RESOURCE CONSERVATION AND ALLOCATION VIA PROCESS INTEGRATION

A Dissertation

by

DUSTIN ASHLEY HARELL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2004

Major Subject: Chemical Engineering

RESOURCE CONSERVATION AND ALLOCATION VIA PROCESS INTEGRATION

A Dissertation

by

DUSTIN ASHLEY HARELL

Submitted to Texas A&M University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Approved as to style and content by:

Mahmoud El-Halwagi (Chair of Committee)	Guy Curry (Member)
Sam Mannan (Member)	Charles Glover (Member)
Kenneth Hall (Head of Department)	

May 2004

Major Subject: Chemical Engineering

ABSTRACT

Resource Conservation and Allocation via Process Integration. (May 2004)

Dustin Ashley Harell, B.S., Michigan Technological University

Chair of Advisory Committee: Dr. Mahmoud El-Halwagi

Throughout the process industry, the conservation and allocation of mass and energy resources plays a pivotal role in the site wide optimization of a plant. Typically, raw materials are transformed into products, byproducts and wastes through pathways involving heating/cooling, pressure changes, mixing, reactions and separations. These pathways often require the addition or removal of energy from the system. The optimal management of such a system therefore requires conserving resources through the appropriate allocation of materials and energy.

In a typical plant, there are both mass and energy objectives that require optimization. This dissertation will focus on optimizing the mass and energy resources present in a utility system. This will entail developing a novel framework of techniques to: target and design steam cogeneration networks while minimizing fuel requirements, identifying and utilizing sources of waste heat and incorporating heat pipes to enhance heat exchange networks. Additionally, a specific case of waste recovery will be examined when properties are the primary concern.

DEDICATION

This dissertation is dedicated to my loving wife Georgina. Since our decision that I would pursue a PhD, she has stood by my side regardless of the difficult times we have faced both together and individually. Her quick-witted and high-spirited nature constantly challenges me to improve myself both mentally and physically, and for that I thank her. She has a loving and unselfish nature that is truly rare in today's society, and I am fortunate to have her by my side.

ACKNOWLEDGEMENTS

I wish to express my gratitude to my advisor, Dr. Mahmoud El-Halwagi, for providing both guidance and encouragement during my career as a graduate student. His patience for his students and novel approach to examining any problem are inspirational.

Many thanks to the numerous group members I have had the pleasure of working alongside while I have been a student under Dr. El-Halwagi. I consider myself fortunate to have been able to meet and interact with such a diverse group of people.

A special note of gratitude to Fred and Qin whom I spent many long hours with discussing everything from research to Chinese politics while in the lab.

Finally, I would like to thank my loving parents for always supporting me in my endeavors.

NOMENCLATURE

AUP	augmented property index
C1	cold stream 1
C2	cold stream 2
C3	cold stream 3
C4	cold stream 4
$\overline{C}_i$	average cluster of property *i*
$C_{i,s}$	cluster of property *i* from source *s*
$Cost_k$	cost of interception technology *k*
C_p	heat capacity
$C_{p,s}$	heat capacity of source *s*
e	extractable energy
E	extractable power
F	flow rate
F_s	flow rate of source *s*
$F_{s,k}$	flow rate of source *s* to interceptor *k*
g	a function
G	flow rate of a sink
G_j	flow rate to sink *j*
G_j^{lower}	lower bound on flow rate to sink *j*
G_j^{upper}	upper bound on flow rate to sink *j*

h	a function
H	enthalpy
$H1$	hot stream 1
$H2$	hot stream 2
$H3$	hot stream 3
$H4$	hot stream 4
H^{in}	inlet enthalpy
H_{header}^{out}	outlet header enthalpy
H_{is}^{out}	outlet isentropic enthalpy
HEN	heat exchange network
HP	high pressure
$HRSG$	heat recovery steam generation
i	index of property
I_k	binary integer for interceptor k
j	index of sinks
k	index of interceptors
K_k	flow rate to interceptor k
$K_{k,j}$	flow rate from interceptor k to sink j
K_k^{int}	intercepted flow rate from interceptor k
LP	low pressure or linear program
$\dot{m}$	mass flow rate

