogicIJK1(I,J)	Logical constraint 13 at stage K1	
LogicIJK2(I,J)	Logical constraint if at stage KI	
LogicIJK3(I,J)	Logical constraint 13 at stage RJ	
LogicIJK8(1,J)	Logical constraint if at stage R4	
LogicIJK5 (I, J)	Logical constraint ij at stage #5	
LogiciJKe(1,J)	Logical constraint 1) at stage El	
Logicium/(1,J)	Logical constraint 13 at stage FL	
Todrorawe(1'a)	rodical constraint 17 at stage M.	
LogicIJE10(I.J)	Logical constraint if at stage 25	
and a second sec	and and a support of the state by	
LogicUTi (J)	Logical constraint for cold utility	
LogicUT <sub>2</sub> (I)	logical constraint for hot utility;	
LogicIJK1(I,J)	+. q(1, J, 'E1')-CHEGA+=(1, J, 'E1") -L= 0;	
LogicIJH2(1,J)	q(I,J,'EI')-CHEGA'z(I,J,'EI') =L= 0;	
LogicIJE3(I,J)	q(1, J, 'E3') - ONEGA* # (1, J, 'E3') =L= Or	
LogicIJEs(I,J)	q(I,J,'E+')-OMEGA'z(I,J,'E+') =L= 01	
LogicIJK5(I,J)	q(I,J,'K5')-OMEGA+=(I,J,'K5') =L= 0;	
LogicIJR4(1,J)	+- q(I,J,'K6')-CMEGA*±(I,J,'K(') =L= 0;	
LogicidK7(1,J)	q(1, J, 'N7')-CHEGA*=(1, J, 'N7') =L= Q;	
LogicIJK8 (I, J)	+, Q(I,J,'NO')-ONEGA'#(I,J,'NO') =L* O:	
LogicIJK9(I, J)	<pre>q(I,J,'K9')-CHEGA*z(I,J,'K9') =L= 0)</pre>	
LogicIJE10(I,J)	g(I,J, 'K10') -CMEGA*g(I,J, 'K10') =L= 0;	
Louisette un		
LogicUT3 (I)	gcu(I)-ONEGA*zcu(I) =L= 0;	
140	SOT AND COLD OFFLATS LOADS -	
EQUATIONS	an annual te	
HOTUT(I)	Hot utility last	
COLDUI (J)	cord AttillA 1080:	
Monthly Law	(access that the a water of the balance of the second second	
HATTY (1)	<pre></pre>	
2000001101	the reasonable of the section of the district	

**Figure P2** The hot utility without minimizing area at EMAT 35 °C for Nop=1-year of the case study 3 CHAMENS (continued).

