OPTIMAL DESIGN OF HEAT RECOVERY SYSTEM

AZRI BIN MARMOH

A project report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor (Hons.) of Chemical Engineering

MARCH 2013

FACULTY OF CHEMICAL & NATURAL RESOURCES ENGINEERING
UNIVERSITI MALAYSIA PAHANG

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UMP or other institutions.

Signature: ___________________________

Name: ___________________________

ID No. : ___________________________

Date: ___________________________

APPROVAL FOR SUBMISSION

I certify that this project report entitled “OPTIMAL DESIGN OF HEAT RECOVERY SYSTEM” was prepared by AZRI BIN MAROH has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Chemical Engineering at Universiti Malaysia Pahang.

Approved by,

Signature: __________________________

Supervisor: Zainatul Bahiyah Handani

Date: __________________________

Specially dedication to my beloved mother and father for their support and conditional love.

ACKNOWLEDGEMENTS

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Cik Zainatul Bahiyah Handani for her invaluable advice, attention, careness, guidance and her enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to my loving parent, brothers and friends who had helped and given me encouragement.

OPTIMAL DESIGN OF HEAT RECOVERY SYSTEM

ABSTRACT

High energy usage has been a huge problem in all areas of the chemical industry. With the growing awareness of green engineering, energy usage needs to be reduced by some means. This study explains how energy usage is reduced through atechnique called process integration which is achieved through mathematical programming. Software called Generalized Algebraic Modeling System (GAMS) is used to do the mathematical programming. Although many methods can be used, this paper covers the usage of Linear Programming (LP) to reduce energy usage. An ethylbenzene plant in Korea was used as a case study (Yoon et al., 2007) to verify the model developed. Transportation model was used as the mathematical model to solve this problem. The procedures involved 3 steps, (1) data extraction from the process data, (2) superstructure representation, and (3) mathematical modeling. The simulation results produced by GAMS were analysed based on three important criteria to select the valid match ups between hot streams and cold streams. As a result, usage of cooling and heating utility was reduced by 79.3% and 28.2% respectively.

REKA BENTUK OPTIMUM SISTEM PEMULIHAN HABA

ABSTRAK

Penggunaan tenaga yang terus menerus meningkat telah menjadi satu masalah yang besar dalam semua bidang industri kimia. Hal ini kerana sumber tenaga seperti bahan bakar semakin berkurangan. Oleh itu, beberapa pendekatan digunakan untuk mengurangkan masalah ini. Sehubungan itu, kajian ini menerangkan bagaimana penggunaan tenaga dikurangkan melalui integrasi aliran proses yang dicapai melalui pengaturcaraan matematik. Perisian yang dipanggil Pemodelan Umum Sistem Algebra (PUSA) digunakan untuk melakukan pengaturcaraan matematik. Walaupun banyak kaedah boleh digunakan, kertas ini meliputi penggunaan Pengaturcaraan Linear (LP) untuk mengurangkan penggunaan tenaga. Sebuah kilang ethylbenzene di Korea telah digunakan sebagai kajian kes (Yoon et al., 2007) untuk mengesahkan kebolehan sistem ini. Model pengangkutan telah digunakan sebagai model matematik untuk menyelesaikan masalah ini. Prosedur yang terlibat 3 langkah, (1) pengekstrakan data dari data proses, (2) mahastruktur perwakilan, dan (3) pemodelan matematik. Keputusan simulasi yang dihasilkan oleh PUSA dianalisis berdasarkan tiga kriteria penting untuk memilih integrasi sah antara aliran panas dan sungai sejuk. Hasilnya, penggunaan penyejukan dan utiliti pemanasan telah dikurangkan sebanyak 79.3% dan 28.2%.

TABLE OF CONTENTS

DECLARATION **ii**
APPROVAL FOR SUBMISSION **iii**
ACKNOWLEDGEMENTS **vi**
ABSTRACT **vii**
TABLE OF CONTENTS **ix**
LIST OF TABLES **xii**
LIST OF FIGURES **xiii**
LIST OF SYMBOLS / ABBREVIATIONS **xv**

CHAPTER

1 **INTRODUCTION**

1.1 Research Background 1
1.2 Problem Statement 4
1.3 Objective of the Study 4
1.4 Scope of Study 4
1.5 Significance of Research 5

2 **LITERATURE REVIEW**

2.1 Introduction 6
2.2 Heat Exchanger Network 6

2.3 The relation of Energy Recovery and Energy Cost 7

2.3.1 Pinch Analysis Technique 8
2.3.1.1 Previous Works on Pinch Analysis Technique 9
2.3.2 Mathematical Programming 12
2.3.2.1 Previous Works on Mathematical Programming Technique 13
2.4 Other Techniques 15
2.5 Problem and Selection 16

3 METHODOLOGY

3.1 Introduction 17
3.2 Step 1: Data Extraction from the Process Data 18
3.3 Step 2: Superstructure Representation 20
3.4 Step 3: Mathematical Modeling 21
3.4.1 Transportation Model 22
3.5 Step 4: Model Application 24

4 RESULTS AND DISCUSSIONS

4.1 Introduction 25
4.2 Limitation Heat Data Extraction 25
4.3 Optimization Results 32
4.3.1 First Stage of Oprimization 33
4.3.2 Second Stage of Optimization 37
4.4 External Utility 45

5 CONCLUSION AND RECOMMENDATIONS
5.1 Conclusion 46
5.2 Recommendation 47

REFERENCES 48

APPENDICES 52

LIST OF TABLES

TABLE	TITLE	PAGE
Table 4.1	Hot Stream Data	26
Table 4.2	Cold Stream Data	27
Table 4.3	The Remain Hot Streams	28
Table 4.4	The Remain Cold Streams	29
Table 4.5	Transportation Model	30
Table 4.6	GAMS Result with Valid Connection	39
Table 4.7	Temperatures Changes of Streams	40

LIST OF FIGURES

FIGURE	TITLE	PAGE
Figure 1.1	Energy Consumption (BTU) by Sector. (Source: Annual Energy Outlook Consumption 2010)	2
Figure 1.2	Industrial Energy Used with Proportion by Industry. (Source: Annual Energy Outlook Consumption 2010)	2
Figure 2.1	Historical panorama of Pinch Technology approaches over the last decades. (Escobar & Trierweiler, 2013)	10
Figure 2.2	Type of Mathematical Programming	13
Figure 2.3	Historical panorama of Sequential Synthesis approaches over the last decades. (Escobar & Trierweiler, 2013)	14
Figure 2.4	Historical panorama of Simultaneous approaches over the last	

decades. (Escobar & Trierweiler, 2013) 15

Figure 3.1 Flow of Methodology 18

Figure 3.2 Superstructure Representation 20

Figure 3.3 Transportation Model Superstructure (Rezaei and Shafiei, 2008) 21

Figure 4.1 Optimisation Result for Stage 1 33

Figure 4.2 Grid Diagram Illustration 34

Figure 4.3 Optimization Result For Stage 2 37

Figure 4.4 HEN Grid Diagram after Simulation 39

Figure 4.5 HEN Grid Diagram after Simulation with Utilities 41

LIST OF SYMBOLS / ABBREVIATIONS

cp	specific heat capacity, J/(kg□K)
F	flowrate, kg/hr
Hn	hot stream number
Cn	cold stream number
Xn	amount of heat energy that will be shared by two streams, kW
Z	total heat duty / total enthalpy, kW
ΔH	enthalpy / heat duty, kW
Tin	inlet temperature, °C
Tout	outlet temperature, °C
ΔT	temperature difference, °C

GAMS	general algebraic modelling system
HEN	heat exchanger network
HENS	heat exchanger network synthesis
LP	linear programming
MILP	mixed integer linear programming
MINLP	mixed integer non linear programming
NLP	non linear programming

CHAPTER 1

INTRODUCTION

1.1 Research Background

Energy demand is increasing as a consequence of population growth and economic development. Economists will consider on profit, trading, and market of energy when they give definition on it. It is differ with socialists and humanists; they are talk lots about the future energy needs for living life being. The politicians look energy as could be manipulated in order to maintain their power either by using military and government that they care off. Even though, the fact that energy productive sources continue to decrease which correspond to less renew energy cannot be denied. This make the energy conservation remains the prime concern for many organizations, authority, and private institution especially in process industries. In December, the U.S. Energy Information Administration released a sneak preview of the 2011 outlook report. The consumption numbers is expressed in graphical form because it is most effectively portrayed that way. Figure 1.1 shows that industries lead the consumption of energy and the detail for componwnt in industies is illustrated in Figure 1.2.

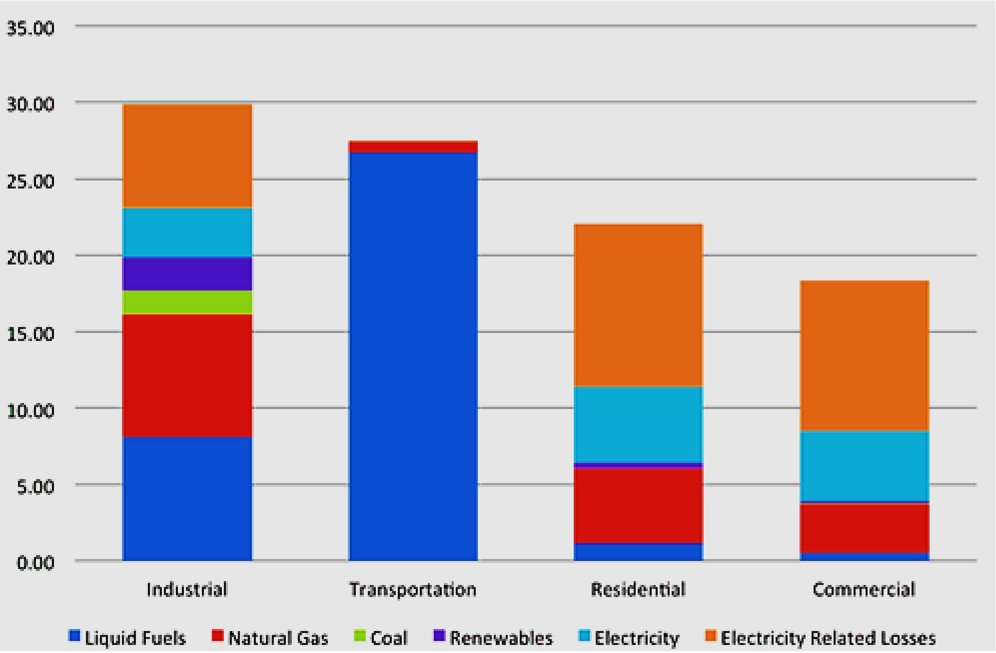


Figure 1.1 Energy Consumption (BTU) by Sector. (Source: Annual Energy Outlook Consumption 2010)

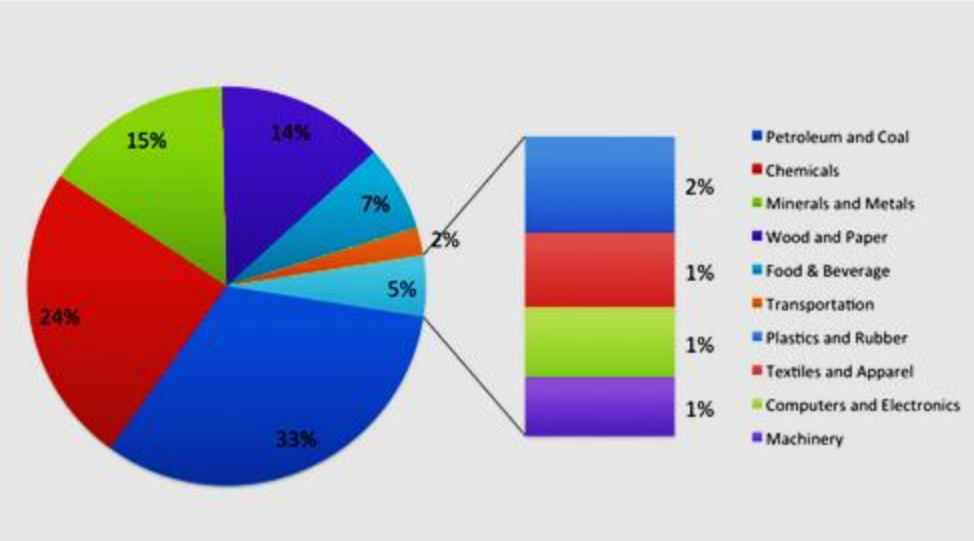


Figure 1.2 Industrial Energy Used with Proportion by Industry. (Source: Annual Energy Outlook Consumption 2010)

Since industry sector leads the consumption of energy, the purpose of energy savings, the methods of analysis, synthesis and optimization are becoming more important. Some challenges must be face and overcome such to optimize energy consumption with industrial rapid growth. Sometimes, the step to achieve this purpose will deplete lots of money after considering capital investment, operational costs related to friction losses, and maintenance costs deriving from the cleaning schedule (Antone *et al*,. 2011). Lizbeth *et al*. (2010) have been proved in their work which is minimizing costs and optimal energy savings could be achieved simultaneously. Heat integration become the famous focussed activity in industry or process plant in term of the development of optimal design system. The optimal design could be done by fixed the objective function as to maximize heat recovery.

Heat exchanger become a very useful equipment but it is not effective if it just to function without any adjustment. Kesler and Parker (1969) have noticed about this thing started long time ago and they decided to divide each stream into small heat duty elements of equal size and posed the matching between hot and cold elements as an assignment problem. The reseach has been improved and has many new tecnology researches on it until this thesis was written with introduce the mathematical modelling development. The common topic about heat exchanger network (HEN) was included a set hot streams that need to be cooled at the inlet temperature to the outlet temperature, a set cold streams that need to be heated at the inlet temperature to the outlet temperature, the heat capacities and flow rate of the all streams, the utilities available, and heat exchanger costs.

1.2 Problem Statement

Energy sources are kee decreasing which is corresponding to the growth of energy consumption and demand. It was getting more complicated because of the limited alternatives for unrenewable energy sources. It was giving impact to the cost of the energy in market that doing energy businesses. At the same time, industrial sectors have very instant energy consumption which needs to be optimized. Optimization of heat integration was really help in reduce the cost that spent for large number of heat exchangers, utility used and other related variables. Thus, the reduction of heat consumption can be done by maximizing heat recovery through development of mathematical modelling.

1.3 Objective of the Study

The objective of this study is to develop a mathematical approach for designing and formulate a system in order to achieve the optimum heat recovery.

1.4 Scope of the Study

There are three research scopes for this work which are:

i) To analysis techniques related to energy reduction.
ii) To develop mathematical formulation for optimal design of maximum heat recovery.
iii) To applied for optimization model on industrial case study in order to illustrate the effectiveness of the proposed approach.

1.5 Significant of Study

This study is very important in order to determine the optimal design of heat recovery which corresponds to minimize utility consumption.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes all the selected researches and works that have been done by previous researchers. A general review on heat exchanger network, using pinch analysis and mathematical programming are discussed in Section 2.1. The explanation about these two methods is focused on current and previous works. Several other methods also be introduced and the last is problem and selection.

2.2 Heat Exchanger Network

Heat exchanger network (HEN) synthesis is a study on how to develop network either integration of utilities or process streams in process engineering systems which can affect the energy recovery and energy costs. The common subjects that are discussed in HEN designation are set of hot process streams to be cooled from the inlet temperatures to the outlet temperatures, set of cold process streams to be heated from the inlet temperatures to the outlet temperatures, the heat capacities and flow rates of the hot and cold process streams, the utilities available and the temperatures or temperature ranges and the costs for these utilities, and heat-exchanger cost data. Historically, Broeck (1994) had proposed this kind of design basic problem and before that Hwa (1965) take more seriuos to extend the research till the grassroots. Masso & Rudd (1969) took initiatives progrresively manage the basic problems using algorithm methode involving often some established optimization principles. Extensively, Shenoy (1995) and Smith (1995) have been proposed the fundamental of HEN systematically.

2.3 The relation of Energy Recovery and Energy Cost

Heat exchanger network synthesis (HENS) problems have the significant priority to be solved. It is because lots of energy can be saved and be used back. As correspond to the energy costs increament, industries have greater incentive to apply heat integration as broadly as possible in its facilities (Errico, 2006). In practice, industrial plants are usually cold process streams that need heating and hot process streams that need cooling, usually achieved using hot and cold utilities and consequently increasing energy costs. One way to reduce these costs is by matching and configuring the process streams, which is the hot process streams would be match with cold stream process streams, with all possible routes and with certain constraints. In order to reduce the energy costs to a minimum, the most effective exchange of energy between process streams must be obtained. The trade-off between energy recovery and energy costs involved really complex design of solution. Conventional methods do not, however, accurately capture the three-way trade-off between heat exchanger units, heat exchange area and energy used (Sethna et al., 2000). Besides, utilities also are one of the important factors that affect the trade-off.

The most widely used utilities belong to three different types which are hot utility, including steam, coal, hydrocarbon fuels; the cold utility including cooling water, and air; and work utility, which transports process loads within the system, with the simultaneous generation or consumption which is electricity and shaft work. Each utility has an associated unit cost (Konstantinos & Vasilios, 2002). As far as the objective function is considered, Capturo et la., 2008 make conclusion there are most authors consider the sum of capital investment related to the heat transfer area, and energy related costs. In order to get the optimum solution and to overcome the complexity, pinch analysis techniques and mathemathical modelling become famous widely used method and always continuously improved from day to day. Pinch analysis was presented (Linhoff, 1979), and mathematical modelling was proposed (Weaterberg & Grossmann, 1985).

2.3.1 Pinch Analysis Technique

In this technique, hot and cold streams are match to get the maximum energy recovery (MER) network. The search space of possible design solution can be reduced. The essential matches, matching option, and the requirement of streams splitting are decided by certain feasibility criteria. The criterion that needs to be concerned too is the number of streams in the pinch. This implies that to bring the hot streams to their pinch temperature with the cold streams helps. The next criterion is about the temperature in the pinch point. As the temperature is minimum in the pinch, the temperature driving pinch cannot decrease as one move further away from the pinch. Hot and cold streams must almost just present one segmented straight line in T-Q graph. Linnhoff and Hindmarh (1983) have been explained detail in their research about rule of using this technique. Now, the fundamental principles about this technique have been solved for the past several decades and the research now will not in the pinch technology itself, but with the integration with the other technology or solution such meta-heuristic method (Mofid et al., 2011). However, the pure works on pinch technology will be explained in the next subtopic. It will include the important concepts, targets, synthesis methods, optimization, and flexibility.

2.3.1.1 Previous Works on Pinch Analysis Technique

In this subtopic, the explanation is divided into two phases of work, which are year before 2000 and year after. As reminder, the researches for the first phase will present the fundamental and most of their evolutions on pinch techniques have been accomplished. Linnhoff and Hindmarsh (1983) had solved the HENS problems and achieve in most cases of heat integration a nearly optimal solution using pinch analysis. The method was simple enough to be used with manual calculation and by using this method it is possible to find the highest degree of energy recovery with a given number of capital items (Errico et al., 2007). However, it cannot solve many objective functions simultanuosly. As the alternatives and complementary, most of the methods either use mixed integer linear or non-linear formulations or are based on the pinch method.

Mixed integer formulations are capable of providing the global optimal solution to these problems and may ultimately prevail as the method of choice for HENS, but computational effort currently limits their application in the case of large problems. On the other hand, the pinch method is not able to find the global solution but its application is simple and large HENS problems can be solved especially for industrial designer plant. This, for sure introduce some limitation since the trade-offs between the utility consumption, the number of matches, and the minimum investment cost are not take into account appropriately and it may result in HEN designs that are suboptimal networks (Floudas, 1995). The sequential approach stated by him has limitation, caused researches in the late 1980s and early 1990s focused on simultaneous approaches with focus on the synthesis as a single-task problem considering all trade-offs simultaneously (Ciric & Floudas 1991). These approaches are for sure result in more complex models. However, advances in theoretical and algorithmic aspects of optimization have allowed large scale complex model problems to be solved. Figure 2.1 shows the historical panorama of pinch technology approaches over the last decades.