M1	mass flow rate of header 1
M2	mass flow rate of header 2
M3	mass flow rate of header 3
M4	mass flow rate of header 4
MINLP	mixed integer nonlinear program
MP	medium pressure
N_{int}	number of interceptors
N_{prop}	number of properties
N_{sinks}	number of sinks
$N_{sources}$	number of sources
$\overline{P}$	average property
P_i^{ref}	reference of property i
P_s	property of source s
q	constant observed by Salisbury
Q	heat load to be supplied by turbine
s	index of sources
T_{in}^{sat}	inlet saturation temperature
T_{out}^{sat}	outlet saturation temperature
$T_{supply,s}$	supply temperature of stream s
$T_{target,s}$	target temperature of stream s
TID	temperature interval diagram
u	index of substreams

VHP	very high pressure
w	specific work
W	power
WHB	waste heat boiler
x_s	fractional contribution of source s
b_s	cluster domain fractional contribution of source s
DH^{header}	enthalpy difference between headers
$DH^{isentropic}$	isentropic enthalpy difference
DH^{real}	actual enthalpy difference
$DQ^{C}{}_{min}$	minimum cooling utility
$DQ^{H}{}_{min}$	minimum heating utility
DT_1	temperature difference in interval 1
DT_2	temperature difference in interval 2
DT_3	temperature difference in interval 3
DT_4	temperature difference in interval 4
DT_{min}	minimum temperature driving force
e	power coefficient
h_c	carnot efficiency
h_{header}	header efficiency
$h_{i,k}$	removal factor of interceptor k for property i
h_{is}	isentropic efficiency

r	density
W	dimensionless property
y	property operator
$y_i(P_{i,j}^{sink})$	average operator of property i going to sink j
$y_i(P_{i,k})$	average operator of property i going to interceptor k
$y_i(P_{i,k}^{\mathrm{int}})$	intercepted operator of property i from interceptor k
$y_i(P_{i,j}^{lower})$	lower operator bound of property i for sink j
$y_i(P_{i,j}^{upper})$	upper operator bound of property i for sink j
$y_i(P_{i,j}^{source})$	operator of property i from source s

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

Page

Page

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

In the process industry, raw materials are converted into product, byproduct and waste streams through unit operations involving heating/cooling, pressure changes, mixing, reactions and separations. These pathways often involve the addition of power and energy, or the removal of energy from a unit. The energy needs are usually satisfied by directly purchasing a utility, such as cooling water, or by generating a utility, such as steam, by burning fuel. Similarly, power requirements are often satisfied by purchasing electricity directly from the power company. Unfortunately, the amount of fuel, electricity and utilities purchased from external sources is often unnecessarily high because, although individual units within the plant are optimized, the plant as a whole has not been integrated and optimized.

Additionally, within a plant many waste streams are often sent to treatment or disposal without examining recycling opportunities or waste heat potential. Often times, waste streams contain valuable raw materials that can be recycled. Furthermore, waste streams often contain combustible materials that can be converted into useful forms of energy like steam. These opportunities are often missed because, although individual units within the plant are optimized, the plant as a whole has not been optimized.

This dissertation follows the style and format of *Chemical Engineering Communications*.

The standard techniques used to optimize individual units cannot be employed to optimize an entire plant. In order to optimize an entire plant the interactions between units must be understood and all units must be considered simultaneously. As such, the field of process integration has been advancing techniques to analyze and optimize entire plants. Currently, there are several major approaches in the field of process integration: heuristics, thermodynamic techniques, graphical techniques and mathematical modeling techniques. While heuristics and thermodynamic approaches to optimization are important, this dissertation focuses on improving the graphical and mathematical approaches. Graphical techniques provide quick and relatively accurate targets for minimum utilities, wastes, raw material requirements, etc. Additionally, graphical techniques provide insights into the process that would not normally be seen with traditional design approaches, and they lay the foundation for designs that can meet the aforementioned targets. Meanwhile, mathematical modeling approaches can handle larger problems and provide rigorous targets and designs, but they are typically less insightful and more labor intensive.

The field of process integration is typically further broken down within graphical and mathematical techniques into three key areas: energy integration, mass integration, and the burgeoning field of property integration. Energy integration typically involves targeting the minimum heating and cooling duties required to operate a plant, and designing a heat exchange network that can achieve the aforementioned targets. Mass integration, usually focuses on achieving a set mass objective, such as: reducing waste water, maximizing a product’s yield, decreasing raw materials, etc. Finally, property integration, like mass integration, is geared toward achieving a specific goal. However, unlike mass integration, property integration, as the name implies, deals with property constraints rather than concentration constraints.