1		MEAT EXCRAMPED DESIGNATION PORCES AT BACK 2	
EQUATIONS	SecTam NLIT. 7	Annual Constanting 12 or atom Fi	
	AAnTempK1 (1. J	The other approach temperature 1' at	stage El
	AppTempK2(I,J	Approach temperature 1) at stage #2	
	AApTempK2(1,J	) The other approach temperature at at	stage W2
	AppTempH3(1,J	Approach temperature 1) at stage Hi	
	AApTempR3(I,J	) The other approach temperature 15 at	stage ML
	AppTempH4(I,J	Approach temperature 15 at stage #2	
	AApTempK4(1,J	) The other approach temperature 13 at	stage #2
	AppTempRS(1,J	Approach comperature is at stage RI	
	AApTempK5(I, J	) The other approach temperature 17 at	stage H1
	Apprempke(1,J AApTempke(1,J	The other approach temperature 13 at	stage #2
		and the second sec	
	AppTempK7(I,J	Approach temperature 13 at stage El	and the second se
	Applemph/11, J	Approach temperature 11 at store #2	stade at
	AApTempK8 (I.J	The other approach temperature 13 at	stage #2
	AppTempR9(1,J AApTempR9(1,J	Approach temperature 13 at stage K2 The other approach temperature 13 at	stage #2
	Destant t to	PULT constraint	
	dtreal(I,J,K)	EPAL CONSELATION	
	dqueme		
	dparms.		
	wonl, con2		
	AppTempH1(1.J	dr(I,J, *#1*) =L= (t1(I, 'M1*)=t)(J	, 'EL')) +TAL+ (1-z(1, J, 'E1'));
	AApTempH1(I,J	) dt(1,3,'#2') =L= (t1(3,'#2')-t)(3	,"#2'))+TAL*(1-=(I47,"#1'));
	AppTempH2 (I, J	) dt(I,J,*H1*) =L= (t1(I,*H1*)-t3(J	, *K2*)) +TAL*(1-z(I,J,*K2*));
	AApTempH2 (1, J	) dz(1,3,'E3') =L= (z1(1,'E3')-c3(3)	,"R3"))+TAL*(1-=(I,U,"K2"));
	SenTampitit .T	dert.d 18111 ata (es)t. 18111.es)(3	TERTILIZTSTATION T TERTIL
	AArTempK3(I.J	dt/1.7. We'l =L= (t1/1. 'Ke'l-t1/3	"R4'))+TAL*(1-z(1.3."R3'));
	AppTempK4(I.J.	dt(I.J. '#4') =L= (t1(I. 'Me')-t2(J	'R4'))+TAL+(1+=(T.J.'K4'));
	AApTempH4 (I.J	dt [1, J, 'ES'] =L= (t1 (1, 'RS')-t3 (J	, 'KS'))+TAL*(1-=(T, 7, 'K4'));
	Incluse Phil 7		IPRILLETATION OF TAXABLE
	hheremasil.J	dt(I.S. 1001) =L= (t1(I. 1001)-t1(S	*R6*))+TAL*(1=x(T.J.*R5*));
	AppTempKs(I,J	at(1, J, 'SE') =L= /t1/1, 'Ke')=tj(J	"E6'))+TAL'(1-z(I,N, 'E6'));
	AApTempK6(1,J	) de(I.J. * M?*) =L= (c1(I. * M7*)-c1(J	*****)) *TAL* (1-2(1,J,****));
		A second a lower of the state of the second second	
	Apprempk7(1,J	<pre>def1 0.4000 eta (es/1, 004)_e4/0</pre>	
	AppTempKS II.J	dt(I.J. '80') =L= (t1(I. '80')-t1/3	*#8*11+TAL*11-#11.7. *#8*11.
	AApTempH8(1,J	· de(1,3,'29') =L= (c1(1,'%9')-t1(3	.*R9*))+TAL+(1-z(I,J,*E8*));
	AppTempR9(1,J	at(1,3,'E3') =L= (t1(1,'S9')-t3(3	, 'RD')) +TAL* (1-=(1,2, 'RD'));
	AApTempH9(1,J	dr(I, 0, 'MIO') =1= (t1(I, 'WiO')-tj	(J, *K10*1)+TAL*(1-±(1, J, *K0*));
	dtrwal(I,J,K)	dot(1,J,R) *E* t1(1,R)-t3(J,R);	
		the second second second	
	doarna .	gcs *** scs(1,gcs(1));	
		and a second second	
	conl des .	-#- 0:	
	proper to other of		
in the second		STATISTICS PROVIDED IN	
PARAMETER	15	EPersonal Constant	
	CCU .	Cost coefficient for cold utility	1.2071
	CHU	Gest coefficient for hot utility	1 50/
	ALFHA	Cust coefficient process exchanges	12281.091
	cont FE	Cost confilcient for molet	2. 602
	HEATER	Cost coefficient for heater	7. 80/
	stop	(perstional time (year)	11/
	TA		10.007
FOR STORE			
PERSONAL TORIS	MINU	minisire utilities and it matches	
	SINU	TAC -E- (	
( (1/Nop)	*		
1	and an and the second second	The lot of the second states	
+/ COOLER	singen(I)) = i	LEW BEATER+SCH(J) :)	
/((1+za)+	*1)	in the second se	
11			
+	the supervision	and a strate of a left	
( ( (1/Móg	St. ( WTERFARM	((1,4,8)) (1,4,8) ))	
117			

Figure P3 The hot utility without minimizing area at EMAT 35 °C for Nop=1-year of the case study 3 CHAMENS (continued).

```
MODEL CASESTUDY1 /ALL/ ;
SOLVE CASESTUDY1 USING MINLP MINIMIZING TAC;
PARAMETERS
U
HI(I) the heat transfer coefficient of the hot stream 1 in the source plant
/LP=1/
HJ(J) the heat transfer coefficient of the cold stream j in the sink plant
/C1=0.05,C2=0.05, C3=0.05, C4=0.05,C5=0.05,C6=0.05,C7=0.05/;
U(I,J) = ((HI(I)*HJ(J))/(HI(I)+HJ(J)));
display U;
DISPLAY z.l,q.l,FI.l,TAC.L,dt.L,ddt.L,ti.L,tj.L;
```

**Figure P4** The hot utility without minimizing area at EMAT 35 °C for Nop=1-year of the case study 3 CHAMENS (continued).