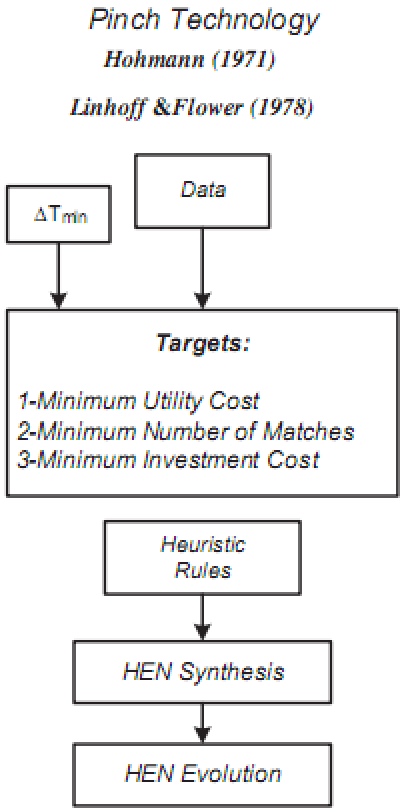


Figure 2.1 Historical panorama of Pinch Technology approaches over the last decades. (Escobar & Trierweiler, 2013)

Through the previous continuous improvement on pinch analysis, Ciric and Floudas, (1990) were obviously explained of their proposal using three temperature approaches with formulate the pseudo-pinch problem for simultaneous network optimization. Approximately one year later, in different paper they came out with the specific simultaneous optimization, included utilities, number of matches, and network configuration. Meanwhile, Jowski (1991) has introduced dual temperature approach (DTA), which is can cause cross-pinching. Even though, this method suitable to be used for stemming from physical insights for HENS. He approved thi work with concern to the PDM, DTA, various HENS targets, and super targeting. In other work, Hui and Ahmad (1994) have been proposed heat integration between different chemical processes in a plant. This is for optimizing the common utility system.

Lee and Yoo (1995) addressed the multiple pinch points with the separation of system which subdivides the HENS problems into independent subsystem with specific one pinch point. Kane and Favrat (1999) have been work on using pinch technology for design HEN for integrated solar combined cycle system. Klemes et al., (1999) have been presented that the pinch method for HENS is applied to an oil-refining plant in the Ukraine which similar to Lababidi et al., (1999) work, but their work was on a retrofit study of an ammonia plant is performed using pinch technology. Pinch technology shows the good progress on solving things regarding to HENS. But, as said by Massimiliano (2007), this method is easy to be utilized, but it is not possible to be sure to achieve the optimal configuration because it is necessary to make heuristic choices. Hossein Y. et al., (2011) still try to defend about the advantage of this method, which is flexible and provides a good view for the designer.

2.3.2 Mathematical Programming

Mathematical Programming Method is very important in order to solve the complex modal. The programming used well known as linear programming(LP), non-linear programming (NLP) mixed integer linear programming (MILP), and mixed integer non linear programming (MINLP) models whereby continuous variables represent process parameters such heat-exchanger duties and stream-split fractions and integer variables represent discrete decisions that is heat-exchanger matches. The applications include methods either with or without decomposition. The problem decomposition is generated by the need to simplify the optimisation. Its most successful version has been proposed in the form of a MILP-NLP approach (Floudas et al., 1986).

The MILP model functions as to determine targets and matches while the NLP is used to optimises the heat transfer areas and the overall cost. If without decomposition, the simultaneous optimisation of matches and heat transfer area are result the complication and make the problem very difficult to solve. Even Viswanathan and Grossmann (1990) said heuristic strategies have been used to try to reduce the effect of non-linear none of the above techniques can guarantee global optimum solutions when solving non-linear MINLP problems. Jelodar et al., (2010) also said the same thing which mathematical formulation of these methods is such that for the bigger networks higher than medium, volume of the optimization problem grows uncontrollably. Figure

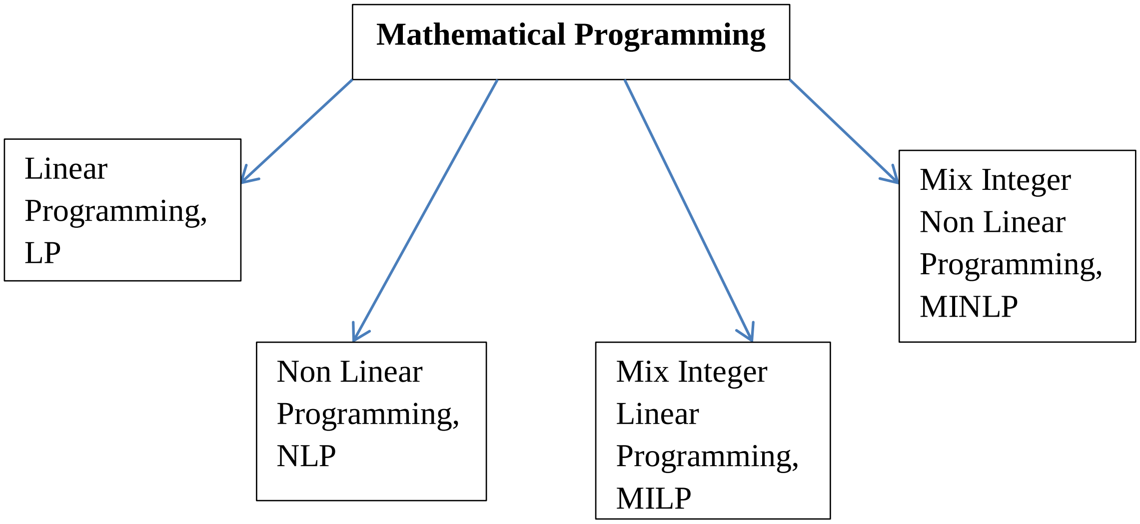


Figure 2.2 Type of Mathematical Programming

2.3.2.1 Previous Works on Mathematical Programming Technique

Papoulias and Grossmann (1983) introduced the linear programming (LP) transshipment for energy targeting. MILP is used by them to formulate the minimum unit problem. Ciric and Floudas (1990) developed an MINLP formulation of the retrofit HENS problem. They solved the formulation using generalized Benders decomposition. In the other work, they discussed retrofit HENS by using an MINLP formulation method that selects process stream matches and match-exchanger assignments while simultaneously optimizing the network structure. This will cause the basis of actual area requirements, as opposed to estimates of area and piping costs.

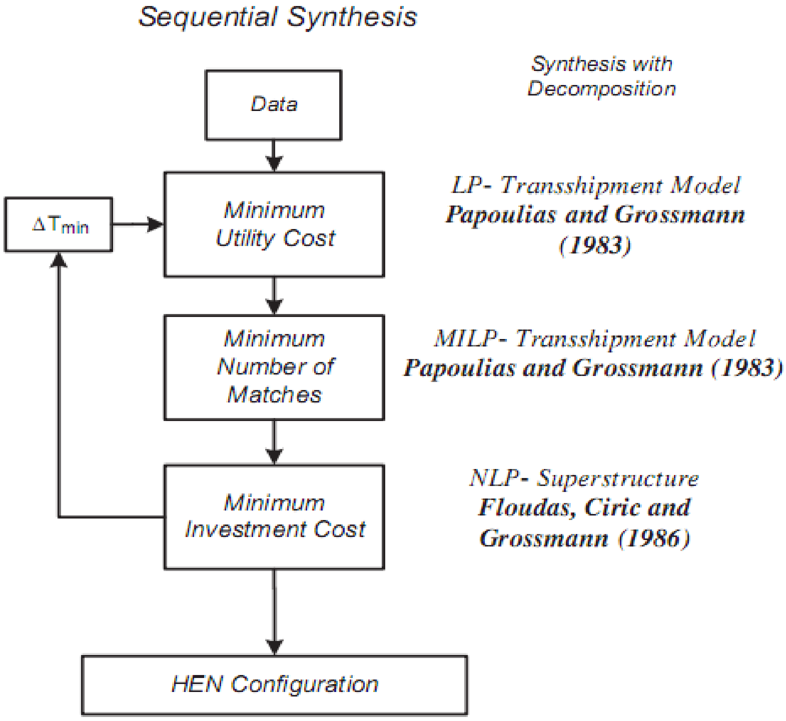


Figure 2.3 Historical panorama of Sequential Synthesis approaches over the last decades. (Escobar & Trierweiler, 2013)

Daichendtand Grossmann (1994) made the effort of Yee and Grossmann (1990) with used in a preliminary screening procedure to determine a subset of solutions from the original superstructure that are bounded to a base-case design. This will reduce the complicated structure of the superstructure. Grossmann and Kravanja, (1995) continue their work on process design and optimization by using MINLP technique. Even this work looks near to completion, Galli and Cerda (1998) have been tried develop three-stage framework for sequential HENS with specified structural conditions involved MILP. It advantage was structural restriction is generalized to allow split networks. An existing HEN is audited for possible modifications, and then these modifications are screened using MILP models (Brionass and Kokossis, 1999). The hypertarget concepts are applied to retrofit HENS.

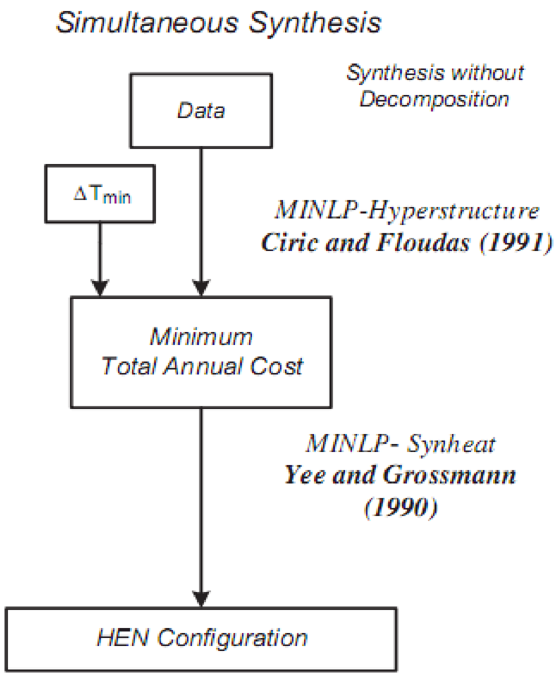


Figure 2.4 Historical panorama of Simultaneous approaches over the last decades. (Escobar & Trierweiler, 2013)

2.4 Other Techniques

Both pinch and mathematical programming methods have their own obvious weaknesses. Therefore, the method to solve for the suboptimal part have introduce by Atheir et al. (2010) as Meta-heuristic Optimization Methods. The example of this method are Genetic Algorithm (GA) (Androulakis & Venkatasubramanian, 1991), Simulated Annealing techniques, (Le Van, 1987), combination of GeneticAlgorithm and simulated annealing (Yu, Fang et al. ,2000), Tabu search (Lin & Miller, 2004), deterministic algorithm (Ericco et al. 2006). Of all these, Genetic Algorithm has been the most popular. GA belongs to a new generation type of methods called Evolutionary Algorithms (EA).

2.5 Problem and Selection

Now, let discuss about the focus issue. The target now is to maximize the heat recovery from the network. This problem is not just about to reduce the costs aspects, but to minimize the energy used so that energy could be conserve for future. This is of course will give impact to the environment which means such good and optimum utilities need the compatible site or land for the plant. In this work, we will not try to consider all of those things and solve it simultaneously, but only highlight on the efficiency of heat transfer between two interval streams temperatures. Mathematical programming method is enough to identify the optimal design and formulate the appropriate model. This paper describes a general model for the HEN which can be solved with a mathematical programming method to design the network of heat exchangers which recovers the maximum amount of energy. A methodology based on Linear programming (LP) model for synthesizing and optimizing large heat exchanger networks has been presented. The proposed technique allows both the topology and the heat load distribution to be solved simultaneously.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will present a detail procedure for the optimal design of heat recovery network. There are four major steps in order to solve this work. Step 1 would be data extraction from retrieved case study. Step 2 involved the superstructure representation which means the integration of the streams. Then, mathematical formulation is developed. After that, the formula is coded in the Generalized Algebraiac Modelling System (GAMS) software through Linear Programming (LP) route. Lastly, the result from GAMS software is analyzed.

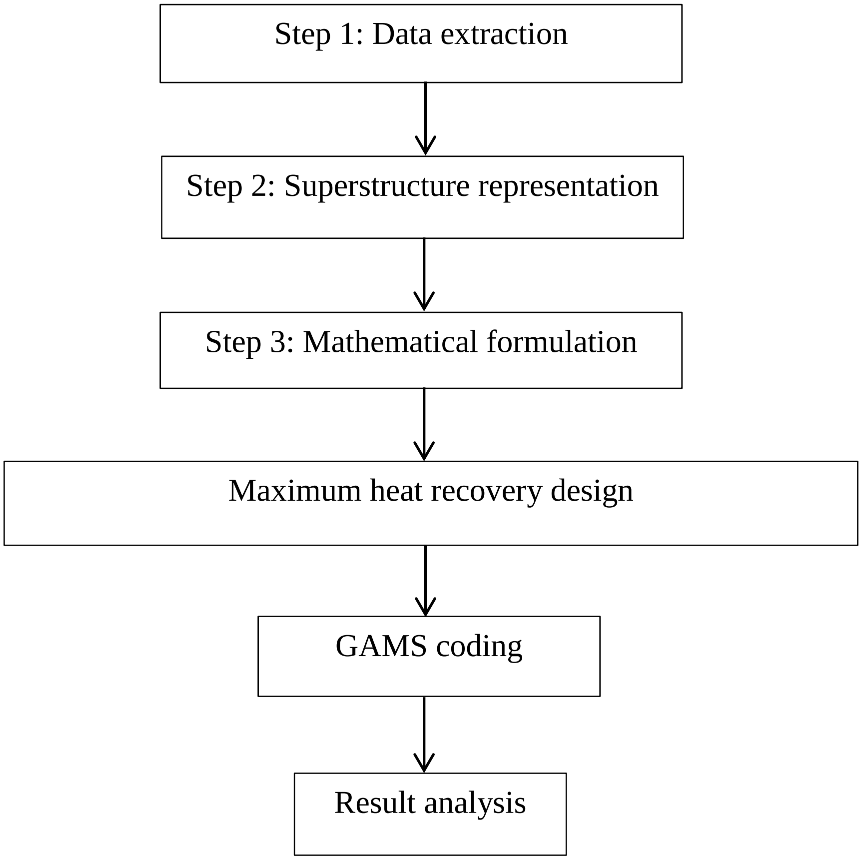


Figure 3.1 Flow of Methodology

3.2 Data Extraction

The main data that was obtained is the hot stream data and the cold stream data. These data should include parameters such as entering temperature, exiting temperature, heat duty and heat capacity. There are several sources where these data can be obtained:

1) Existing plant records

This is the most obvious source. Most of facilities may have computerised monitoring of process flows throughout the plant.

2) Design data

Where available and still reasonably applicable, the original design figures can be utilised to estimate the missing data.

3) Manual measurements

Many smaller streams or non-process streams may not be monitored. Sometimes these streams cannot be estimated from mass balance calculations. Although not as accurate as plant records, manually measuring streams where data are not available can give an estimation of typical stream flows if several measurements are taken over a representative time interval.

4) Personal communication

The estimation of relevant flows can be provided by plant personnel who are experienced with plant operating conditions when other data are not available. This is the least reliable form of data, but can provide a quick insight into relative flow rates. In this study, the first form of data source which is the most reliable one, existing plant records was used.

3.3 Superstructure representation

The second step is to generate the superstructure. This superstructure was used in any other optimization study on process synthesis. This step must be clarified because involved the view on the matching between hot and cold streams. All the possible connection between the hot and cold streams is presented in the figure 3.2. The meaning of possibility in the figure is the hot streams will not only give the heat to the only one of cold streams. A cold stream has the possiblity accept heat from two or more hot streams.

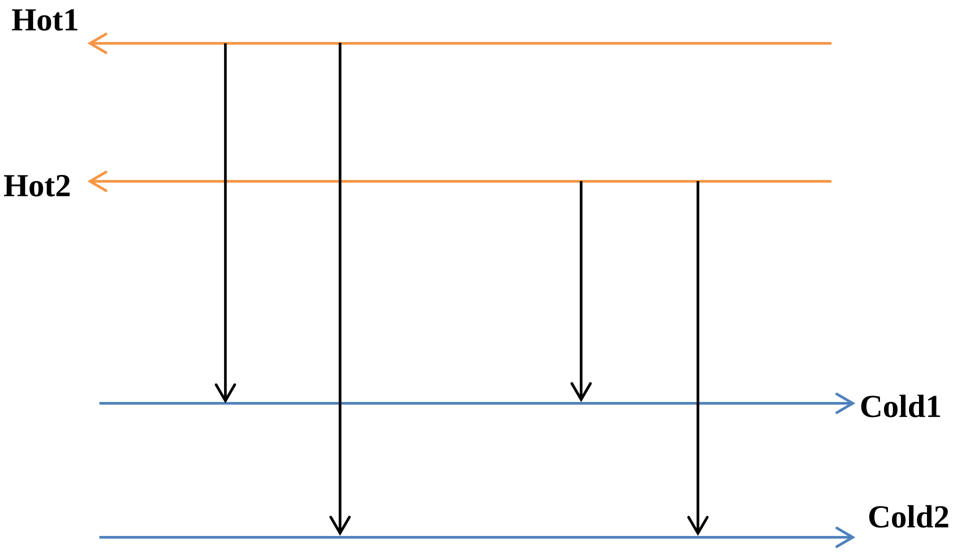


Figure 3.2 Superstructure Representation

3.4 Mathematical Formulation

Closely related to the selection of the superstructure, is the selection of level of detail of the optimization model. A common misconception about the mathematical programming approach is that models are always detailed and require a great deal of information. This, however, is not necessarily true. In general mathematical programming models can be classified into three main classes:

a) Aggregated Models
b) Short Cut Models
c) Rigorous Models

Aggregated models refer to high level representations in which the design or synthesis problem is greatly simplified by an aspect or objective that tends to dominate the problem at hand. Examples of aggregated models include the transshipment model for predicting minimum utility and minimum number of units in heat exchanger networks (Papoulias & Grossmann, 1983). These models were specific to the corresponding problem at hand.

Short cut models refer to fairly detailed superstructures that involve cost optimization (investment and operating costs), but in which the performance of the units is predicted with relatively simple nonlinear models in order to reduce the computational cost, and for exploiting the algebraic structure of the equations, especially for global optimization. Examples of such models include synthesis models for heat exchanger networks (Yee et al., 1990).

Rigorous models rely on detailed superstructures, but involve rigorous and complex models for predicting the performance of the units. The area of synthesis of distillation sequences (ideal and non-ideal) is perhaps the one that has received the most attention for developing rigorous models.

It should be noted that aggregated models give rise to simpler types of optimization models. They are often Linear Programming (LP), Non-Linear Programming (NLP) or Mixed Integer Linear Programming (MILP) models of modest size that are simpler to solve than larger Mixed Integer Non-linear.

3.4.1 Transportation Model

The transportation model is a special case of the linear programming model. Given m sources and n destinations, the supply at source i is ai and the demand at destination j is bj. The cost of shipping one unit of goods from source i to destination j is cij. The goal is to minimize the total transportation cost while satisfying all the supply and demand restrictions. The basic idea in a transportation problem is that there are sites or sources of product that need to be shipped to destinations. Typically the routes and the amounts shipped on each route must be determined and the goal is to minimize the cost of shipping. The constraints are that you can not ship more from a source than made at that source and you do not want to ship more to a place than needed.

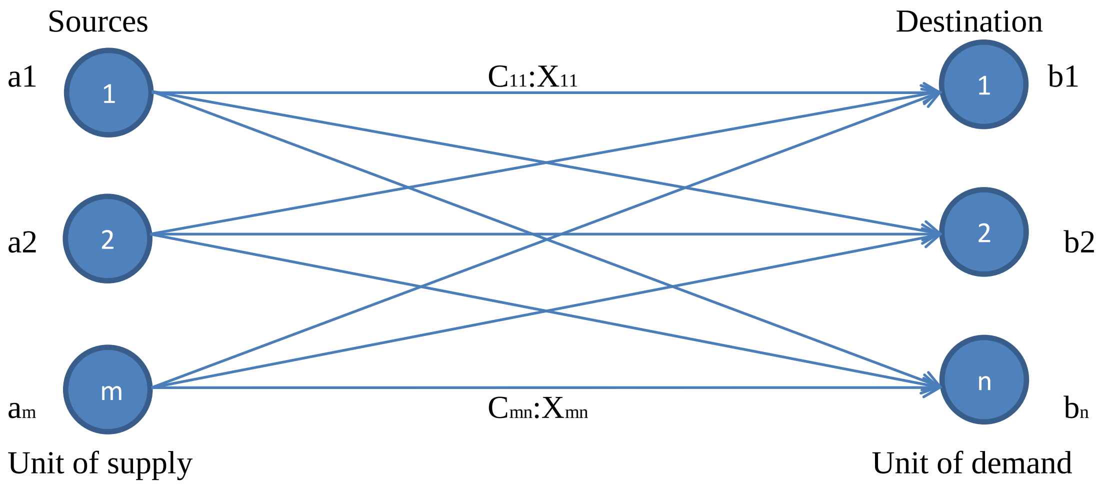


Figure 3.3 Transportation Model Superstructure (Rezaei and Shafiei, 2008)

In this work, this model is applied. It is because transportation model is the simplest model that can be used to solve a heat exchanger network synthesis problem. It usually can be solved simply using linear programming. Moreover, in this project we only focus on reducing the energy usage, not the operating cost of the plant. This makes transportation model perfect for this problem.