This dissertation focuses on the research being conducted to advance the field of process integration through developing techniques to enhance resource conservation and allocation. The work presented within this dissertation will focus on optimizing the mass and energy resources present in a utility system. To accomplish this, techniques will be developed to optimize steam utility systems and recover property constrained wastes. Enhancing steam utility systems will entail three concepts: targeting steam cogeneration potential and designing feasible cogeneration networks while minimizing fuel requirements, identifying and exploiting sources of waste heat, and incorporating heat pipes into heat exchange networks. Property constrained resource recovery will examine the adaptation of established mass integration techniques for property objectives and look at incorporating programming techniques to design property interception networks to recover effluent wastes.

The optimization of steam utility systems, as mentioned, will encompass three concepts: targeting and designing cogeneration networks, utilizing waste heat and utilizing heat pipes to enhance heat exchange networks. In order to target cogeneration potential, the novel concept of extractable power will be introduced. Additionally, a graphical technique will be introduced that utilizes the idea of extractable power to quickly and easily target the cogeneration potential of a plant. Furthermore, the graphical technique provides the foundation to generate several feasible cogeneration networks. The utilization of waste heat will entail the identification of waste heat sources including both hot waste streams exiting the facility and waste streams with the potential to become combustible fuels. After the identification of potential waste heat sources, a methodology will be introduced that appropriately allocates these resources into a heat exchange network (HEN). Finally, the use of heat pipe technology to improve existing heat exchange networks will be assessed.

The secondary objective, as mentioned, involves the design of property interception networks to recover effluent waste streams. To accomplish this, the transformation of well established mass integration techniques to property based techniques will be examined. Additionally, the use of computer programming techniques will be incorporated to aid in the design of property interception networks.

Having briefly discussed the ideas of process integration and the work to be completed within this dissertation, it is important to lay out the format of material to be covered within this work. The problem to be addressed within this body of work will be fully described within Chapter II. Prior to delving into the new material presented within this work, a brief overview of previous work in the area of process integration will be presented. Chapter III will include a literature review of relevant techniques in the field of process integration. The literature review will provide an overview of the areas of energy, mass, property integration, waste heat recovery and heat pipe technology.

Additionally, an emphasis will be placed on the evolution of methods for targeting and designing cogeneration networks. The optimization of steam systems will be handled in Chapter IV and Chapter V. Chapter IV will examine the use of heat pipes to improve heat exchange networks. Then, Chapter V will introduce the concept of extractable energy and the accompanying graphical technique for targeting and designing cogeneration networks. Additionally, Chapter V will also address the utilization of waste heat sources. The development of property interception networks will be discussed in Chapter VI. To illustrate the usefulness of the presented techniques and methodologies, relevant case studies will be solved at the end of Chapters IV through VI. Conclusions regarding this work will be contained within Chapter VII. Finally, areas of future work concerning the material presented will be discussed in Chapter VIII. References and Appendices will be contained in Chapters IX and X respectively.

CHAPTER II

PROBLEM STATEMENT

Within a typical plant there are both mass and energy oriented objectives that require optimization. Consider Figure 2.1, which represents an overview of a typical plant. Within the plant, there are several processes that produce and require steam at various levels. To satisfy these needs, a centralized utility system is present that produces steam and power by burning fuel. Additional power demands are satisfied by the power company. Finally, the overall plant brings in raw material and subsequently produces products, but in the process also produces wastes.