## Appendix Q Result Case Study 3: CHAMENS (Hot Utility Without Minimizing Area at EMAT 35 °C for *N<sub>op</sub>=1 year*)

O INPERSING ġ UNRECTRICK) ERACUS. GMUF 24,2.1 reabtr Released Dec 4, 2017 MEX-MER ate ce/dm Bindows 06/29/20 06r20131 Page 6 Daneral Algebraic Nodeling Tystem GARGERI ALGORATO NODELING Execution JPL EASAMETER U 21 125 (z)D4 -15 24 0.090 0.045 0.045 0.090 0.000 0.046 38 .  $\mathbf{C}^{(i)}$ 3.545 2.9 290 VARIABLE z.L. Exchanger matching between not I and cold I at arage a 32 ės. 1.000 LP.CI 19.03 19.03 19.06 19.07 1.005 1.005 1.005 1.005 19.03 1.000 3,000 193 MARIANI Q.L. Heet exchanged netween not I and mold 2 82 24 1001.470 11.710 #2242.444 50855.84# 13700.640 3269.750 LEGER 33.205 100 VARIABLE FL.L. LF HE HE FUEL five rate -----1# 011040.000 - 37043,300 Total Annual Cost ---- INC VARIABLE TAULL INE VARIABLE dt.L. Approach semperature × 5 82 K3 83 24 164 18.03 18.03 18.03 18.03 35.000 35.000 26,000 35.099 25,020 35.000 35,000 35,000 35,000 35.000 35.000 35.000 55,000 35,000 35,000 35.000 551000 85.000 35,000 35,000 86.000 \$5,000 18.05 18.05 18.05 35.000 35.000 35.000 35.000 35,000 35,000 35,000 33.000 35.000 35.000 85.000 85.000 85.000 18.000 35,000 \$5.000 85.000 35.000 35.000 88.000 \$3.000 38,000 88.000 LPICE. 35,000 LP.CF 38.000 35.000 05.000 35.000 381000 85.005 - 4 .87 65 89 K10 18,01 18,03 18,03 18,000 35,000 25,000 \$3.000 38.000 138.000 35.000 35.000 35.000 35.000 35.000 35,000 18.04 18.000 14.000 18,000 19.03 #1.000 #1.000 31.000 35.000 18.000 38.000 38.000 55.000 33.000 35.000 35.000 35,000 35,000 18.03 38,000 15.072 18.09 33.000 10,000 18.000 38.000 232 VARIABLE dot.L Stel Approach Temperature 12 32 13 84  $\mathbf{x} \in$ 85 175.005 175.000 144.800 1741800 174.800 178.800 18,51 10.03 10.03 132,000 133.000 Gaz.000 189.950 134,900 124,000 109,900 104.000 134,900 134,200 188,900 154,800 154.000

**Figure Q1** The result the hot utility without minimizing area at EMAT 35 °C for Nop=1 year of case study 3 CHAMENS.

75.403	42.000	42+000	724,200	724.200	724.200	7241200
LP.C6	43.000	43.000	134.900	134.900	134.900	134.900
LP.C7	43.000	43.000	134.900	134.900	134.900	134,900
LP.C8	43.000	43.000	99.900	99.900	99,900	99,900
LF.C9	43.000	43.000	42.900	42.900	92.900	42.900
+	87	KS	K9	K10		
LP.CI	174,900	174,900	174,900	174,900		
LP.C2	134,900	134,900	134,900	134,900		
LP.C3	134,900	134,900	134,900	134,900		
LP.C4	189,900	189,900	189,900	189,900		
LP.CS	134,500	134,900	134,900	134,900		
LP.C6	134,900	134,900	134,900	134.900		
LP.C7	134.900	134,900	134,900	134.900		
LP.CS	99,900	99,900	99,900	99,900		
LP.C9	194.900	194.900	194.900	194.900		
	292 VARIAN	BLE ti.L Ter	merature of	hot stream i	at hot end	of stage k
	KI	K2	K3	K4	K5	K6
LP	230.000	230.000	229.900	229.900	229.900	229.900
+	K7	KS	K9	K10		
LP	229.900	229.900	229,900	229,900		
	292 VARIA	BLE tj.L Te	mperature of	cold stream	] at hot en	d of stage k
	K1	K2	K3	K4	R5	R6
Cl	55.000	55.000	55.000	55.000	\$5.000	55.000
CZ	98+000	98.000	95.000	95.000	95,000	95.000
C3	98.000	98.000	95.000	95.000	95.000	95,000
C4	40.000	40.000	40.000	40.000	40.000	40.000
C5	187.000	187.000	95.000	95.000	95.000	95,000
C6	187,000	187.000	95.000	95,000	95.000	95,000
C7	187.000	187.000	95.000	95.000	95.000	95.000
CS	187.000	187.000	130.000	130.000	130.000	130.000
C9	187.000	187.000	187.000	187,000	187,000	187.000
÷	K7	KS	89	KIO		
Cl	55,000	55.000	55.000	55.000		
C2	95.000	95.000	95.000	95,000		
C3	95.000	95.000	95.000	95.000		
C4	40.000	40.000	40.000	40.000		
C5	95,000	95.000	95.000	95,000		
C6	95.000	95.000	95.000	95.000		
C7	95.000	95.000	95.000	95.000		
C8	130.000	130.000	130.000	130.000		
C9	35,000	35.000	35.000	35,000		
		G.				
	TTON TTUP					