So the way transportation model is defined was changed in terms of this project. In this problem, heat is transported as good. The two point of location was two different streams, a cold stream and a hot stream. The hot stream served as the supply since the hot stream loses heat to cool down and the cold stream was the demand since it absorbs heat to increase its temperature. So, the total heat duty or enthalpy, kW of hot stream represents the total supply, amount of heat ready to be supplied. Whereas, the total heat duty or enthalpy, kW of cold stream will represent the total demand, amount of heat needed. Heat duty of both cold streams and hot streams directly represent the amount of heating utilities and cooling utilities that are used in a chemical plant. Whereas, the amount of heating utilities and cooling utilities represent the portion of energy used in a plant. Therefore, heat duty, kW is the variable aimed to reduce.

3.5 Model Application

Step 4: Model Application

Development model will be implemented in General Algebraic Modeling System (GAMS). This model designs a heat exchanger network which has the target to maximize energy recovery using linear programming through CPLEX solver. Operate at 2.4 GHz with operating system of windows 7 64-bit.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter discusses and explains the results obtained from the implementation of developed model on the selected case study. Since the main aim of the applied technique is to reduce the energy consumption in plant by retrofiting the heat exchanger network, a case study of Ethylbenzene plant in Korea (Yoon et al., 2007) was chosen to show the applicability of this method.

4.2 Limiting Heat Data Extraction

A case study on heat used in Ethylbenzene plant in Korea (Yoon et al., 2007) was taken to show the applicability of the proposed model. The main data that was obtained is the hot stream data and the cold stream data. These data include parameters such as entering temperature, exiting temperature, heat duty and heat capacity. Table 4.1 and 4.2 show hot streams and cold streams data of the plant.

Table 4.1 Hot Streams Data

Stream No.	**T in(°C)**	**T out(°C)**	**HeatDuty (kW)**	**FCp (kW/°C)**
H1	250	221	7655	264
H2	250	215	9021	258
H3	105	31	1908	26
H4	99	98	363	363
H4	98	35	147	2
H5	151	30	422	4
H6	103	31	2759	38
H7	91	90	962	962
H7	90	26	375	6
H8	151	31	705	6

Table 4.2 Cold Streams Data

Stream No.	T in (°C)	T out (°C)	Heat Duty (kW)	FCp (kW/°C)
C1	162	206	9020	205
C2	158	200	3210	76
C3	205	206	4445	4445
C4	40	180	75	0.5
C5	34	87	1007	19
C6	241	242	8999	8999
C7	221	244	5951	259
C8	271	279	2105	263
C9	55	130	230	3
C10	33	90	2625	46
C11	242	246	16989	4247
C12	221	236	8082	539
C13	268	282	3789	271
C14	55	130	512	7
C15	38	48	537	54
C16	104	105	447	447
C17	103	104	407	407

In Table 4.1, the hot streams H4 and H7 presents two different streams which in liquid and gas phases. The phase changes happened with the temperature changes. Thus, in this work, these two streams were ignored since their characters cannot be predicted accurately instead of focus to optimize the other streams. It makes sense that the heat transfer from hot stream to cold stream will be unstable. Same goes with stream C6, C7, C8, C11, C12, and C13 also eliminated, because of their temperatures were very high, and sometimes over the value of hot streams. After screening the feasible stream to be integrated, the left streams data are presented in Table 4.3 and Table 4.4.

Table 4.3 The Remain Hot Streams

Stream	**In (°C)**	**Out (°C)**	**(kW/°C)**	**FCp**
H1	250	221	7655	264
H2	250	215	9021	258
H3	105	31	1908	26
H5	151	30	422	4
H6	103	31	2759	38
H8	151	31	705	6

Table 4.4 The Remain Cold Streams

Stream	In (°C)	Out (°C)	(kW/°C)	FCp
C1	162	206	9020	205
C2	158	200	3210	76
C3	205	206	4445	4445
C4	40	180	75	0.5
C5	34	87	1007	19
C9	55	130	230	3
C10	33	90	2625	46
C14	55	130	512	7
C15	38	48	537	54
C16	104	105	447	447
C17	103	104	407	407

Before mathematically formulating the problem, there are few assumptions that need to be made. First is the process is adiabatic. Secondly, it must be no heat lost to the environment. Lastly, there are no flow rate losses or gains, and hence, no changes in energy flow rates in the energy operations.

Now, since to express the way of the heat duty from the hot streams transferred to cold streams by mathematically formulated, the data in Table 4.3 and 4.4 were rearranged in Table 4.5 which represented as transportation model.

Table 4.5 Transportation Model

j														
i	C1	C2	C3	C4	C5	C9	C10	C11	C12	C14	C15	C16	C17	
H1	X1	X3	X5	X7	X13	X19	X25	X32	X34	X36	X42	X48	X54	7655
H2	X2	X4	X6	X8	X14	X20	X26	X33	X35	X37	X43	X49	X55	9021
H3				X9	X15	X21	X27			X38	X44	X50	X56	1908
H5				X10	X16	X22	X29			X39	X45	X51	X57	422
H6				X11	X17	X23	X30			X40	X46	X52	X58	2759
H8				X12	X18	X24	X31			X41	X47	X53	X59	705
	9020	3210	4445	75	1007	230	2625	16989	8082	512	537	447	407	

Based on the Table 4.5, the necessary formulas can be formulated. This formula shows the relation of supply and demand heat with some constraints.

Objective Function:

$$Z = \Sigma Xn, \tag{4.1}$$

Where,

n = {1,2,3,...59}
Xn = Heat duty that will be shared among two streams, kW
Z = Total heat duty, kW 24

Demand Constraints:

$X1 + X2 \geq 9020$ (4.2)

$X3 + X4 \geq 3210$ (4.3)

$X5 + X6 \geq 4445$ (4.4)

$X7 + X8 + X9 + X10 + X11 + X12 \geq 75$ (4.5)

$X15 + X16 + X17 + X18 \geq 1007$ (4.6)

$X19 + X20 + X21 + X22 + X23 + X24 \geq 230$ (4.7)

$X25 + X26 + X27 + X28 + X29 + X30 + X31 \geq 2625$ (4.8)

$X32 + X33 \geq 16989$ (4.9)

$X34 + X35 \geq 8082$ (4.10)

$X36 + X37 + X38 + X39 + X40 + X41 \geq 512$ (4.11)

$X42 + X\ 43 + X43 + X44 + X45 + X46 + X47 \geq 537$ (4.12)

$X48 + X49 + X50 + X51 + X52 + X53 \geq 447$ (4.13)

$X54 + X55 + X56 + X57 + X58 + X59 \geq 407$ (4.14)

Supply Constraints:

$X1 + X3 + X5 + X7 + X13 + X19 + X25 + X32 + X34 + X36 + X42$
$+ X48 + X54 \leq 7655$ (4.15)

$X2 + X4 + X6 + X8 + X14 + X20 + X26 + X33 + X35 + X37$
$+ X43 + X49 + X55 \leq 9021$ (4.16)

$X9 + X15 + X21 + X27 + X38 + X44 + X50 + X56 \geq 1908$ (4.17)

$X10 + X16 + X22 + X29 + X39 + X45 + X51 + X57 \geq 422$ (4.18)

$X12 + X20 + X32 + X40 + X52 + X60 + X67 + X73 \geq 2759$ (4.19)

$X13 + X21 + X33 + X41 + X53 + X61 \geq 510$ (4.20)

$X12 + X18 + X24 + X31 + X41 + X47 + X53 + X59 \geq 705$ (4.21)

4.3 Optimization Results

The selection of the streams was formulated in GAMS software. The simulation was based on temperature constraint and heat duty. The higher temperature must give energy to the lower stream and just hot streams were allowed to do so. This constraint is determined earlier during streams screening at the beginning. Since this optimization using the concept of transportation model which is put heat duty as the constraint, the greater heat duty bear by any streams will have the priority to give heat to the other streams. This means that cold streams also have the possibility to do so. To avoid problem such complexity in the simulation, with obey to the constraint fixed, the streams were selected randomly. Then, to get the optimal solution, second stage of simulation was run later with involve all left streams which still not optimized.

4.3.1 First Stage of Optimization

Figure 4.1 shows the first simulation result with 8 connections occured from 9 possible routes of connections in the modelling before.

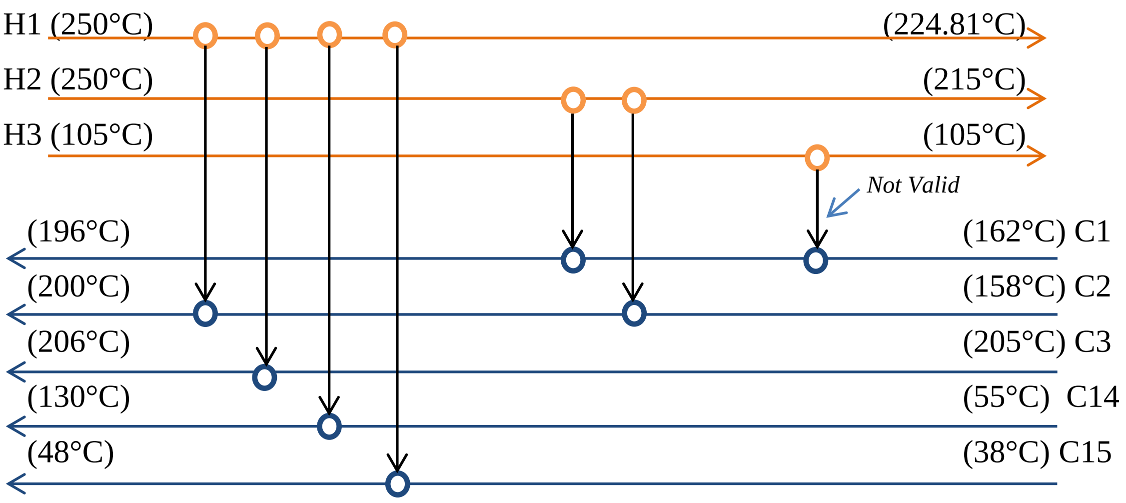


Figure 4.1 Optimisation Result for Stage 1

For the first stage of optimization, there were only 3 hot streams and 6 cold streams selected. Unfortunately, not all among the 8 connections are valid and can be taken into consideration. This is due to temperature constraint as discussed earlier. The inlet temperature of hot stream must be higher than the inlet temperature of cold stream. Before proceed to the justifications of all connections, an important equation must be introduced.

$$\Delta H = FCp\Delta T \qquad (4.2)$$

Where,

ΔH = Enthalpy, W

FCp = (Flow Rate x Heat Capacity), kW/°C
ΔT = Temperature difference, °C

The fact that must be highlighted was a hot stream temperature will be reduced after exchanging heat with a cold stream. So, equation 4.1 was used to find the outlet temperature of the hot stream. If the same hot stream is connected with another cold stream, the outlet temperature of the hot stream from the first connection would become the inlet connection if the same hot stream is then connected to another cold stream. Therefore, in this case, it is important to make sure the outlet temperature of the hot stream from the first connection is higher than the inlet temperature of the cold stream. Figure 4.1 below shows the connection and also the unfavourable way of heat transfer if the temperatures of hot streams lower than cold streams.

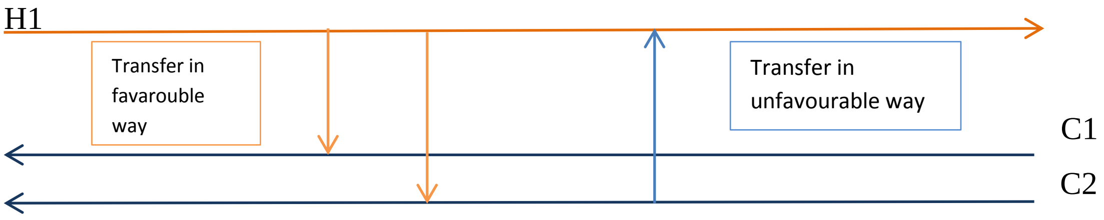


Figure 4.2 Grid Diagram Illustration

According to the system order of the model design in this software, the highest shared of heat duty will be have first turn to be considered. This is one more principle involved. Based on this principle, for hot stream H1, cold stream C3 is the first match since it has the highest amount of heat exchanged. The second stream that can be connected is cold stream C2.

Sample calculation:

ΔH = 4445 kW _____________ GAMS simulation result

FCp = 264 kW/°C ___________ Table 3.1

Tin = 250.00°C

Replacing these values in equation 4.1,

4445 kW = (250°C – Tout) × 264 kW/°C

Tout = 233.16°C

Based on equation 4.1, after the heat transfer has occurred between H1 and C3, the outlet temperature of H1 is reduced to 233.16°C from 250.00°C. From the outlet value of temperature, its value was higher than inlet temperature of C2 which is 150.00°C. Therefore, H1 can then be connected to C2. Since, between H1 and C2, 1301 kW of energy is transferred. This tranfser phonomenan was the second higher amount of transfer from H1. It must be clear that the heat transfers to the C2 still not enough as the target heat to be transferred. Then, to overcome this H2 will give heat to C1 until it achieve the target as coded in GAMS which will be explain later. The energy released caused a temperature drop for H1 and the outlet temperature will be 228.23°C. This value was still much higher than the inlet temperature of C14 which is 55.00°C. So this connection was also valid. After exchanging heat, H1 stream temperature was reduced to 226.29°C. Since C15 temperature was still lower than 226.81°C, H1 can be connected to C15. Lastly, H1 cannot connect to C18 because C18 was a dummy variable.

Next analysis was on stream H2. H2 can connect with C1 because the heat duty bear by H2 was higher than C1. Heat duty was more significant than temperrature constraint because temperature constraint not included in GAMS. It must not be wrong that in reality, temperature constraint was the absolute constraint rather than heat duty. So, in the other word, GAMS just help to determine how much heat duty must be transferred with optimized instead of wasting it around. This is goes same with analysis on all over streams involved. Heat energy worth of 7112 kW was transferred first from H2 to C1. After energy was exchanged, the temperature of hot stream 2 would reduce to 222.43°C. So, since GAMS matched H2 with C2, hot stream 2 will be connected to cold stream 2. However, the temperature of C2 need to be checked since it is already been connected to H1 either its temperature is higher than 222.43°C after absorbing heat from hot stream 1 or not. If higher, the stream cannot be connected to hot stream 2. So, outlet temperature of C2 was calculated using equation 4.1. The outlet temperature of C2 after connecting with H1 is 175.12°C.

Since it is still lower than H2 outlet temperature, these two streams can be connected. However it is also important to consider the outlet temperature of C2 after connecting it with H1 and H2. Calculating in a similar manner would give a C2 outlet temperature of 200°C. So, it is possible to connect both H1 and H2 to C2. H1 released 1301 kW of energy and H2 released 1909 kW of energy into C2. Next connection that needs to be analyzed based on GAMS result is H3 and C1. This connection was not possible since C1 inlet temperature was higher than H3 inlet temperature. Based on the analysis above, there are 6 valid connections that are H1-C2, H1-C3, H1-C14, H1-C15, H2-C1, and H2-C2.

However, since stream H3 is not valid in the first stage of optimization, due to the unfavourable connection, it was brought to the second stage of optimization which is includes all other streams that are not connected yet. Figure 4.2 shows the second simulation.

4.3.2 Second Stage of optimization

This stage was simulating all the balance streams that not optimize yet included the hot stream H3. Figure 4.1.2 shows the connection for the second stage of simulation. There are 5 valid connections among the 9 connections.

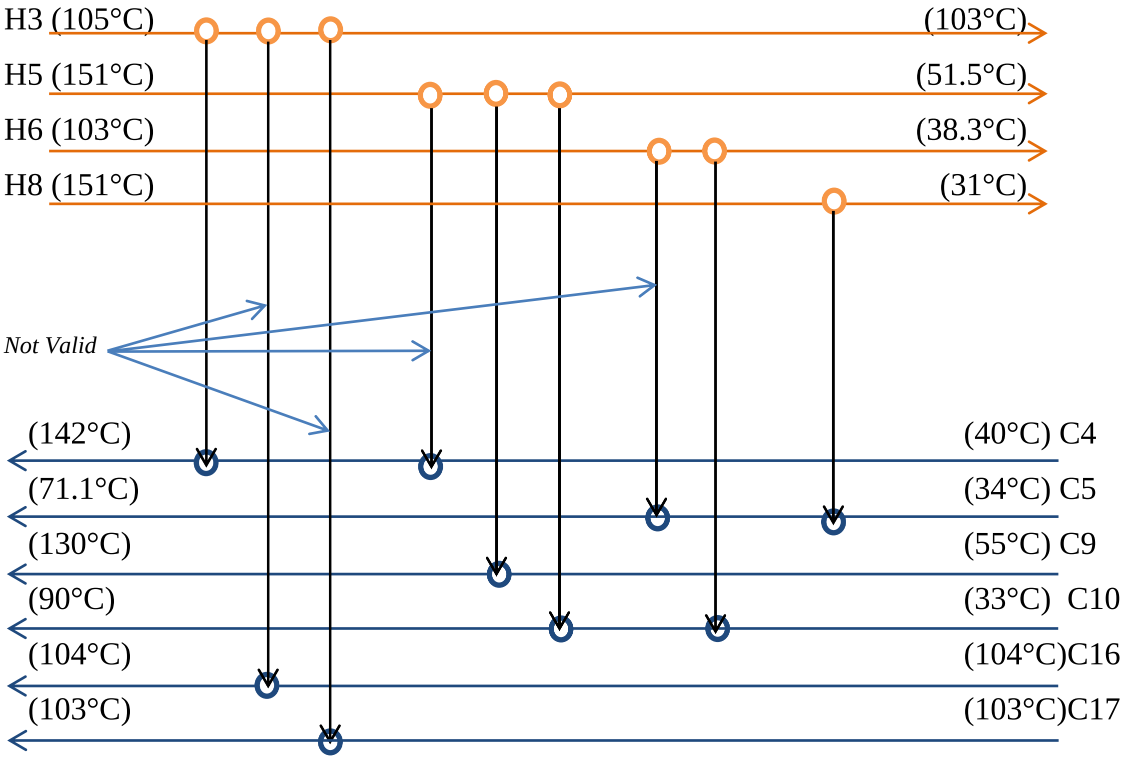


Figure 4.3 Optimization Result for Stage 2

The concept and principle still same with the first simulation. Stream H3 transfer 51 kW to stream C4. This connection was valid since temperature own by stream C4 was only 40°C, lower then inlet temperature of stream H3. Next, stream H3 give energy to streams C16 and C17. These connection were not valid as well as others because stream C16 and C17 have a very slightly differences between their streams temperature with temperatures of stream H3 even looks C16 have potential to accept heat from stream H3. The fact was no significant changes would happen. After releasing heat to C4, H3 temperature is 103°C. This temperature is low compared to the inlet temperature of both C16 and C17.

Next was H5 matched with C4, C9 and C10. As usual, look at the connection with highest amount of heat transfer first, H5 to C9. There was 230 kW of energy being transferred between these streams. This energy transfer resulted in H5 temperature decrease to 93.5°C from 151°C. This also caused the temperature of C9 to increase to 130°C from 55°C, which is exactly the aimed temperature. Then, H5 is connected to C10. This reduced H5 temperature to 51.5°C from 93.5°C and raised C10 temperature to 36.7°C from 33°C. The match between H5 and C4 was not possible since the temperature of H5 has drop significantly below C4 temperature after releasing heat to C9 and C10. H6 is matched to C10 and C5. The connection with C10 would reduce H6 temperature to 38.3°C from 103°C. C10 has already absorbed energy from H5 which caused the temperature raise to 36.7°C.

After absorbing 2457 kW of energy from H6, the temperature of C10 became 90°C which is the exact target temperature. So, H6 was not connected to C5 due to its temperature drop below C5 temperature. The next connection is between H8 and C5. The exchange of heat caused by this connection will reduce H8 temperature to 31°C which is the target temperature and increase C5 temperature to 71.1°C. H3C19 connection is not possible since C19 is a dummy variable. From the analysis above, the result was filtered based on the principles discussed earlier to select any valid stream connections. In this secondary simulation, there were 5 different valid connections which were H3-C4, H5-C9, H5-C10, H6-C10 and H8-C5. Again, transport model, brief table, and heat exchanger network integration diagram are tools used to express the total possible connections and the final validation of connections. Table 4.5 shows all the valid connections. Thus, table 4.5 concludes all the valid connections.