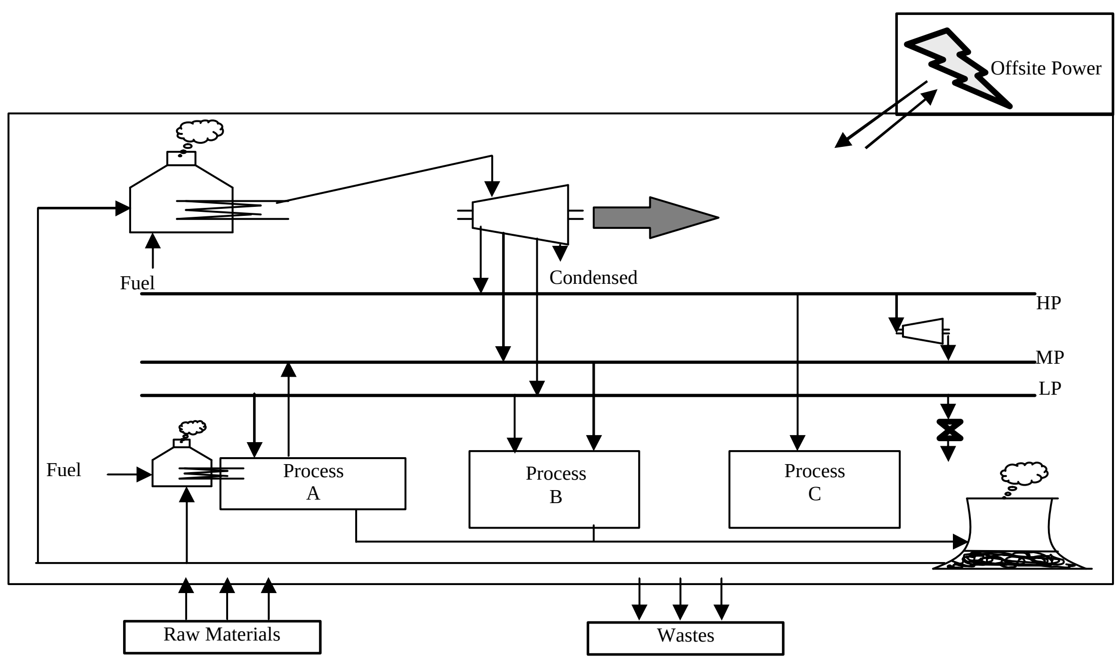


Figure 2.1: Typical plant

Therefore, the problem to be addressed is as follows: given a site with specific mass and heat demands, develop a systematic procedure for the optimal allocation of resources, and a targeting procedure for the cogeneration potential of the process as well as minimum fuel demands. Furthermore, devise an implementation scheme for both the steam and power generation system. Finally, within the process, develop a property interception network that can recycle/recover waste effluent streams back to the process while satisfying a number of property constraints.

CHAPTER III

LITERATURE REVIEW

The scope of research presented in this dissertation requires a broad review of literature in the areas of process integration, waste heat recovery, heat pipes and cogeneration. Within process integration there are three distinct focus areas: energy integration, mass integration and property integration. Energy and property integration are directly applicable to the work presented within this dissertation and therefore will be discussed extensively. Mass integration, on the other hand, is not as applicable and will only be discussed briefly for completeness. An overview of waste heat recovery as it pertains to this dissertation and heat pipe technology will also be examined. The concept of cogeneration will be defined and discussed as it is applicable to steam systems. Additionally, the use of steam turbines is intimately tied to the idea of cogeneration and therefore, a review of steam turbines will also be covered.

Process Integration

Process integration looks at the overall process rather than focusing on individual units that make-up the process. The basis for this approach is that, without a thorough understanding of the interaction between all units, it is impossible to determine if a change in one portion of the process will adversely affect another portion of the process. As such, there are three main aspects of process integration: synthesis, analysis and optimization (El-Halwagi, 1997).

Synthesis is the development of a process to achieve a specified product or products given a set of inputs. The objective of a synthesis is to ascertain the optimal connectivity and selection of equipment as well as operating conditions to achieve the objectives set forth. Analysis, on the other hand, focuses on predicting and verifying the performance of every process within a synthesized design to insure the product objectives are achieved. Therefore, synthesis determines the process flow sheet and analysis determines a feasible set of conditions that allows the process to operate. Having established a working process through synthesis and analysis, it is then important to establish if the objectives have been met optimally. Therefore, optimization involves systematically revising and reanalyzing a process until the objectives are met optimally.

The objectives to be optimized within any process can typically be related to optimizing energy, optimizing mass or optimizing properties. Consequently, process integration tools can be lumped into three categories: energy integration, mass integration and property integration.

Energy Integration

The focus of energy integration is to minimize the energy demands associated with a process. In order to accomplish this, energy integration focuses on reducing the energy requirements of given units or, more commonly, by utilizing energy within the process rather than using utilities. For instance, a hot stream that requires cooling can be paired with a cold stream that needs heating rather than adding a heating and cooling utility to accomplish these demands. As with all areas of process integration, energy integration can be broken down into graphical and mathematical approaches. The focus of this research is graphical in nature and therefore, the principal review of energy integration will focus on graphical techniques. Mathematical approaches will be discussed where applicable.

Prior to delving into the details regarding energy integration, it is important to define the following common terms: hot, cold, source and sink. For the remainder of the literature review on energy integration, the term hot will describe a stream or unit that is at a temperature T_{supply} and requires cooling to reach a temperature T_{target}. Similarly, the term cold will describe a stream or unit that is at a temperature T_{supply} and requires heating to reach a temperature T_{target}. Furthermore, the terms source and sink will refer to a stream or unit that can give up energy or accept energy respectively.