**Figure Q2** The result the hot utility without minimizing area at EMAT 35 °C for Nop=1 year of case study 3 CHAMENS (continued).

EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
			Nop	1 year					
35	H1.C4.K9	130	106.875	40	35	81	284	0.025	141
	H3.C5.K9	78.339	74.667	41.948	30	40	8,512	0.025	8,431
	H3.C1.K8	81.149	78.339	45.698	21	46	6,512	0.025	5,723
	H2.C1.K7	130	98	55	45.698	63	2,453	0.025	1,558
	H3.C2.K2	130	81.149	95	21	46	25,443	0.025	21,917
	H3.C3.K2	130	81.149	95	35	40	1,314	0.025	1,304
	H3.C5.K2	130	81.149	95	41.948	37	37,794	0.025	40,792
	H3.C6.K2	130	81.149	95	21	46	40,936	0.025	35,263
	H3.C7.K2	130	81.149	95	43	37	7,744	0.025	8,474
Hot utility	LP.C2.K2	230	229.9	98	95	133	1,031	0.048	161
	LP.C3.K2	230	229.9	98	95	133	66	0.048	10
	LP.C5.K2	230	229.9	187	95	80	65,541	0.048	16,999
	LP.C6.K2	230	229.9	187	95	80	50,894	0.048	13,200
	LP.C7.K2	230	229.9	187	95	80	13,701	0.048	3,553
	LP.C8.K2	230	229.9	187	130	67	3,870	0.048	1,195
	LP.C9.K6	229.9	229.9	187	35	100	33	0.048	7
Cold utility	H1.WATER.K1	106.875	55	5.1	5	73	636.195	0.048	182
	H3.WATER.K1	74.667	40	5.1	5	50	80354.501	0.048	33,278
EMAT	Stream matching	fik	tik+1	tik	tik+1	LMTD	0	U	Area
	stream mattering		Nop	2 year	·j	2			
35	H3.C2.K2	130	80.643	95	42.609	36	18,014	0.025	19,743
	H3.C3.K2	130	80.643	95	35	40	1,314	0.025	1,311
	H3.C5.K2	130	80.643	95	30	42	46,207	0.025	43,656
	H3.C6.K2	130	80.643	95	21	46	41,050	0.025	35,523
	H3.C7.K2	130	80.643	95	43	36	7,744	0.025	8,532
	H2.C1.K7	130	98	55	45.643	63	2,453	0.025	1,557
	H3.C1.K8	80.643	74.647	45.643	21	44	6,460	0.025	5,919
	H3.C2.K8	98	75.647	42.609	21	55	7,430	0.025	5,402
Hot utility	LP.C2.K2	230	229.9	98	95	133	1,031	0.048	161
	LP.C3.K2	230	229.9	98	95	133	66	0.048	10
	LP.C4.K2	230	229.9	40	35	192	284	0.048	31
	LP.C5.K2	230	229.9	187	95	80	65,400	0.048	16,963
	LP.C6.K2	230	229.9	187	95	80	51,035	0.048	13,237
	LP.C7.K2	230	229.9	187	95	80 67	13,701	0.048	3,553
	LP.Co.K2	230	229.9	187	130	0/	3,870	0.048	1,195
	ID COV6	220.0	220.0	No. 1					
Cold utility	LP.C9.K6 H1 WATER K2	229.9	229.9	51	35 5	82	1034 775	0.048	264