Table 4.6 GAMS Result with Valid Connections

j														
i	C1	C2	C3	C4	C5	C9	C10	C11	C12	C14	C15	C16	C17	
H1		**1301**	**4445**							**512**	**527**			**7655**
H2	**7112**	**1901**												**9021**
H3				**51**										**1908**
H5						**230**	**168**							**422**
H6							**2457**							**2759**
H8					**705**									**705**
	9020	**3210**	**4445**	**75**	**1007**	**230**	**2625**	**16989**	**8082**	**512**	**537**	**447**	**407**	

Table 4.7 Temperature Changes of Streams

Stream	Temperature Before Heat Transfer	Heat Absorbed from	Heat Released to	Temperature After heat transfer
H1	250°C	-	C2,C3,C14,C15	224.81°C
H2	250°C	-	C1,C2	215°C
H3	105°C	-	C4	103°C
H5	151°C	-	C9,C10	51.5°C
H6	103°C	-	C10	38.3°C
H8	151°C	-	C5	31°C
C1	162°C	H2	-	196°C
C2	158°C	H1,H2	-	200°C
C3	205°C	H1	-	206°C
C4	40°C	H3	-	142°C
C5	34°C	H8	-	71.1°C
C9	55°C	H5	-	130°C
C10	33°C	H5,H6	-	90°C
C14	55°C	H1	-	130°C
C15	38°C	H1	-	48°C

Now, figure 4.3 shows the overall grid diagram of HEN with the new temperature outlet.

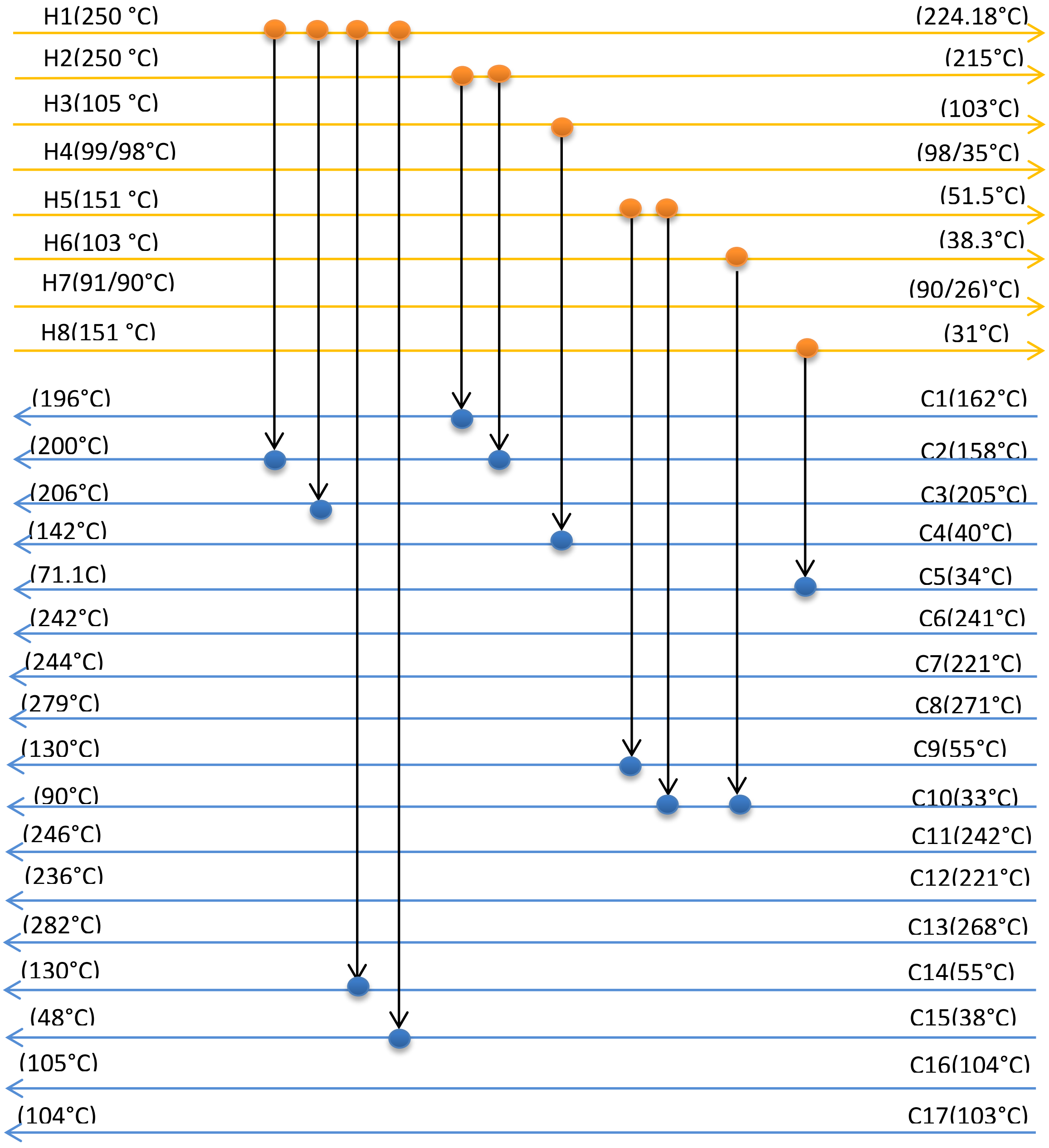


Figure 4.4 HEN Grid Diagram after Simulation.

From Table 4.3 and 4.4, total heat duty of both hot streams and cold streams were added up respectively. Hot streams has a total heat duty of 24 317 kW and the cold streams has a total heat duty of 68 430 kW. Its mean the hot streams need 24 317 kW of energy were released and cold stream needs 68 430 kW of energy to be absorbed. Based on the the original journal, external heating and cooling utilities were used to cater these kind of energy transferred. In this problem, Yoon, Lee and Park (2007) proposed 4 types of utilities used. 3 of them are heating utilities and 1 of them is a cooling utility. The 3 different types of heating utility used are fired heaters, medium pressured steam (MP) and low pressured steam (LP).

The cooling utility used was cooling water. As shown in Table 4.1, among the 11 connections of streams, there was a total of 19 280 kW of energy being transferred from a hot stream to a cold stream or in some cases from two hot streams to one single cold stream. This simply means that 19 280 kW of energy was released by hot stream and 19 280 kW of energy absorbed by the cold stream. Its mean that less utility used since 19 280 kW of the energy from hot streams were simply cooled by cold streams. The streams integration made 38 560 kW of energy was reduced by reducing the amount of heating utility and cooling utility used and by transferring heat between the streams. In the order hand, 19280 kW in hot streams, and 19 280 kW in cold streams were catered by theirself with exchanged heat among them.

$Percentage\ Energy\ Reduced,$

$$= \frac{Amount\ of\ Energy\ Reduced\ from\ Optimization, kW}{Total\ Energy\ used\ Before\ Optimization, kW} \times 100\% \qquad (4.4)$$

Based on equation 4.1, the percentage of cooling utility usage that was reduced was calculated,

$$Pecentage\ energy\ Reduced = \frac{19280}{24317} \times 100\%$$

$$Percentage\ Energy\ Reduced = \ 79.3\%$$

So, 79.3% of energy in terms of cooling utilities is reduced.

Based on equation 4.1, the percentage of heating utility usage that was reduced was also calculated,

$$Pecentage\ energy\ Reduced = \frac{19280}{68430} \times 100\%$$

$$Percentage\ Energy\ Reduced = \ 28.2\%$$

So, 28.2% of energy in terms of heating utilities is reduced. So, from the simulation a staggering 79.3% reduction in cooling utility usage and 28.2% reduction in heating utility usage were achieved. This is a significant reduction in energy usage.

4.4 External Utility

Although high amount of heating and cooling utility used has been reduced. There were still needs for the usage for external utilities because of there are streams without any heat exchangers or any integration with other streams for heat energy exchange. Besides, among the streams that were connected, only few reached their target temperatures. After comparing the target temperature of each stream from Table 4.3 and 4.4 to the temperature achieved through process integration, it is observed that only 8 streams reached their target temperature that are H2, H8, C2, C3, C9, C10, C14, and C15. Figure 4.4 shows the new HEN grid diagram of streams that achieved the target temperature with new configuration of utility system.

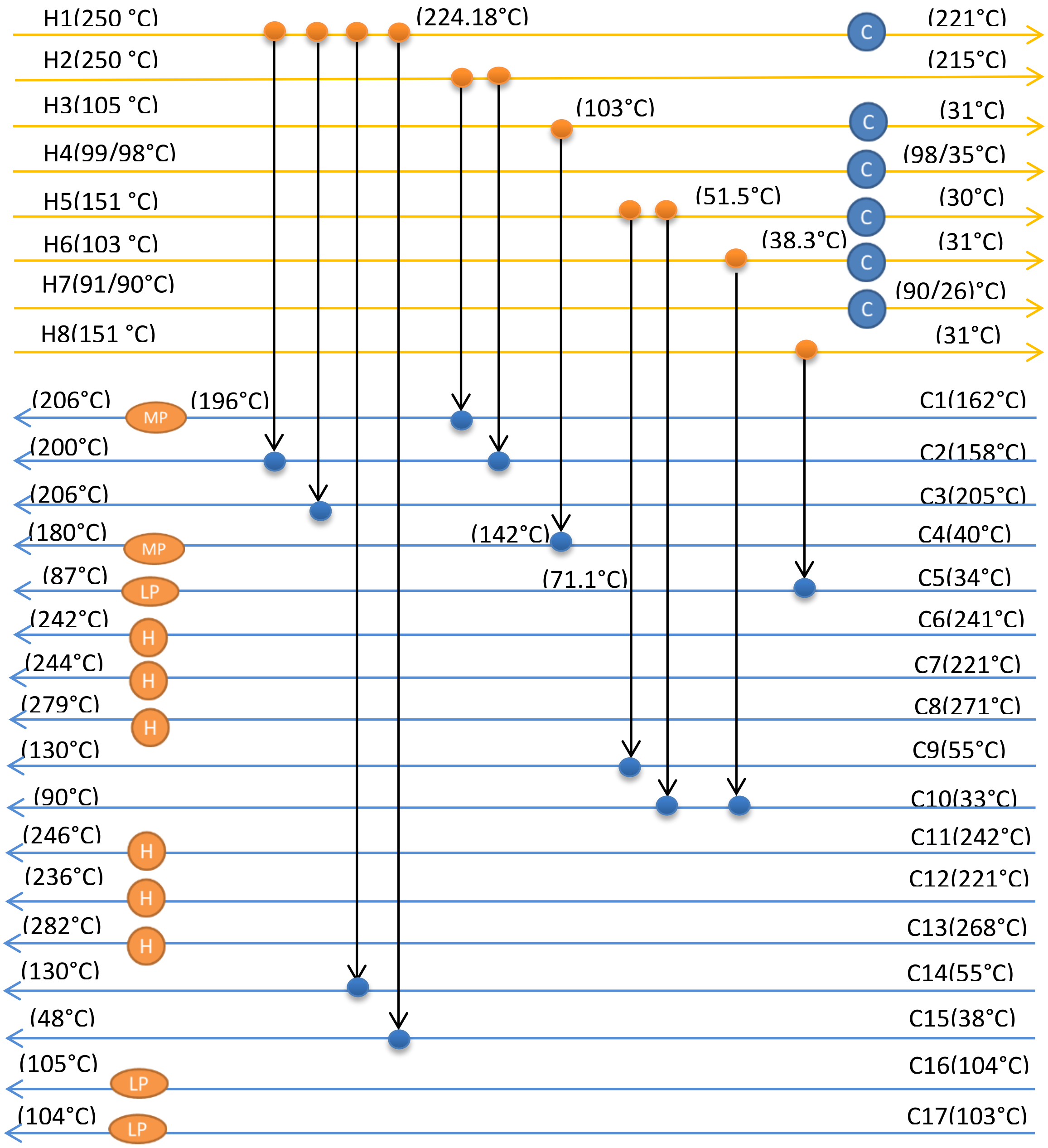


Figure 4.4 HEN Grid Diagram after Simulation with Utilities

So, external utilities were used for the rest of the streams. For all the hot streams that did not reach its target temperature, cooling water was used to cool it down. As for the heating utilities, the temperature was considered to decide the type of heating utilities needed to be used. Streams with target temperature below 150°C used a low pressured steam as the heating utility. Streams with target temperature above 150°C and below 200°C used a medium pressured steam as the heating utility. Streams with target temperature above 200°C used fired heater as the heating utility. This classification is corresponding to the real plant system. These differences are because of the variety of heating capabilities of these different heating utilities. Based on these principles, cold streams C5, C16 and C17 should use low pressured steam as the heating utility. Cold stream C4 should use medium pressured steam. Cold streams C5, C6, C7, C8, C11, C12 and C13 should use fired heater as the heating utility because all these streams have a target temperature well above 200°C.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This work has provided such a practical framework on heat recovery system. Integration of hot streams and cold streams are very useful in reduced the energy consumption and utility capacity in the process plant. In addition, a new optimisation formulation which by using the transportation model has been developed and applied for the retrofitting of heat exchanger networks or process integration. The technique has enabled the integrated process to minimize the energy used.

Simulation, optimization, and integration have been applied on the data extracted from industrial ethylbenzene plant data analysis. As a result, there were 11 stream pairs that contain and shared 19 280 kW of heat among them. Some either hot streams or cold streams were connected to more than one stream. External utility was used on streams which did not reach the target temperature. A total of 79.3% of cooling utility usage and 28.2% of heating utility usage were reduced.

5.2 Recommendations

For future work, firstly, this study can be improved by focusing on the enhancement of heat transfer capacity between streams. Secondly, this work can be expanded by considering total cost and rate investment of return as objective functions However, for the existing plant, improvement of heat transfer efficiency is become more preferable. It is because most of plant has existing heat exchanger network configuration.

Furthermore, the operating cost of plant after process integration must be evaluated properly in order to determine the profitability of integrating the process. Other integration such mass integration, waste recovery system, should also be used to optimize the plant system. An continuous analysis must be done to examine the changes in the process design and operation with changing production rates or quality of feedstock. Also, for future plant expansion needs of the process, process integration should be used.

REFERENCES

Athier, G., Floquet, P., Pibouleau, L., & Domenech, D. (1997). Synthesis of heat exchanger network by simulated annealing and NLP procedures. *AIChE Journal*, 43 (11) 3007-3019.

Briones, V., Kokossis, A. C., & Hypertargets. (1999). A Conceptual Programming Approach for the Optimisation of Industrial Heat Exchanger NetworksII. Retrofit Design. *Chem. Eng.Sci.*, 541-561.

Broeck, T. (1994). Economic Selection of Exchanger Sizes, *Ing Chem Eng.*, 64-67.

Floudas, C. A. (1986). Automatic synthesis of optimum heat exchanger network configurations. *AIChE Journal 32 (2)*, 276.

C.A. Floudas, A.R. Ciric, & I.E. Grossmann. (1986). Automatic Synthesis of Optimum Heat Exchanger Network Congurations. *AIChE*, 36, 276-290.

Caputo, A. C., Pelagagge, P. M., & Salini, P. (2008). Heat exchanger design based on economic optimisation. *Applied Thermal Engineering*, 1151-1159.

Ciric, A. R., & Floudas, C. A. (1991). Heat Exchanger Network Synthesis Without Decomposition. *Computers & Chemical Engineering15 (6)*, 385.

Ciric, A. R., & Floudas, C. A. (1990). A Mixed Integer Nonlinear Programming Model for Retrofitting Heat Exchanger Networks. *Ind. Eng. Chem. Res*, 29 (2), 239-251.

Ciric, A. R., & Floudas, C. A. (1990). Application of the Simultaneous Match Network Optimization Approach to the Pseudo-Pinch Problem. *Comput. Chem. Eng*, 14 (3), 241-250.

Ciric, A. R., & Floudas, C. A. (1990). Application of the Simultaneous Match Network Optimization Approach to the Pseudo-Pinch Problem. *Comput. Chem. Eng*, 241-250.

Daichendt, M. M., & Grossmann, I. E. (1994). A Preliminary Screening Procedure for MINLP Heat Exchanger Network Synthesis Using Aggregated Models. *Chem. Eng. Res. Des.*, 72 (A), 357 363.

Rezaei, S. S. (2008). An efficient coupled Genetic Algorithm-NLP method for heat exchanger network synthesis. *Iranian Journal of Chemical Engineering*, 22.

Errico, M. (2006). A deterministic algorithm for the synthesis of maximum energy. *Computers and Chemical Engineering*, 773-781.

Errico, M., Maccioni, S., Tola, G., & Zuddas, P. (2007). A Deterministic Algorithm for the Synthesis of Maximum Energy. *Computers and Chemical Engineering*, 773–781.

Escobar, M., & Trierweiler, J. O. (2013). Optimal heat exchanger network synthesis: A case study comparison. *Applied Thermal Engineering.* 801-826

Floudas, C. A. (New York, 1995). Nonlinear and Mixed-integer Optimization. *Fundamentals and Applications, Oxford University Press*.

Galli, M. R., & Cerda, J. (1998). Synthesis of Structural Costrained Heat Exchanger Networks-II.Split Networks. *Comput. Chem. Eng.*, 22 (7 8), 1017-1035.

Grossmann, I. E., & Kravanja, Z. (1995). Mixed-Integer Nonlinear Programming Techniques for Process Systems Engineering. *Comput. Chem. Eng.*, 189-204.

Holiastos, K., & Manousiouthakis, V. (2002). Minimum Hot/Cold/Electric Utility Cost for Heat Exchanger Network. *Computers and Chemical Engineering*, 3-16.

Hlavaeek, V. (1975) Analysis and synthesis of complex plants. Steady state and transient behaviour. *Proc. Comput. Des. Err. Chem. Plants*, 903-972.

Hlavacek V. (1978). Synthem in the design of chemical proceau. *Comput. chem. Engng* 2, 67-75 (1978).

Hui, C. W., & Ahmad, S. (1994) Total Site Integration Using the Utility System. *Comput. Chem.Eng*. 18 (8), 729 742.

Hwa, C. S. (1965). Mathematical formulation and optimization of heat exchanger networks using separable programming. *AIChE-I Chem E Syrup*, 101-106.

Jez ˇowski, J. A. (1991). Note on the Use of Dual TemperatureApproach in Heat Exchanger . *Comput.Chem. Eng.*, 305 312.

Jez ˇowski, J. (1994). Heat Exchanger Network Grassroot and Retrofit Design. The Review of the State-of-the-Art: Part I. Heat Exchanger Network Targeting and Insight Based Methods of Synthesis. *Hung. J. Ind. Chem.*, 279-294.

Kane, M., & Favrat, D. (1999). Design approach optimization of solar integrate ‘combined cycle' inspired method of pinching. *Int. J. Therm. Sci.,* 38 (6), 512-524.

Klemes, J., Kostenko, Y. T., Tovazhnyanskii, L. L., Kapustenko, P. A., Ul’ev, L. M., Perevertailenko, A. Y., et al. (1990). The Pinch Design Method for Energy-Saving Oil Refining Plants. Theor. Found. *Chem. Eng*, 33 (4), 379 390.

Lababidi, H. M., Alatiqi, I. M., & Nayfeh, L. J. (2000). Energy Retrofit Study of an Ammonia Plant. *Appl. Therm. Eng*, 1495-1503.

Lee, H., Lee, I., & Yoo, K. (1995). The System Separation Method for the Optimal Target of Heat Exchanger Network Synthesis with Multiple Pinches. *Korean J. Chem. Eng*, 12 (5), 589-592.

Lee, H., Lee, I., & Yoo, K. (1995). The System Separation Method for the Optimal Target of Heat Exchanger Network Synthesis with Multiple Pinches. *Korean J. Chem. Eng.* 12 (5), 589-592.

Lin, B., & Miller, D. C. (2004). Solving heat exchanger network synthesis problems with Tabu search. *Computers & Chemical Engineering*, 28(8), 1451–1464.

Linnhoff, B. (1979). Thermodynamic Analysis in the Design of Process Network. *Ph.D. Thesis, University of Leeds*.

Linnhoff, B., & Hindmarsh, E. (1983). The pinch design method for heat exchanger . *Chem. F, Engng Sei*, 745-763.

Mofid G.B., Hossein Y.-J., Mohammadtaghi K. (2011). Optimization of heat exchanger network. *Applied Thermal Engineering*, 779-784.

Shethna, H. K., Jezowski, J., & Castillo, F. (2000). A New Methodology for Simultaneous Optimization of Capital and Operating Costs Target in Heat Exchanger Design. *Applied Thermal Engineering*, 1577-1587.

Hlavacek, V. (1975). Analysis and synthesis of complex plants. Steady state and transient behaviour. *Proc. Comput. Des. Err. Chem. Plants*, Vol. 3, 903-972.

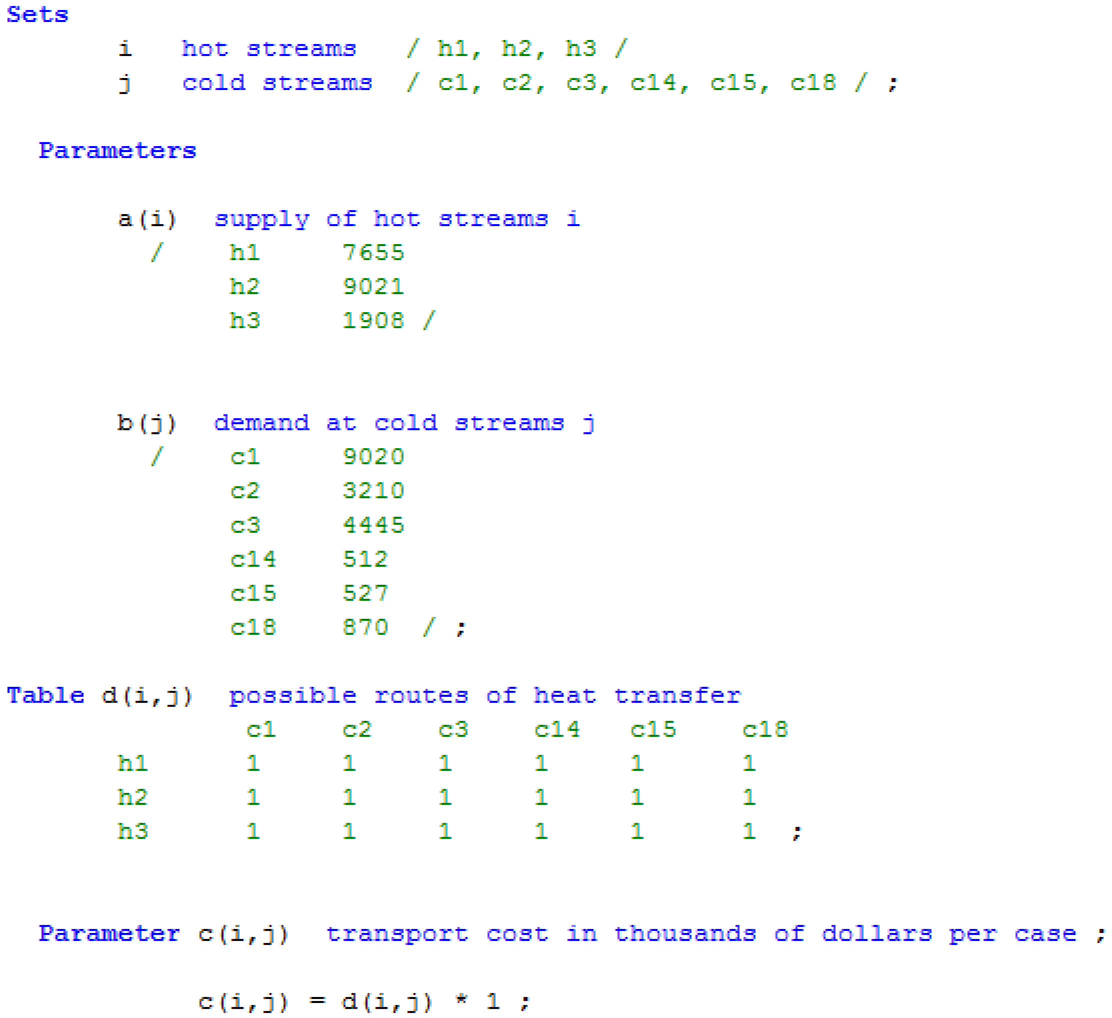
Hlavacek, V. (1978). Synthem in the design of chemical proceau. *Comput. chem. Engng*, 67-75.

Viswanathan, J., & Grossmann, I. E. (1990). A combined penalty function and outer approximation method for MINLP optimization. *Computers chem. Engng.,* 14, 769-782.

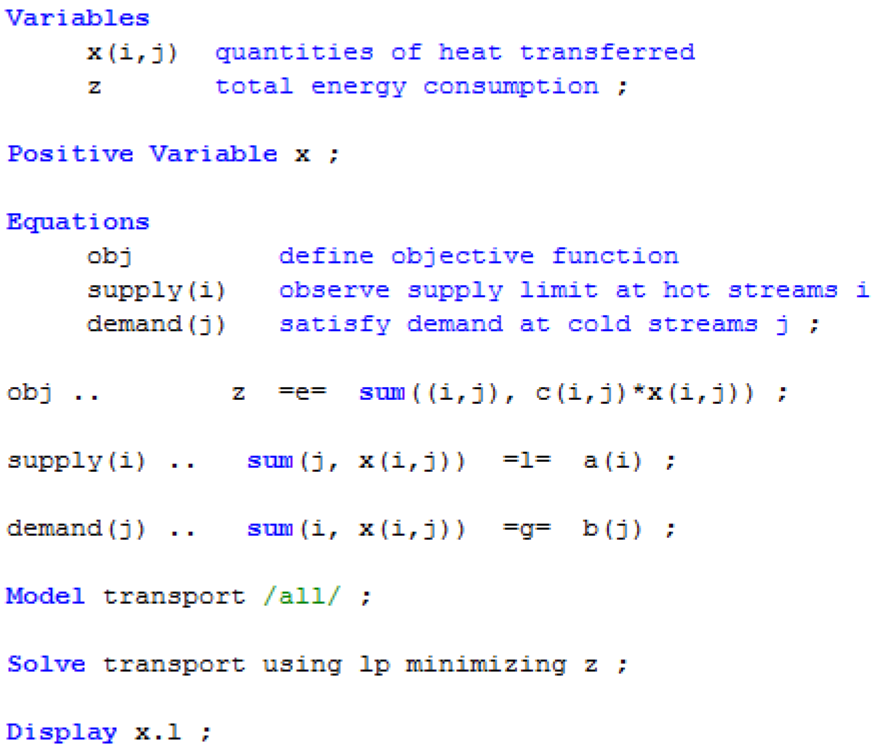
Weaterberg, & Grossman. (1985). Process Synthesis Techniques in the Chemical Industry and their Impact on Energy Used. *Chem. Engng Dept, CMU, Pittsburgh*.

Westerberli, A. W., & Grmmuan , I. E. (1985). Process synthesis techniques in the chemical industry and their impact on energy u,e. *Report. Chem. Engng Dept, CMU. Pitts- burgh*

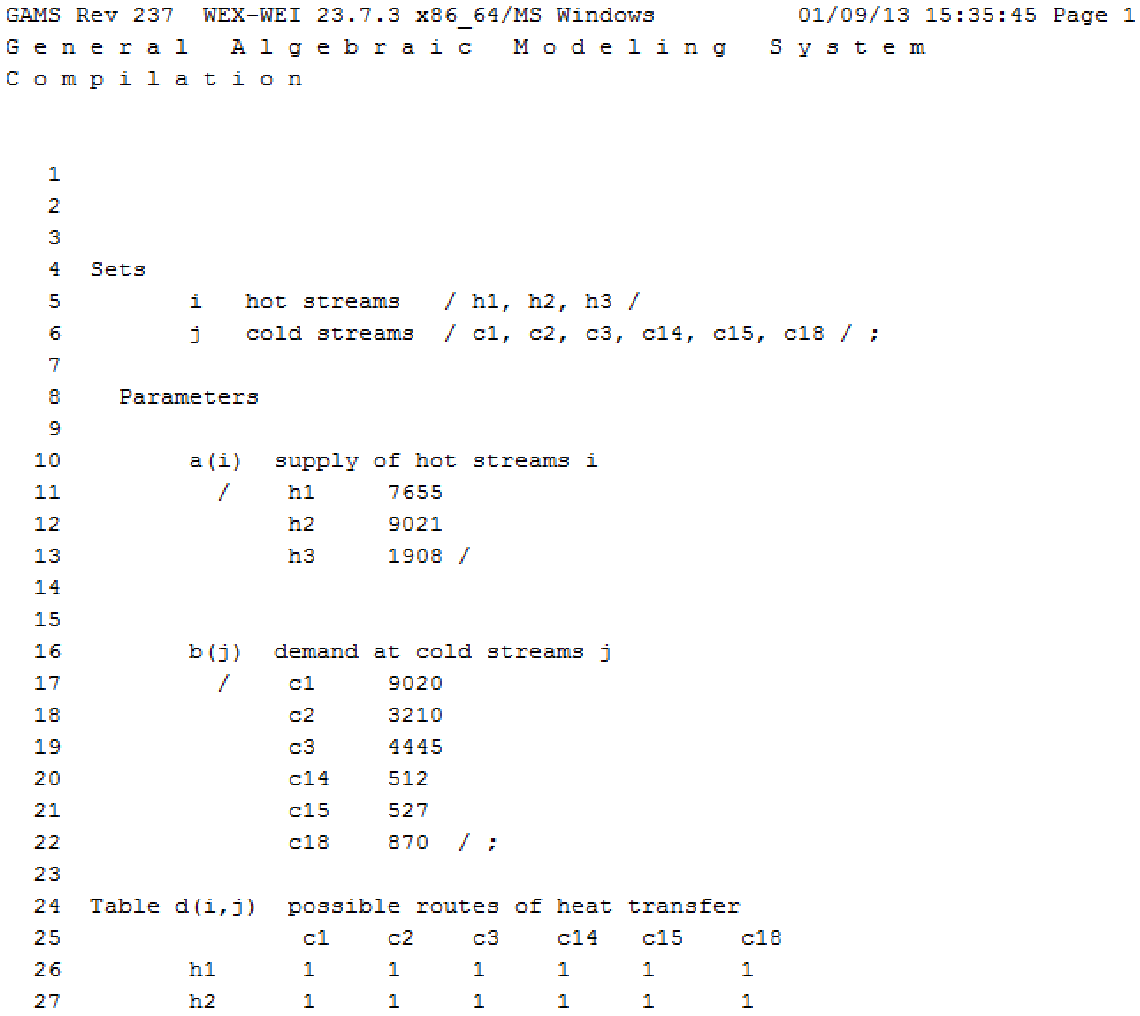
APPENDIX A: GAMS Coding and Result for First Stage of Simulation



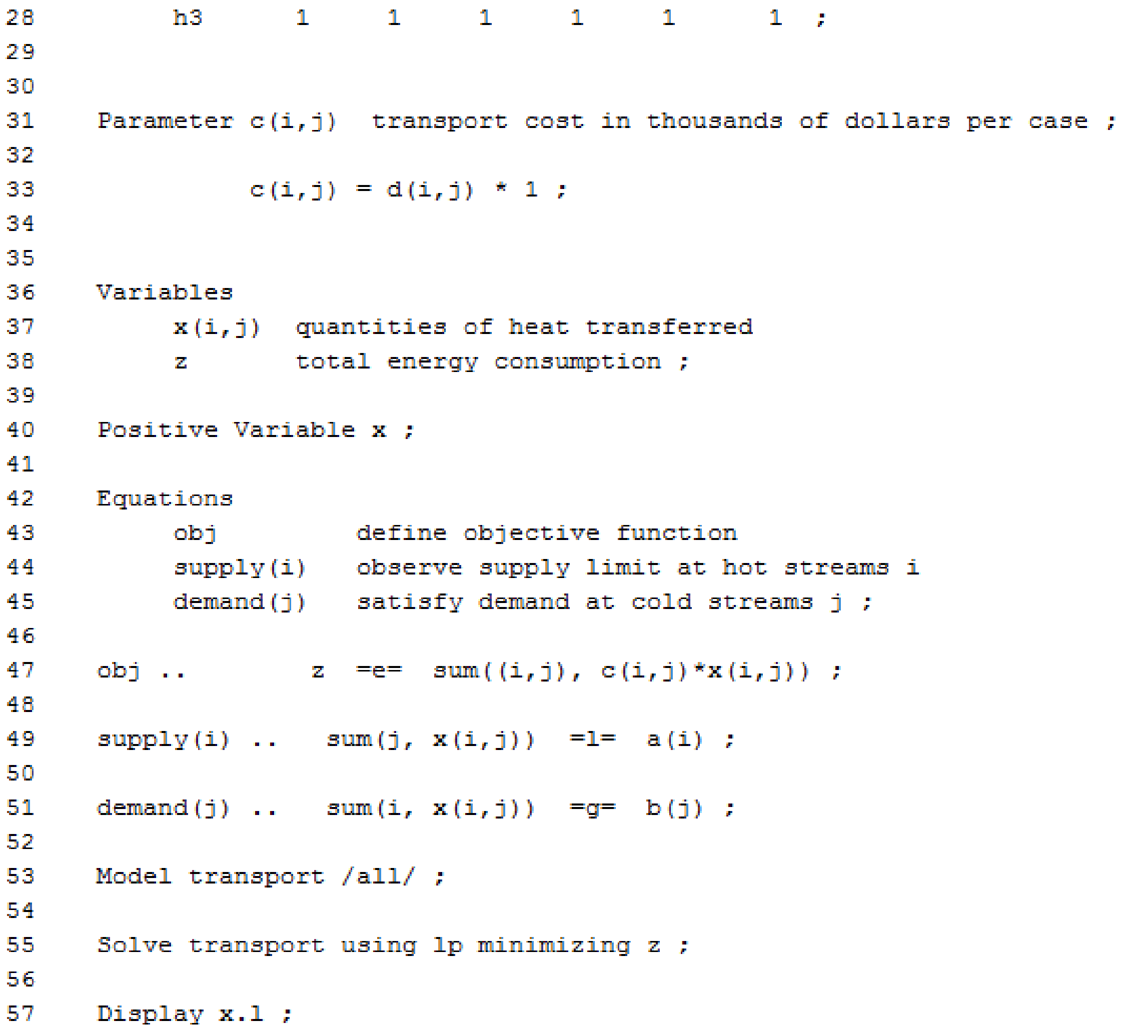
```
Sets
       i   hot streams    / h1, h2, h3 /
       j   cold streams   / c1, c2, c3, c14, c15, c18 / ;

  Parameters

       a(i)  supply of hot streams i
         /     h1      7655
               h2      9021
               h3      1908 /


       b(j)  demand at cold streams j
         /     c1      9020
               c2      3210
               c3      4445
               c14     512
               c15     527
               c18     870   / ;

Table d(i,j)  possible routes of heat transfer
                c1     c2     c3     c14    c15     c18
       h1       1      1      1      1      1       1
       h2       1      1      1      1      1       1
       h3       1      1      1      1      1       1   ;


  Parameter c(i,j)  transport cost in thousands of dollars per case ;

            c(i,j) = d(i,j) * 1 ;
```



```
Variables
     x(i,j)  quantities of heat transferred
     z       total energy consumption ;

Positive Variable x ;

Equations
     obj           define objective function
     supply(i)     observe supply limit at hot streams i
     demand(j)     satisfy demand at cold streams j ;

obj ..         z  =e=  sum((i,j), c(i,j)*x(i,j)) ;

supply(i) ..   sum(j, x(i,j))  =l=  a(i) ;

demand(j) ..   sum(i, x(i,j))  =g=  b(j) ;

Model transport /all/ ;

Solve transport using lp minimizing z ;

Display x.l ;
```

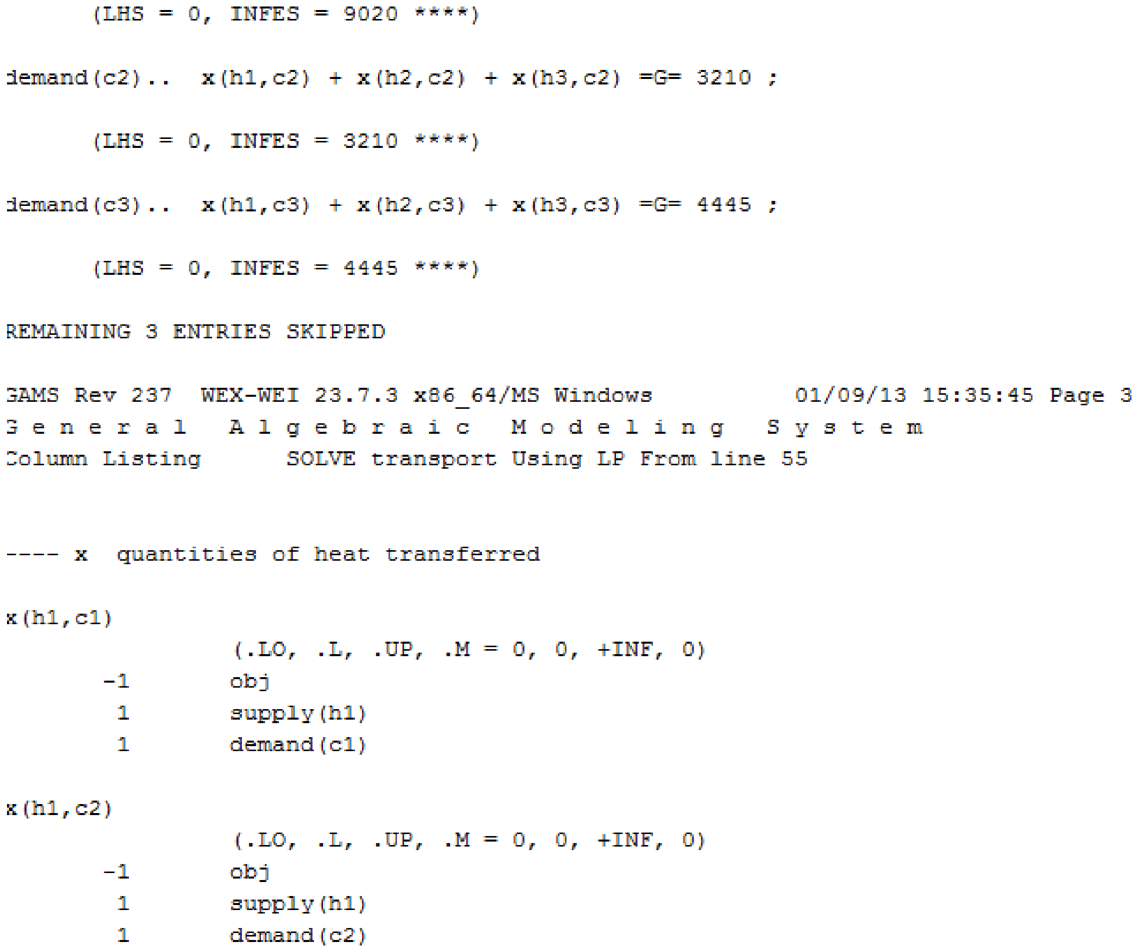


```
GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows         01/09/13 15:35:45 Page 1
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n




Sets
       i   hot streams   / h1, h2, h3 /
       j   cold streams  / c1, c2, c3, c14, c15, c18 / ;

  Parameters

       a(i)  supply of hot streams i
         /    h1     7655
              h2     9021
              h3     1908 /


       b(j)  demand at cold streams j
         /    c1     9020
              c2     3210
              c3     4445
              c14    512
              c15    527
              c18    870  / ;

Table d(i,j)  possible routes of heat transfer
               c1     c2     c3     c14    c15    c18
       h1      1      1      1      1      1       1
       h2      1      1      1      1      1       1
```

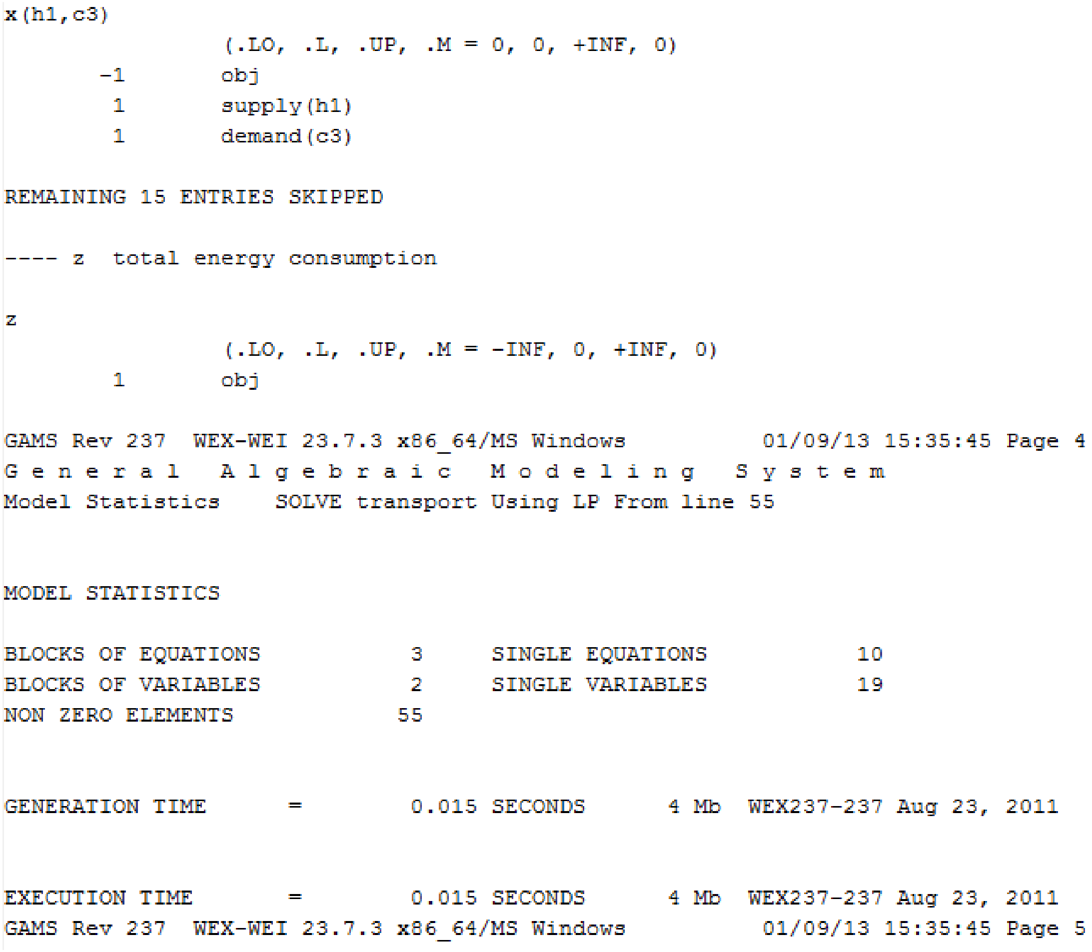


```
     h3      1     1     1     1     1      1  ;


Parameter c(i,j)  transport cost in thousands of dollars per case ;

          c(i,j) = d(i,j) * 1 ;


Variables
     x(i,j)  quantities of heat transferred
     z       total energy consumption ;

Positive Variable x ;

Equations
     obj         define objective function
     supply(i)   observe supply limit at hot streams i
     demand(j)   satisfy demand at cold streams j ;

obj ..        z  =e=  sum((i,j), c(i,j)*x(i,j)) ;

supply(i) ..   sum(j, x(i,j))  =l=  a(i) ;

demand(j) ..   sum(i, x(i,j))  =g=  b(j) ;

Model transport /all/ ;

Solve transport using lp minimizing z ;

Display x.l ;
```