Table R1 The result of the exact area calculation for the case study 3 CHAMENS

EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area		
Nop 2 year											
5	H3.C2.K2	130	91.033	98	21	49	26,475	0.025	21,817		
	H3.C6.K2	130	91.033	116.191	21	35	52,805	0.025	61,049		
	H3.C7.K2	130	91.033	116.75	43	27	10,983	0.025	16,279		
Hot utility	LP.C1.K2	230	229.9	55	21	191	8,913	0.048	970		
	LP.C3.K2	230	229.9	98	35	161	1,380	0.048	178		
	LP.C4.K2	230	229.9	40	35	192	284	0.048	31		
	LP.C5.K2	230	229.9	187	30	102	111,607	0.048	22,791		
	LP.C6.K2	230	229.9	187	116.191	73	39,280	0.048	11,260		
	LP.C7.K2	230	229.9	187	116.75	72	10,462	0.048	3,008		
	LP.C8.K2	230	229.9	187	130	67	3,870	0.048	1,195		
	LP.C9.K6	229.9	229.9	187	35	100	33	0.048	7		
Cold utility	H2.WATER.K1	130	98	5.1	5.098	108	2,453	0.048	473		
	H1.WATER.K2	130	55	5.098	5.097	82	1,035	0.048	264		
	H3.WATER.K3	91.033	40	5.097	5	57	118,211	0.048	43,451		

Table R2	The result	of the exac	t area ca	lculation f	for the	case str	udy 3	CHAMENS
(continued)								

EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area		
Nop 2 year											
10	H2.C1.K7	130	98	55	45.643	63	2,453	0.025	1,557		
	H3.C1.K8	65.38	62.591	45.643	21	29	6,460	0.025	8,817		
	H3.C2.K2	130	65.38	98	21	38	26,475	0.025	27,979		
	H3.C3.K2	130	65.38	98	35	31	1,380	0.025	1,770		
	H3.C5.K2	130	65.38	113.998	30	24	59,712	0.025	97,835		
	H3.C6.K2	130	65.38	113.842	21	28	51,502	0.025	73,795		
	H3.C7.K2	130	65.38	114.28	43	19	10,615	0.025	22,522		
Hot utility	LP.C4.K2	230	229.9	40	35	192	283.605	0.048	31		
	LP.C5.K2	230	229.9	187	113.998	73	51895.224	0.048	14,713		
	LP.C6.K2	230	229.9	187	113.842	74	40582.718	0.048	11,497		
	LP.C7.K2	230	229.9	187	114.28	73	10829.462	0.048	3,075		
	LP.C8.K2	230	229.9	187	130	67	3869.73	0.048	1,195		
	LP.C9.K6	229.9	229.9	187	35	100	33.288	0.048	7		
Cold utility	H1.WATER.K5	130	55	5.002	5	82	1,035	0.048	264		
	H3.WATER.K2	62.591	40	5.1	5.002	45	52,329	0.048	24,060		

EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
Nop 2 year									
15	H2.C1.K7	130	98	55	45.643	63	2,453	0.025	1,557
	H3.C1.K8	65.38	62.591	45.643	21	29	6,460	0.025	8,817
	H3.C2.K2	130	65.38	98	21	38	26,475	0.025	27,979
	H3.C3.K2	130	65.38	98	35	31	1,380	0.025	1,770
	H3.C5.K2	130	65.38	113.998	30	24	59,712	0.025	97,835
	H3.C6.K2	130	65.38	113.842	21	28	51,502	0.025	73,795
	H3.C7.K2	130	65.38	114.28	43	19	10,615	0.025	22,522
Hot utility	LP.C4.K2	230	229.9	40	35	192	284	0.048	31
	LP.C5.K2	230	229.9	187	113.998	73	51,895	0.048	14,713
	LP.C6.K2	230	229.9	187	113.842	74	40,583	0.048	11,497
	LP.C7.K2	230	229.9	187	114.28	73	10,829	0.048	3,075
	LP.C8.K2	230	229.9	187	130	67	3,870	0.048	1,195
	LP.C9.K6	229.9	229.9	187	35	100	33	0.048	7
Cold utility	H1.WATER.K5	130	55	5.002	5	82	1,035	0.048	264
	H3.WATER.K1	62.591	40	5.1	5.002	45	52,329	0.048	24,060

EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
Nop 2 year									
20	H2.C1.K7	130	98	55	45.643	63	2,453	0.025	1,557
	H3.C1.K8	67.802	65.013	45.643	21	32	6,460	0.025	8,117
	H3.C2.K2	130	67.802	98	21	39	26,475	0.025	27,203
	H3.C3.K2	130	67.802	98	35	32	1,380	0.025	1,703
	H3.C5.K2	130	67.802	110	30	28	56,870	0.025	81,372
	H3.C6.K2	130	67.802	110	21	32	49,371	0.025	62,672
	H3.C7.K2	130	67.802	110	43	22	9,978	0.025	17,886
Hot utility	LP.C4.K2	230	229.9	40	35	192	284	0.048	31
	LP.C5.K2	230	229.9	187	110	75	54,737	0.048	15,216
	LP.C6.K2	230	229.9	187	110	75	42,714	0.048	11,873
	LP.C7.K2	230	229.9	187	110	75	11,467	0.048	3,188
	LP.C8.K2	230	229.9	187	130	67	3,870	0.048	1,195
	LP.C9.K6	229.9	229.9	187	35	100	33	0.048	7
Cold utility	H1.WATER.K5	130	55	5.002	5	82	1,035	0.048	264
	H3.WATER.K2	65.013	40	5.1	5.002	46	57,939	0.048	26,051

**Table R3** The result of the exact area calculation for the case study 3 CHAMENS (continued).

EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
			Nop	2 year					
25	H2.C1.K7	130	98	55	45.643	63	2,453	0.025	1,557
	H3.C1.K8	70.855	68.067	45.643	21	35	6,460	0.025	7,383
	H3.C2.K2	130	70.855	98	21	40	26,475	0.025	26,301
	H3.C3.K2	130	70.855	98	35	34	1,380	0.025	1,628
	H3.C5.K2	130	70.855	105	30	32	53,316	0.025	66,075
	H3.C6.K2	130	70.855	105	21	36	46,597	0.025	51,778
	H3.C7.K2	130	70.855	105	43	26	9,233	0.025	13,989
Hot utility	LP.C4.K2	230	229.9	40	35	192	284	0.048	31
	LP.C5.K2	230	229.9	187	105	77	58,292	0.048	15,821
	LP.C6.K2	230	229.9	187	105	77	45,488	0.048	12,346
	LP.C7.K2	230	229.9	187	105	77	12,211	0.048	3,314
	LP.C8.K2	230	229.9	187	130	67	3,870	0.048	1,195
	LP.C9.K6	229.9	229.9	187	35	100	33	0.048	7
Cold utility	H1.WATER.K1	130	55	5.1	5.098	82	1,035	0.048	264
	H3.WATER.K7	68.067	40	5.098	5	48	65,013	0.048	28,447

EMAT	Stream matching	tik	tik+1	tjk	tjk+1	LMTD	Q	U	Area
	Nop 2 year								
30	H2.C1.K7	130	98	53.265	43.909	65	2,453	0.025	1,515
	H3.C1.K8	73.909	71.316	43.909	21	39	6,005	0.025	6,116
	H1.C4.K9	130	109.444	40	35	82	284	0.025	138
	H3.C2.K2	130	73.909	98	21	42	26,475	0.025	25,472
	H3.C3.K2	130	73.909	98	21	42	1,380	0.025	1,327
	H3.C5.K2	130	73.909	100	30	37	49,761	0.025	54,517
	H3.C6.K2	130	73.909	100	21	40	43,823	0.025	43,424
	H3.C7.K2	130	73.909	100	43	30	8,488	0.025	11,150
Hot utility	LP.C1.K2	230	229.9	55	53.265	176	455	0.048	54
	LP.C5.K2	230	229.9	187	100	79	61,846	0.048	16,403
	LP.C6.K2	230	229.9	187	100	79	48,261	0.048	12,800
	LP.C7.K2	230	229.9	187	100	79	12,956	0.048	3,436
	LP.C8.K2	230	229.9	187	130	67	3,870	0.048	1,195
	LP.C9.K6	229.9	229.9	187	35	100	33	0.048	7
Cold utility	H1.WATER.K5	109.444	55	5.1	5.099	74	751	0.048	212
	H3.WATER.K7	71.316	40	5.099	5	49	72,539	0.048	30,874

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