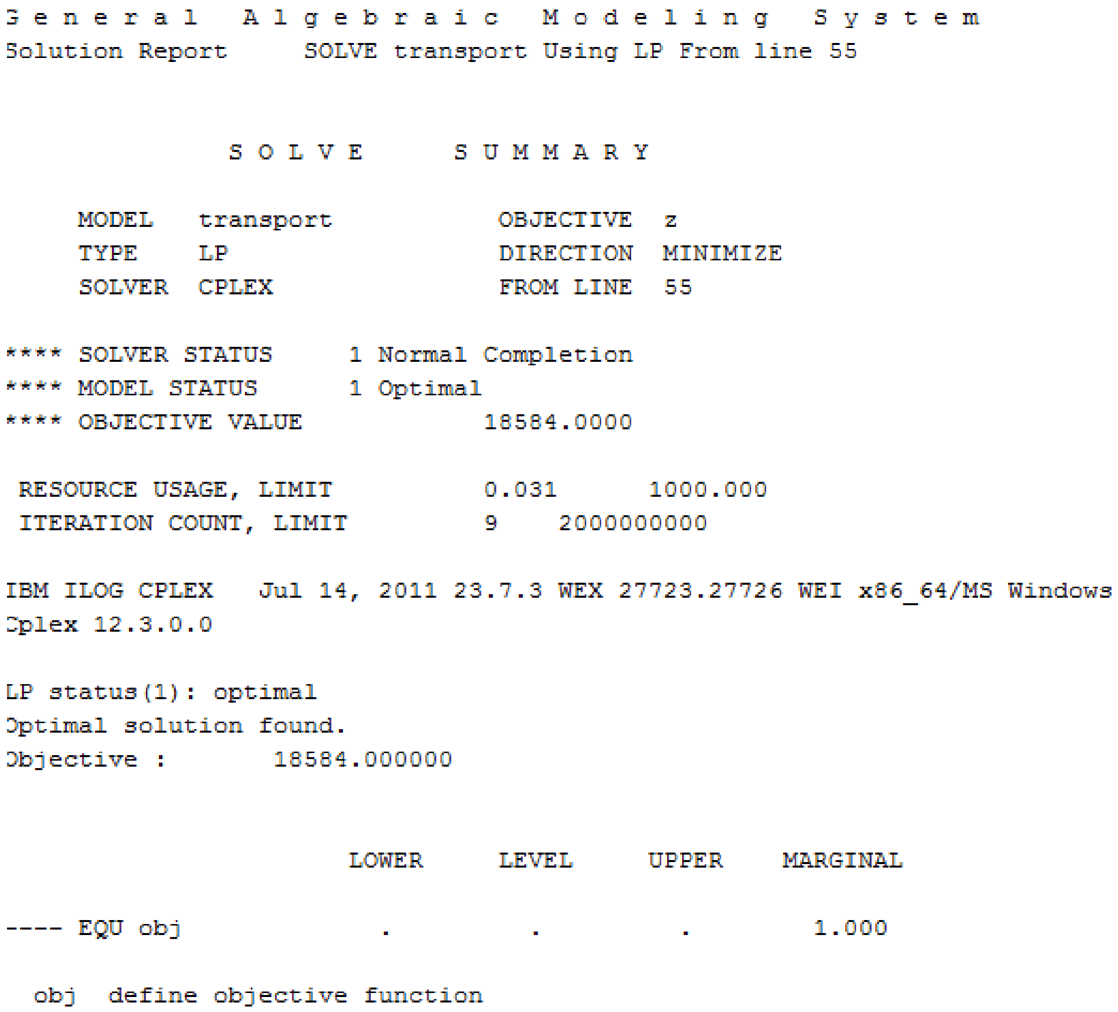
```
COMPILATION TIME     =        0.000 SECONDS      3 Mb  WEX237-237 Aug 23, 2011
GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 15:35:45 Page 2
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Equation Listing    SOLVE transport Using LP From line 55


---- obj  =E=  define objective function

obj..  - x(h1,c1) - x(h1,c2) - x(h1,c3) - x(h1,c14) - x(h1,c15) - x(h1,c18)

      - x(h2,c1) - x(h2,c2) - x(h2,c3) - x(h2,c14) - x(h2,c15) - x(h2,c18)

      - x(h3,c1) - x(h3,c2) - x(h3,c3) - x(h3,c14) - x(h3,c15) - x(h3,c18) + z
      =E= 0 ; (LHS = 0)


---- supply  =L=  observe supply limit at hot streams i

supply(h1)..  x(h1,c1) + x(h1,c2) + x(h1,c3) + x(h1,c14) + x(h1,c15) + x(h1,c18)
      =L= 7655 ; (LHS = 0)

supply(h2)..  x(h2,c1) + x(h2,c2) + x(h2,c3) + x(h2,c14) + x(h2,c15) + x(h2,c18)
      =L= 9021 ; (LHS = 0)

supply(h3)..  x(h3,c1) + x(h3,c2) + x(h3,c3) + x(h3,c14) + x(h3,c15) + x(h3,c18)
      =L= 1908 ; (LHS = 0)


---- demand  =G=  satisfy demand at cold streams j

demand(c1)..  x(h1,c1) + x(h2,c1) + x(h3,c1) =G= 9020 ;
```



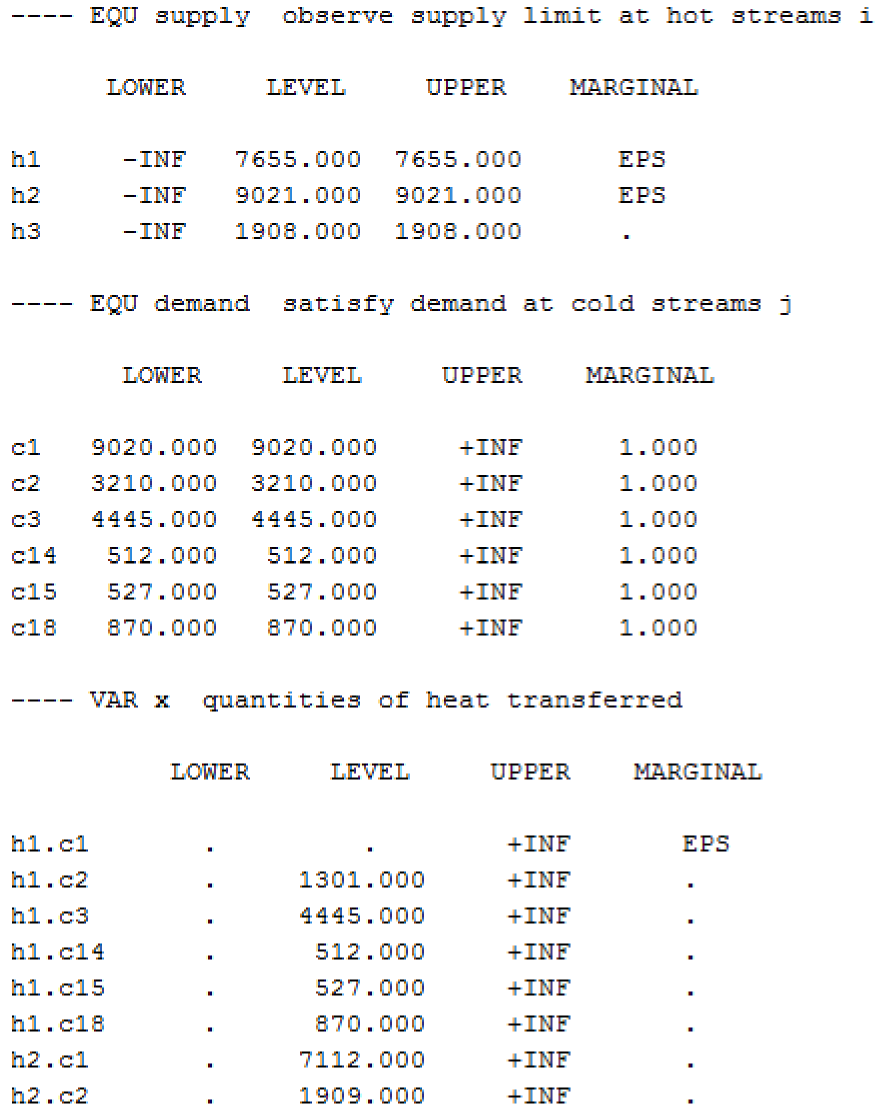
```
      (LHS = 0, INFES = 9020 ****)

demand(c2)..  x(h1,c2) + x(h2,c2) + x(h3,c2) =G= 3210 ;

      (LHS = 0, INFES = 3210 ****)

demand(c3)..  x(h1,c3) + x(h2,c3) + x(h3,c3) =G= 4445 ;

      (LHS = 0, INFES = 4445 ****)

REMAINING 3 ENTRIES SKIPPED

GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 15:35:45 Page 3
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Column Listing      SOLVE transport Using LP From line 55


---- x  quantities of heat transferred

x(h1,c1)
                (.LO, .L, .UP, .M = 0, 0, +INF, 0)
       -1       obj
        1       supply(h1)
        1       demand(c1)

x(h1,c2)
                (.LO, .L, .UP, .M = 0, 0, +INF, 0)
       -1       obj
        1       supply(h1)
        1       demand(c2)
```



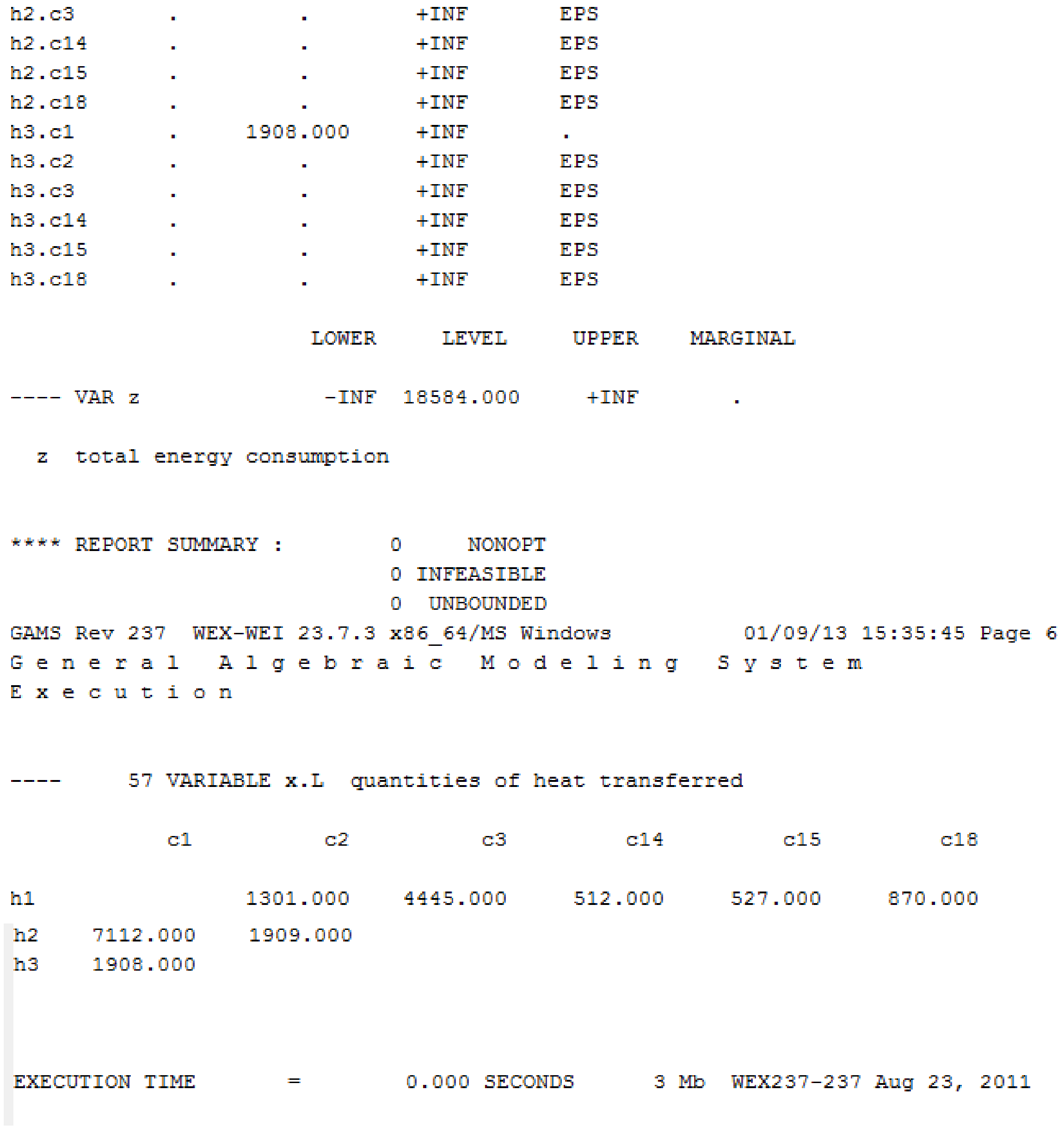
```
x(h1,c3)
                (.LO, .L, .UP, .M = 0, 0, +INF, 0)
       -1       obj
        1       supply(h1)
        1       demand(c3)

REMAINING 15 ENTRIES SKIPPED

---- z  total energy consumption

z
                (.LO, .L, .UP, .M = -INF, 0, +INF, 0)
        1       obj

GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 15:35:45 Page 4
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Model Statistics    SOLVE transport Using LP From line 55


MODEL STATISTICS

BLOCKS OF EQUATIONS           3     SINGLE EQUATIONS           10
BLOCKS OF VARIABLES           2     SINGLE VARIABLES           19
NON ZERO ELEMENTS            55


GENERATION TIME      =        0.015 SECONDS      4 Mb  WEX237-237 Aug 23, 2011


EXECUTION TIME       =        0.015 SECONDS      4 Mb  WEX237-237 Aug 23, 2011
GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 15:35:45 Page 5
```



```
General  Algebraic  Modeling  System
Solution Report     SOLVE transport Using LP From line 55


               S O L V E      S U M M A R Y

     MODEL   transport           OBJECTIVE  z
     TYPE    LP                  DIRECTION  MINIMIZE
     SOLVER  CPLEX               FROM LINE  55

**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      1 Optimal
**** OBJECTIVE VALUE            18584.0000

 RESOURCE USAGE, LIMIT          0.031      1000.000
 ITERATION COUNT, LIMIT         9    2000000000

IBM ILOG CPLEX   Jul 14, 2011 23.7.3 WEX 27723.27726 WEI x86_64/MS Windows
Cplex 12.3.0.0

LP status(1): optimal
Optimal solution found.
Objective :       18584.000000


                       LOWER     LEVEL     UPPER    MARGINAL

---- EQU obj             .         .         .        1.000

  obj  define objective function
```

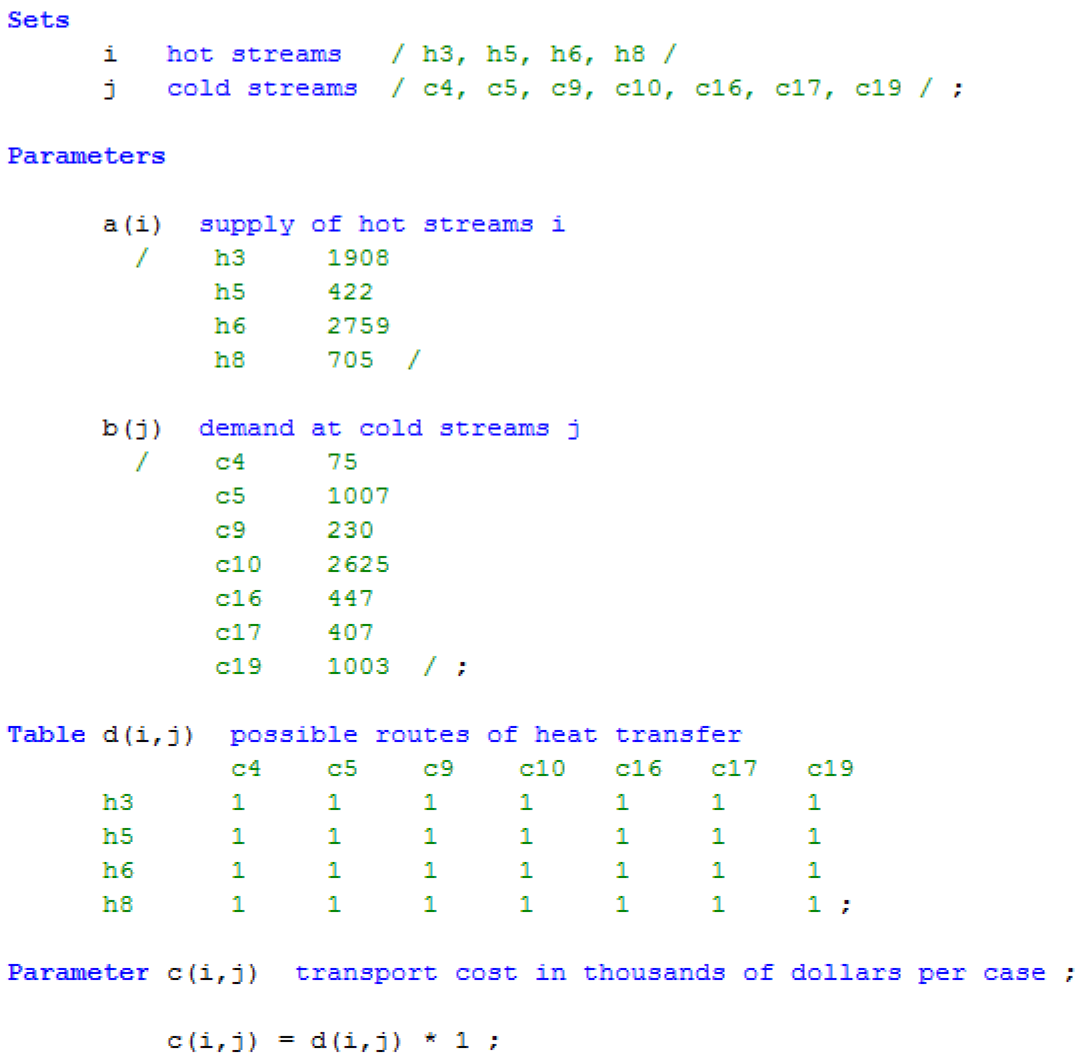


```
---- EQU supply  observe supply limit at hot streams i

      LOWER     LEVEL     UPPER    MARGINAL

h1     -INF   7655.000  7655.000      EPS
h2     -INF   9021.000  9021.000      EPS
h3     -INF   1908.000  1908.000       .

---- EQU demand  satisfy demand at cold streams j

       LOWER     LEVEL     UPPER    MARGINAL

c1   9020.000  9020.000     +INF      1.000
c2   3210.000  3210.000     +INF      1.000
c3   4445.000  4445.000     +INF      1.000
c14   512.000   512.000     +INF      1.000
c15   527.000   527.000     +INF      1.000
c18   870.000   870.000     +INF      1.000

---- VAR x  quantities of heat transferred

          LOWER     LEVEL     UPPER    MARGINAL

h1.c1       .         .        +INF       EPS
h1.c2       .     1301.000     +INF        .
h1.c3       .     4445.000     +INF        .
h1.c14      .      512.000     +INF        .
h1.c15      .      527.000     +INF        .
h1.c18      .      870.000     +INF        .
h2.c1       .     7112.000     +INF        .
h2.c2       .     1909.000     +INF        .
```

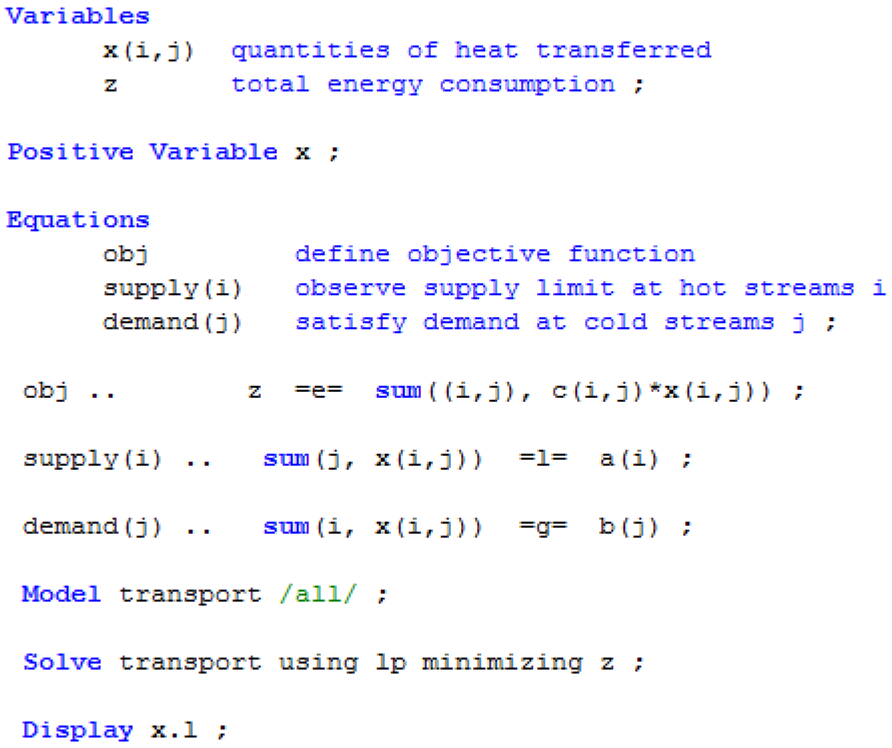


```
h2.c3       .          .         +INF       EPS
h2.c14      .          .         +INF       EPS
h2.c15      .          .         +INF       EPS
h2.c18      .          .         +INF       EPS
h3.c1       .      1908.000      +INF        .
h3.c2       .          .         +INF       EPS
h3.c3       .          .         +INF       EPS
h3.c14      .          .         +INF       EPS
h3.c15      .          .         +INF       EPS
h3.c18      .          .         +INF       EPS

                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR z              -INF  18584.000     +INF       .

  z  total energy consumption


**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows         01/09/13 15:35:45 Page 6
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
E x e c u t i o n


----     57 VARIABLE x.L  quantities of heat transferred

            c1          c2          c3         c14         c15         c18

h1                  1301.000    4445.000     512.000     527.000     870.000
h2    7112.000    1909.000
h3    1908.000



EXECUTION TIME       =        0.000 SECONDS      3 Mb  WEX237-237 Aug 23, 2011
```

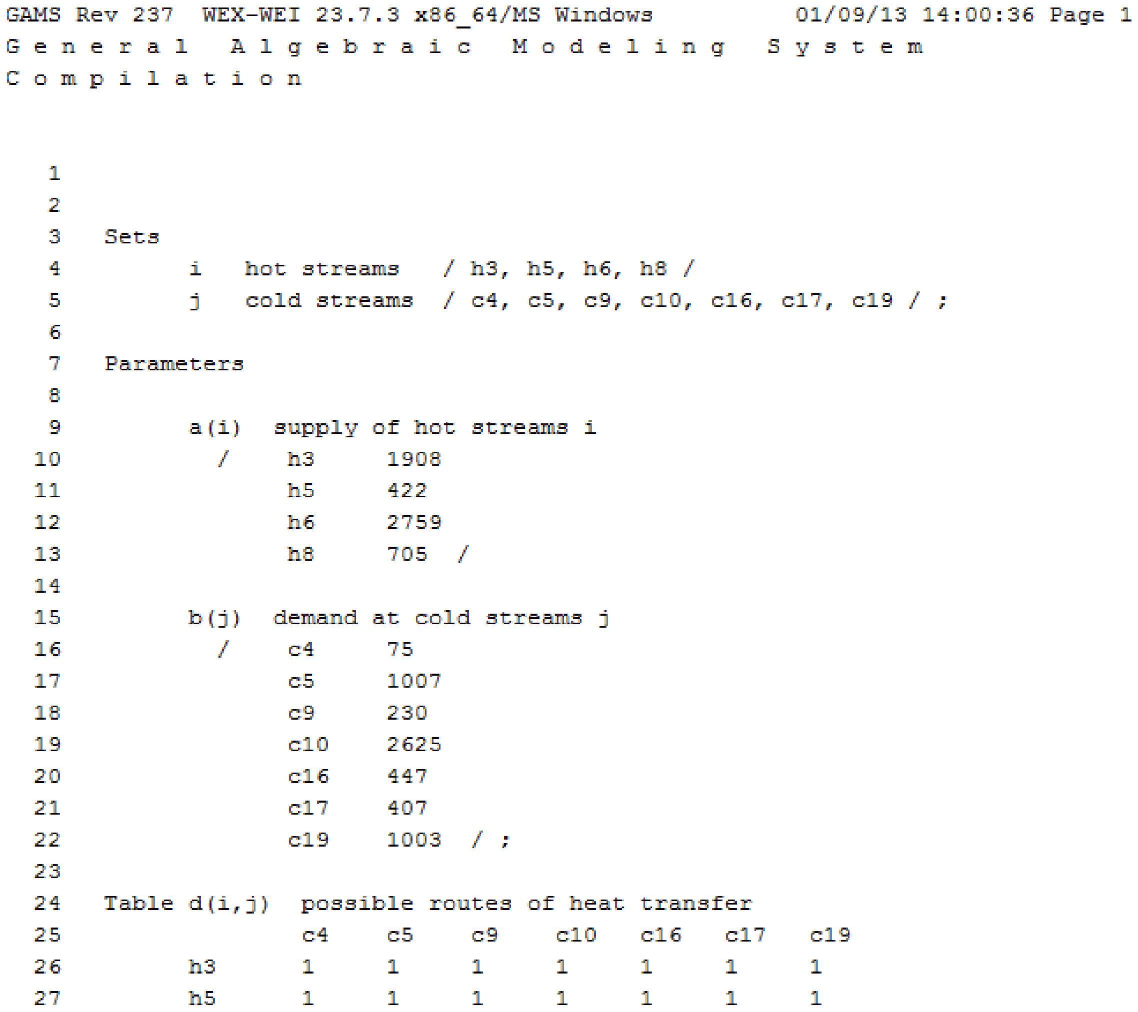
APPENDIX B: GAMS Coding for and Result for Second Stage of Simulation



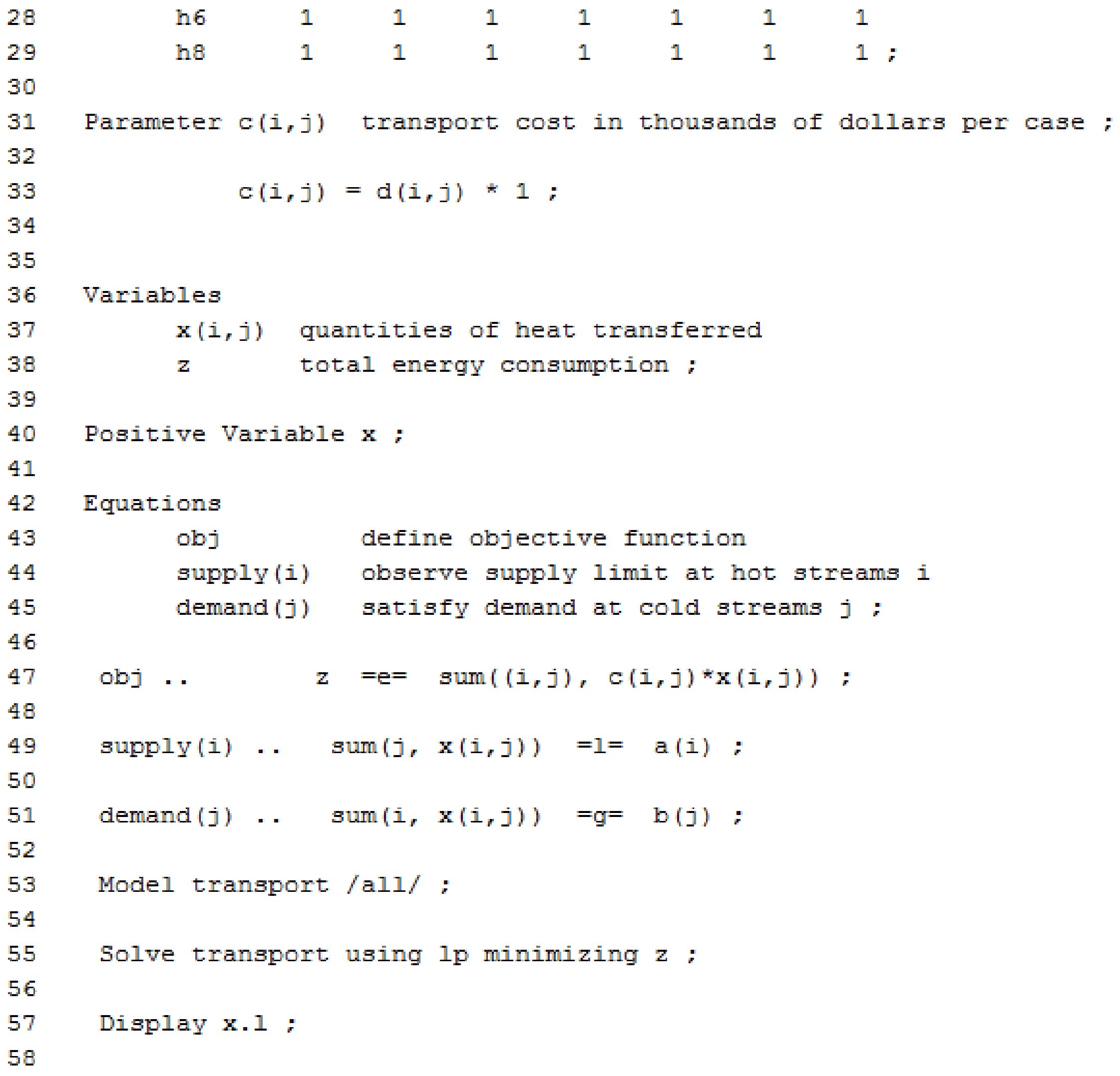
```
Sets
      i   hot streams   / h3, h5, h6, h8 /
      j   cold streams  / c4, c5, c9, c10, c16, c17, c19 / ;

Parameters

      a(i)  supply of hot streams i
        /    h3     1908
             h5     422
             h6     2759
             h8     705  /

      b(j)  demand at cold streams j
        /    c4     75
             c5     1007
             c9     230
             c10    2625
             c16    447
             c17    407
             c19    1003  / ;

Table d(i,j)  possible routes of heat transfer
                c4     c5     c9     c10    c16    c17    c19
      h3        1      1      1      1      1      1      1
      h5        1      1      1      1      1      1      1
      h6        1      1      1      1      1      1      1
      h8        1      1      1      1      1      1      1 ;

Parameter c(i,j)  transport cost in thousands of dollars per case ;

          c(i,j) = d(i,j) * 1 ;
```



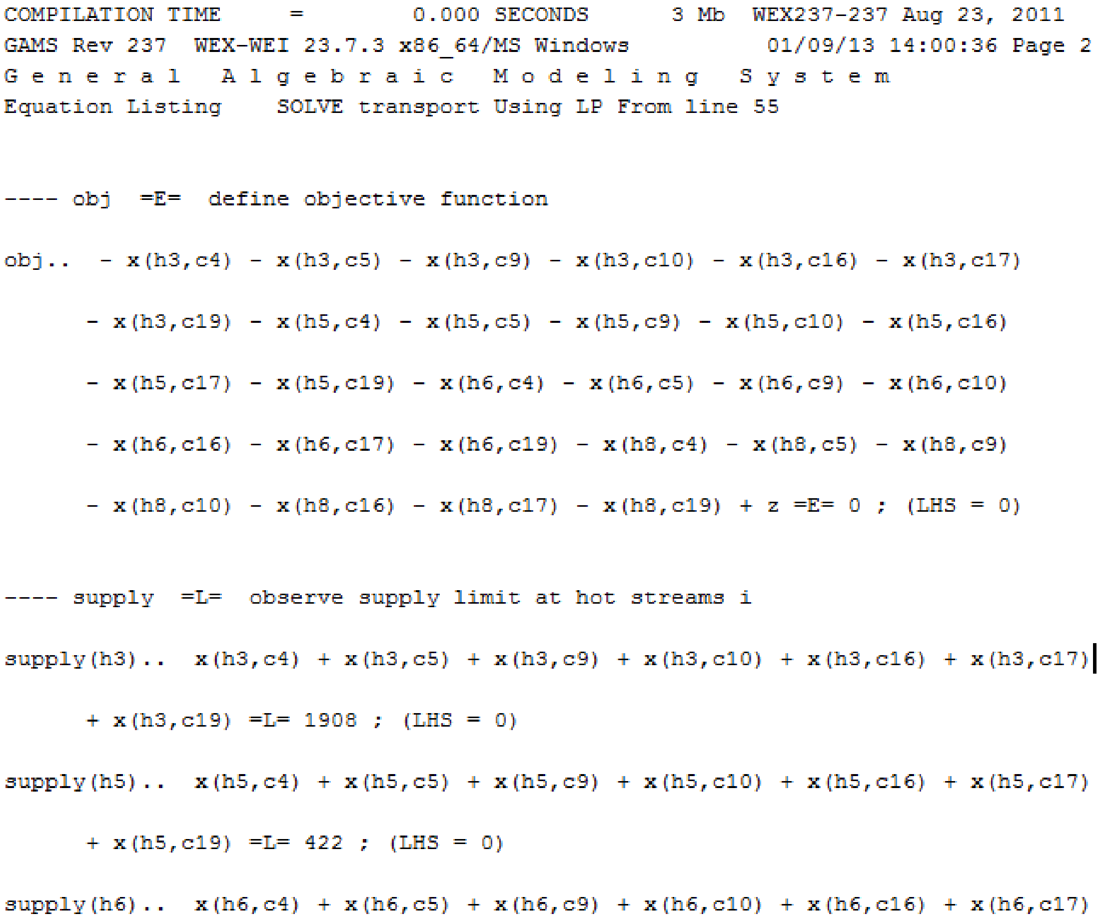
```
Variables
      x(i,j)  quantities of heat transferred
      z       total energy consumption ;

Positive Variable x ;

Equations
      obj          define objective function
      supply(i)    observe supply limit at hot streams i
      demand(j)    satisfy demand at cold streams j ;

 obj ..         z  =e=  sum((i,j), c(i,j)*x(i,j)) ;

 supply(i) ..   sum(j, x(i,j))  =l=  a(i) ;

 demand(j) ..   sum(i, x(i,j))  =g=  b(j) ;

 Model transport /all/ ;

 Solve transport using lp minimizing z ;

 Display x.l ;
```



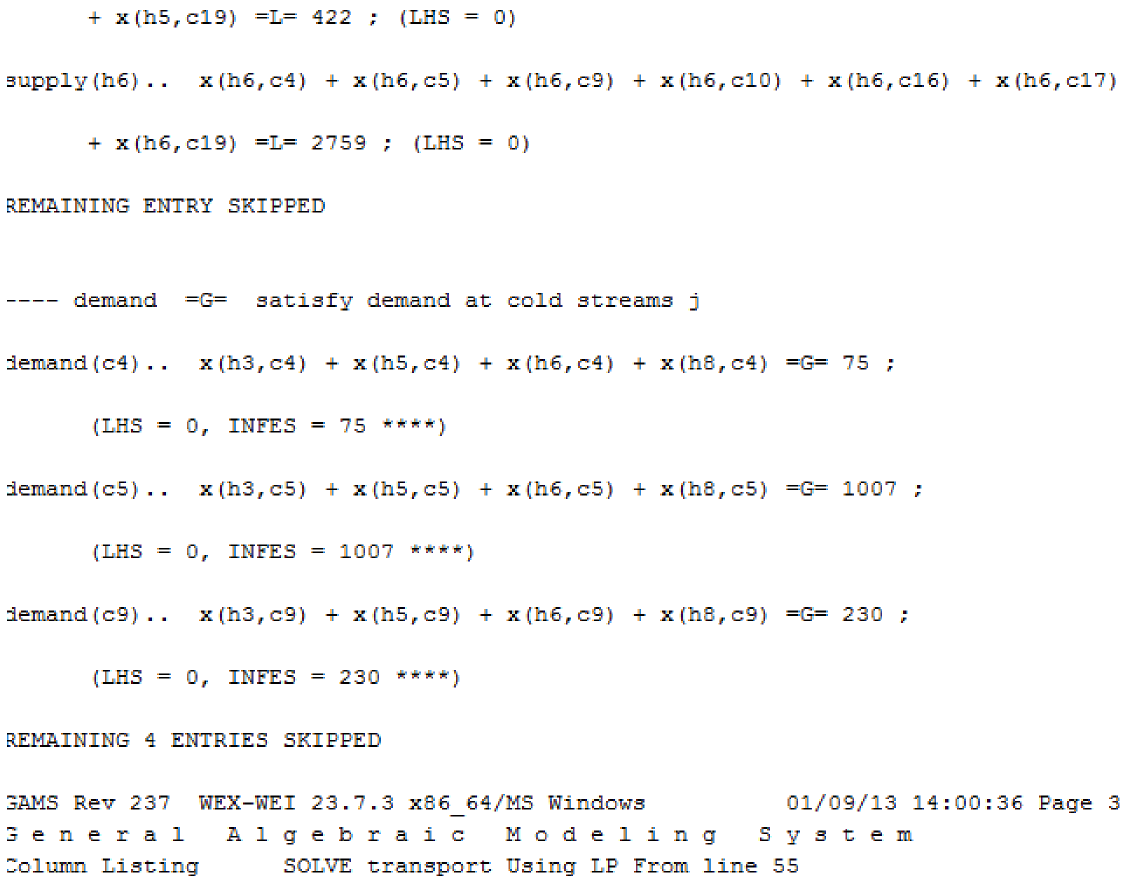
```
GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows         01/09/13 14:00:36 Page 1
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n


   1
   2
   3  Sets
   4        i   hot streams   / h3, h5, h6, h8 /
   5        j   cold streams  / c4, c5, c9, c10, c16, c17, c19 / ;
   6
   7  Parameters
   8
   9        a(i)  supply of hot streams i
  10          /    h3     1908
  11               h5     422
  12               h6     2759
  13               h8     705  /
  14
  15        b(j)  demand at cold streams j
  16          /    c4     75
  17               c5     1007
  18               c9     230
  19               c10    2625
  20               c16    447
  21               c17    407
  22               c19    1003  / ;
  23
  24  Table d(i,j)  possible routes of heat transfer
  25                c4     c5     c9     c10    c16    c17    c19
  26        h3      1      1      1      1      1      1      1
  27        h5      1      1      1      1      1      1      1
```



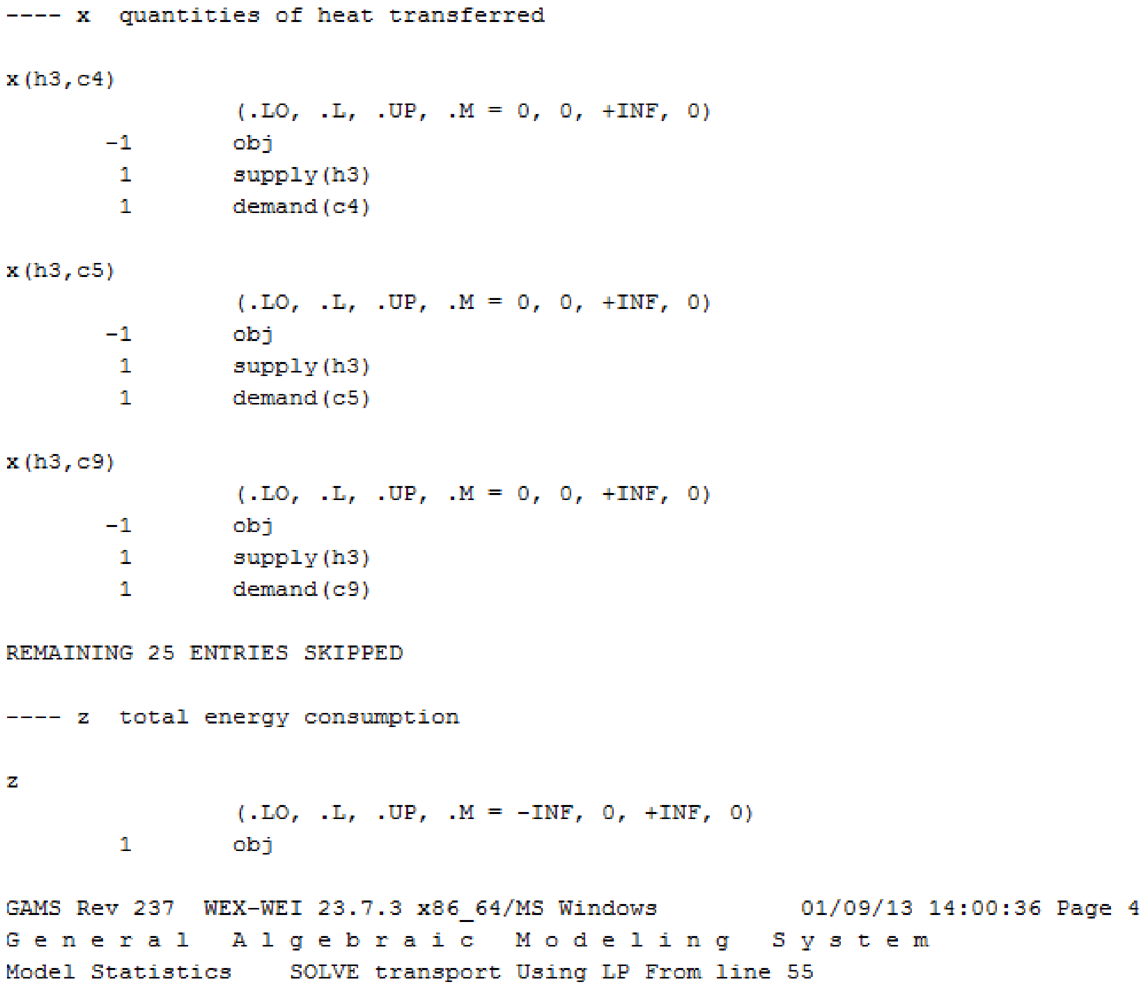
```
      h6      1     1     1     1     1     1     1
      h8      1     1     1     1     1     1     1 ;

Parameter c(i,j)  transport cost in thousands of dollars per case ;

          c(i,j) = d(i,j) * 1 ;


Variables
      x(i,j)  quantities of heat transferred
      z       total energy consumption ;

Positive Variable x ;

Equations
      obj         define objective function
      supply(i)   observe supply limit at hot streams i
      demand(j)   satisfy demand at cold streams j ;

 obj ..        z  =e=  sum((i,j), c(i,j)*x(i,j)) ;

 supply(i) ..   sum(j, x(i,j))  =l=  a(i) ;

 demand(j) ..   sum(i, x(i,j))  =g=  b(j) ;

 Model transport /all/ ;

 Solve transport using lp minimizing z ;

 Display x.l ;

```



```
COMPILATION TIME     =        0.000 SECONDS      3 Mb  WEX237-237 Aug 23, 2011
GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 14:00:36 Page 2
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Equation Listing    SOLVE transport Using LP From line 55


---- obj  =E=  define objective function

obj..  - x(h3,c4) - x(h3,c5) - x(h3,c9) - x(h3,c10) - x(h3,c16) - x(h3,c17)

      - x(h3,c19) - x(h5,c4) - x(h5,c5) - x(h5,c9) - x(h5,c10) - x(h5,c16)

      - x(h5,c17) - x(h5,c19) - x(h6,c4) - x(h6,c5) - x(h6,c9) - x(h6,c10)

      - x(h6,c16) - x(h6,c17) - x(h6,c19) - x(h8,c4) - x(h8,c5) - x(h8,c9)

      - x(h8,c10) - x(h8,c16) - x(h8,c17) - x(h8,c19) + z =E= 0 ; (LHS = 0)


---- supply  =L=  observe supply limit at hot streams i

supply(h3)..  x(h3,c4) + x(h3,c5) + x(h3,c9) + x(h3,c10) + x(h3,c16) + x(h3,c17)

      + x(h3,c19) =L= 1908 ; (LHS = 0)

supply(h5)..  x(h5,c4) + x(h5,c5) + x(h5,c9) + x(h5,c10) + x(h5,c16) + x(h5,c17)

      + x(h5,c19) =L= 422 ; (LHS = 0)

supply(h6)..  x(h6,c4) + x(h6,c5) + x(h6,c9) + x(h6,c10) + x(h6,c16) + x(h6,c17)
```

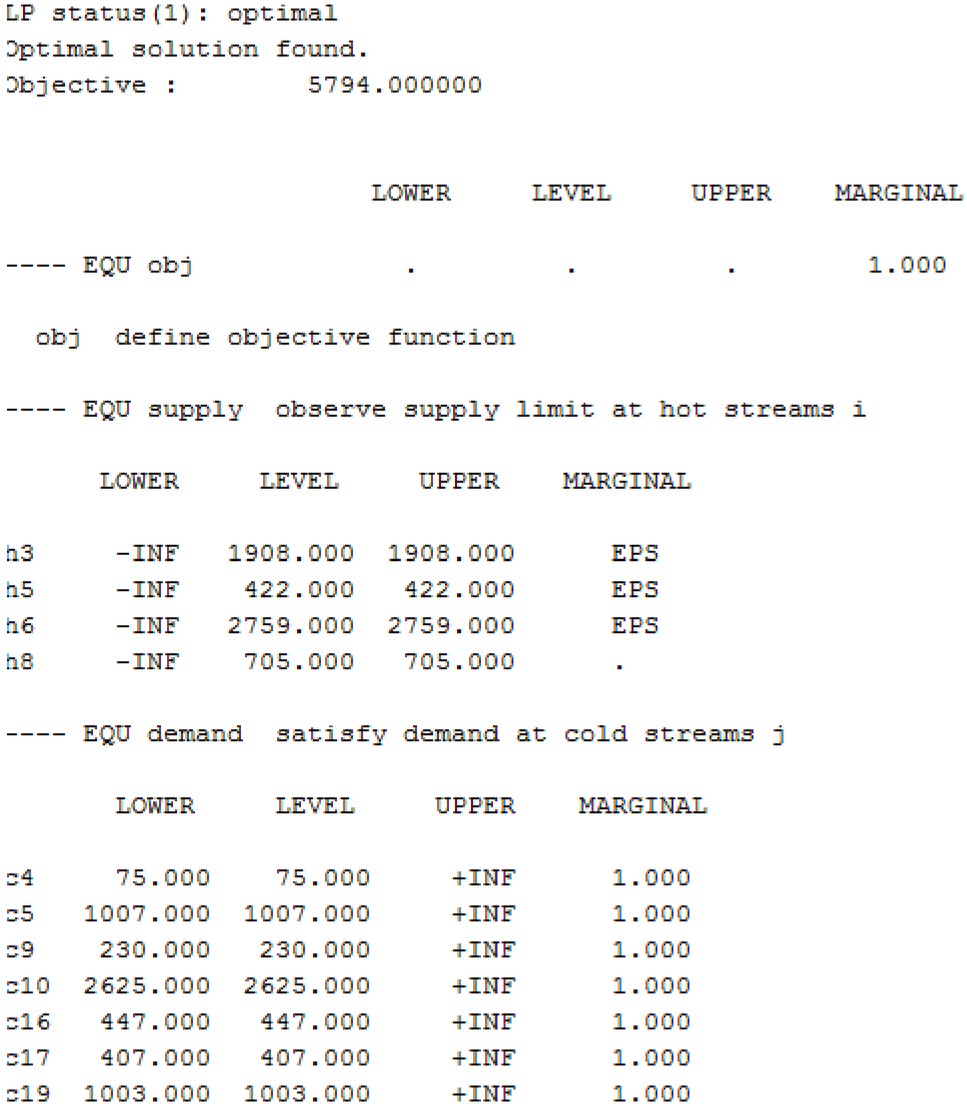


```
      + x(h5,c19) =L= 422 ; (LHS = 0)

supply(h6)..  x(h6,c4) + x(h6,c5) + x(h6,c9) + x(h6,c10) + x(h6,c16) + x(h6,c17)

      + x(h6,c19) =L= 2759 ; (LHS = 0)

REMAINING ENTRY SKIPPED


---- demand  =G=  satisfy demand at cold streams j

demand(c4)..  x(h3,c4) + x(h5,c4) + x(h6,c4) + x(h8,c4) =G= 75 ;

      (LHS = 0, INFES = 75 ****)

demand(c5)..  x(h3,c5) + x(h5,c5) + x(h6,c5) + x(h8,c5) =G= 1007 ;

      (LHS = 0, INFES = 1007 ****)

demand(c9)..  x(h3,c9) + x(h5,c9) + x(h6,c9) + x(h8,c9) =G= 230 ;

      (LHS = 0, INFES = 230 ****)

REMAINING 4 ENTRIES SKIPPED

GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 14:00:36 Page 3
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Column Listing      SOLVE transport Using LP From line 55
```

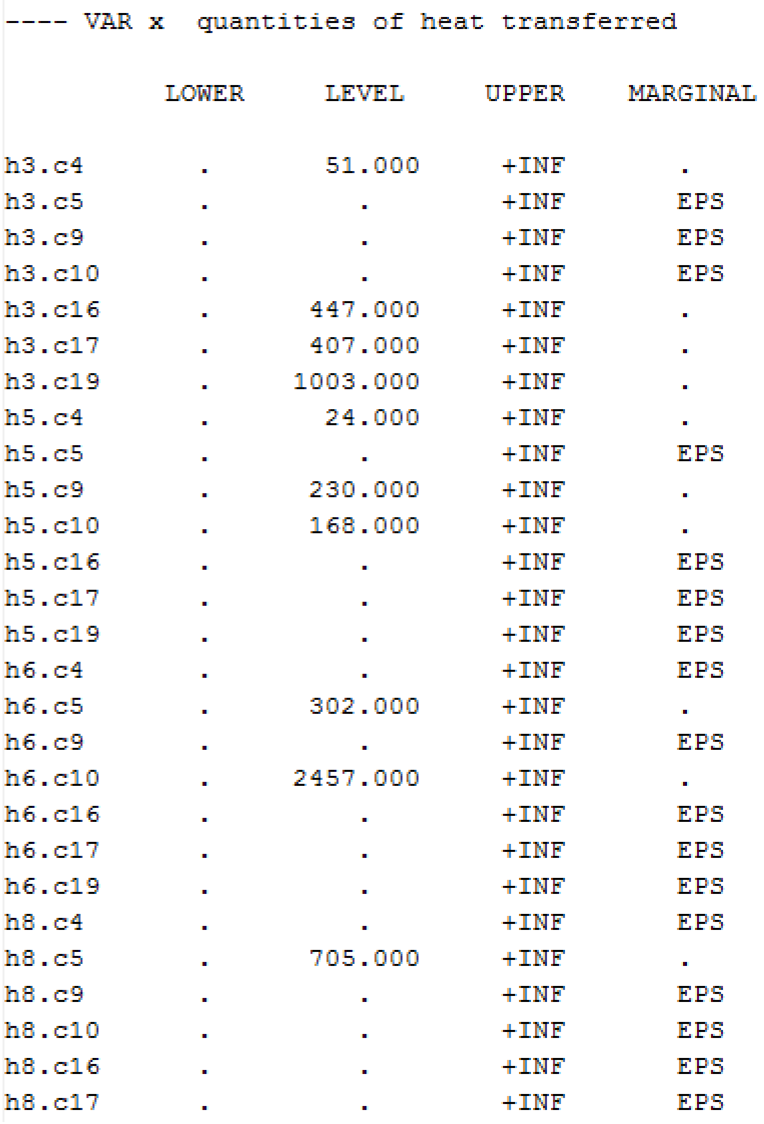


```
---- x  quantities of heat transferred

x(h3,c4)
                (.LO, .L, .UP, .M = 0, 0, +INF, 0)
       -1       obj
        1       supply(h3)
        1       demand(c4)

x(h3,c5)
                (.LO, .L, .UP, .M = 0, 0, +INF, 0)
       -1       obj
        1       supply(h3)
        1       demand(c5)

x(h3,c9)
                (.LO, .L, .UP, .M = 0, 0, +INF, 0)
       -1       obj
        1       supply(h3)
        1       demand(c9)

REMAINING 25 ENTRIES SKIPPED

---- z  total energy consumption

z
                (.LO, .L, .UP, .M = -INF, 0, +INF, 0)
        1       obj

GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 14:00:36 Page 4
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Model Statistics    SOLVE transport Using LP From line 55
```

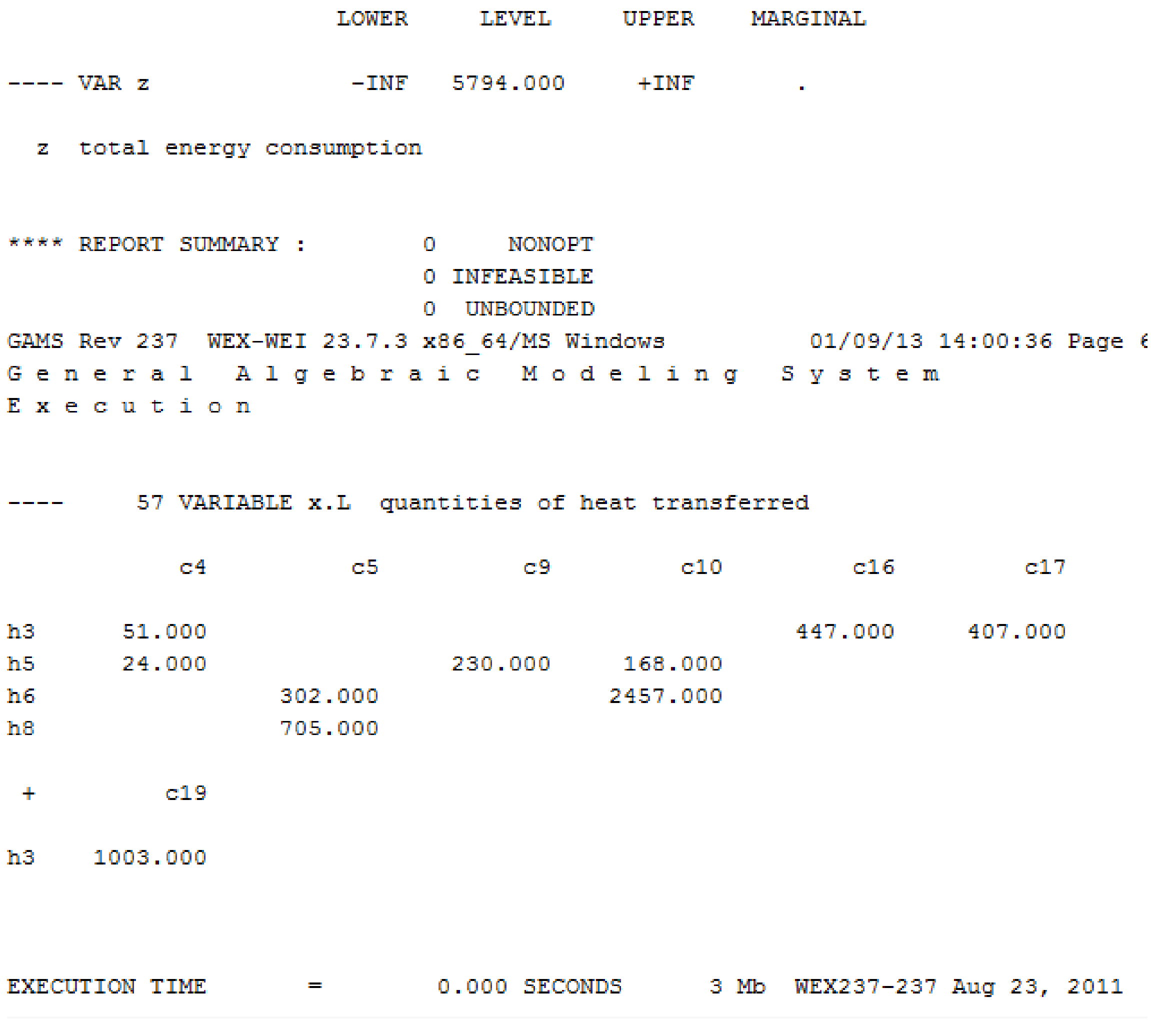
```
MODEL STATISTICS

BLOCKS OF EQUATIONS           3     SINGLE EQUATIONS           12
BLOCKS OF VARIABLES           2     SINGLE VARIABLES           29
NON ZERO ELEMENTS            85


GENERATION TIME      =        0.031 SECONDS      4 Mb  WEX237-237 Aug 23, 2011


EXECUTION TIME       =        0.031 SECONDS      4 Mb  WEX237-237 Aug 23, 2011
GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 14:00:36 Page 5
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Solution Report     SOLVE transport Using LP From line 55


               S O L V E      S U M M A R Y

     MODEL   transport           OBJECTIVE  z
     TYPE    LP                  DIRECTION  MINIMIZE
     SOLVER  CPLEX               FROM LINE  55

**** SOLVER STATUS     1 Normal Completion
**** MODEL STATUS      1 Optimal
**** OBJECTIVE VALUE             5794.0000

 RESOURCE USAGE, LIMIT          0.078      1000.000
 ITERATION COUNT, LIMIT        14    2000000000

IBM ILOG CPLEX   Jul 14, 2011 23.7.3 WEX 27723.27726 WEI x86_64/MS Windows
Cplex 12.3.0.0
```



```
LP status(1): optimal
Optimal solution found.
Objective :        5794.000000


                       LOWER     LEVEL     UPPER    MARGINAL

---- EQU obj             .         .         .        1.000

  obj  define objective function

---- EQU supply  observe supply limit at hot streams i

      LOWER     LEVEL     UPPER    MARGINAL

h3     -INF   1908.000  1908.000      EPS
h5     -INF    422.000   422.000      EPS
h6     -INF   2759.000  2759.000      EPS
h8     -INF    705.000   705.000       .

---- EQU demand  satisfy demand at cold streams j

       LOWER     LEVEL     UPPER    MARGINAL

c4      75.000    75.000     +INF      1.000
c5    1007.000  1007.000     +INF      1.000
c9     230.000   230.000     +INF      1.000
c10   2625.000  2625.000     +INF      1.000
c16    447.000   447.000     +INF      1.000
c17    407.000   407.000     +INF      1.000
c19   1003.000  1003.000     +INF      1.000
```



```
---- VAR x  quantities of heat transferred

          LOWER     LEVEL     UPPER    MARGINAL

h3.c4        .       51.000    +INF       .
h3.c5        .         .       +INF      EPS
h3.c9        .         .       +INF      EPS
h3.c10       .         .       +INF      EPS
h3.c16       .      447.000    +INF       .
h3.c17       .      407.000    +INF       .
h3.c19       .     1003.000    +INF       .
h5.c4        .       24.000    +INF       .
h5.c5        .         .       +INF      EPS
h5.c9        .      230.000    +INF       .
h5.c10       .      168.000    +INF       .
h5.c16       .         .       +INF      EPS
h5.c17       .         .       +INF      EPS
h5.c19       .         .       +INF      EPS
h6.c4        .         .       +INF      EPS
h6.c5        .      302.000    +INF       .
h6.c9        .         .       +INF      EPS
h6.c10       .     2457.000    +INF       .
h6.c16       .         .       +INF      EPS
h6.c17       .         .       +INF      EPS
h6.c19       .         .       +INF      EPS
h8.c4        .         .       +INF      EPS
h8.c5        .      705.000    +INF       .
h8.c9        .         .       +INF      EPS
h8.c10       .         .       +INF      EPS
h8.c16       .         .       +INF      EPS
h8.c17       .         .       +INF      EPS
```



```
                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR z              -INF   5794.000     +INF       .

  z  total energy consumption


**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
GAMS Rev 237  WEX-WEI 23.7.3 x86_64/MS Windows          01/09/13 14:00:36 Page 6
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
E x e c u t i o n


----     57 VARIABLE x.L  quantities of heat transferred

            c4          c5          c9         c10         c16         c17

h3      51.000                                         447.000     407.000
h5      24.000                 230.000     168.000
h6                 302.000                2457.000
h8                 705.000

 +         c19

h3    1003.000


EXECUTION TIME       =        0.000 SECONDS      3 Mb  WEX237-237 Aug 23, 2011
```