The Pinch Diagram

A principal aspect of energy integration is the formulation of heat exchange networks to appropriately pair process streams to minimize the need for external heating and cooling. The pinch diagram is a simple graphical approach that allows heat sources and sinks to be represented by composite curves. Additionally, the pinch diagram allows the determination of the minimum heating and cooling utilities for a process, and provides the framework to create a feasible heat exchange network to achieve the utility targets.

In order to develop a pinch diagram, the first step involves the construction of the hot and cold composite streams. Consider a process containing two hot streams H1 and H2, and two cold streams C3 and C4. Additionally, each stream has a flow rate F_s, a heat capacity Cp_s and a supply and target temperature $T_{supply,s}$ and $T_{target,s}$ where s refers to the stream. Then, the construction of the composite curves can begin on a temperature versus enthalpy diagram.

Consider Figure 3.1, containing both of the hot streams plotted on a temperature versus enthalpy diagram. Note that the streams are plotted in ascending order based on their target temperatures. Also, after H2 is plotted, H1 is plotted with the arrow head aligned vertically with the tail of the H2 line.

Then, in order to generate the hot composite line, vector superposition is used; put simply, the enthalpy in the overlapping temperature region is added and a new line is generated. The hot composite line can be seen in Figure 3.2.

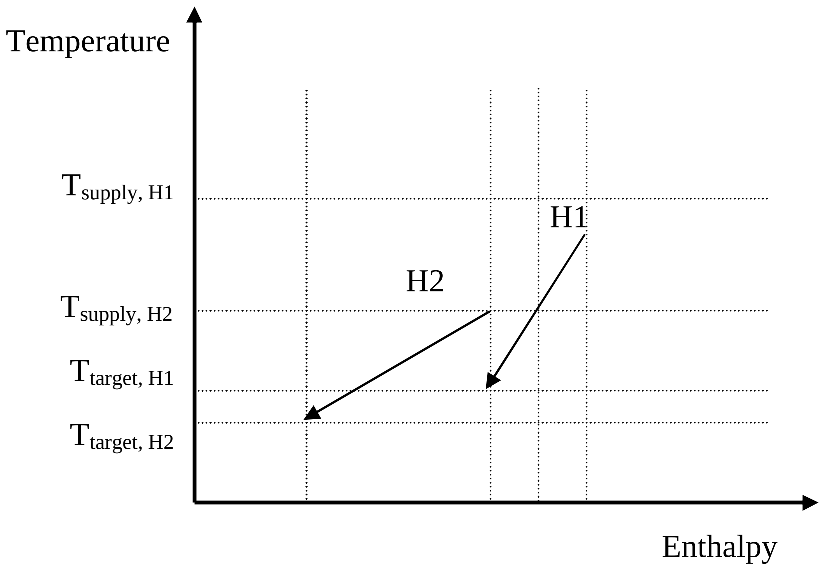


Figure 3.1: Hot streams

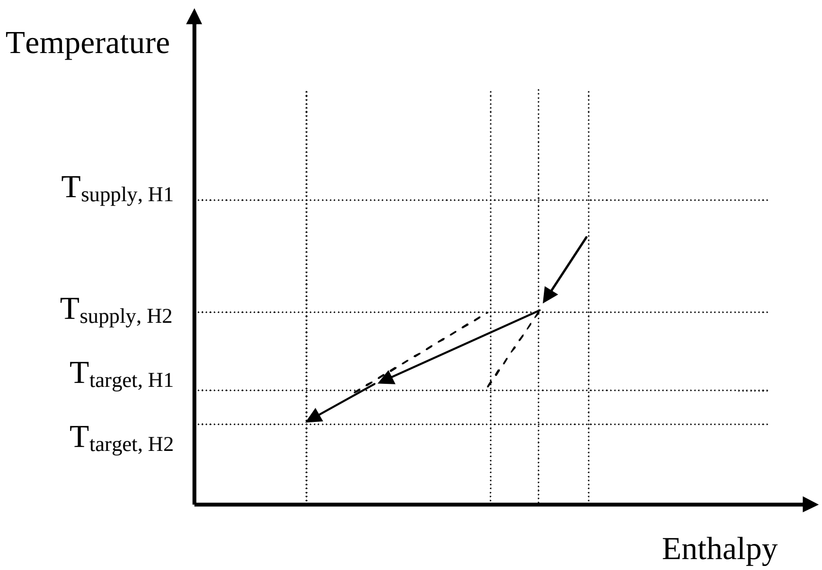


Figure 3.2: Hot composite line

In a similar fashion, the cold composite line can be generated and is shown in Figure 3.3.

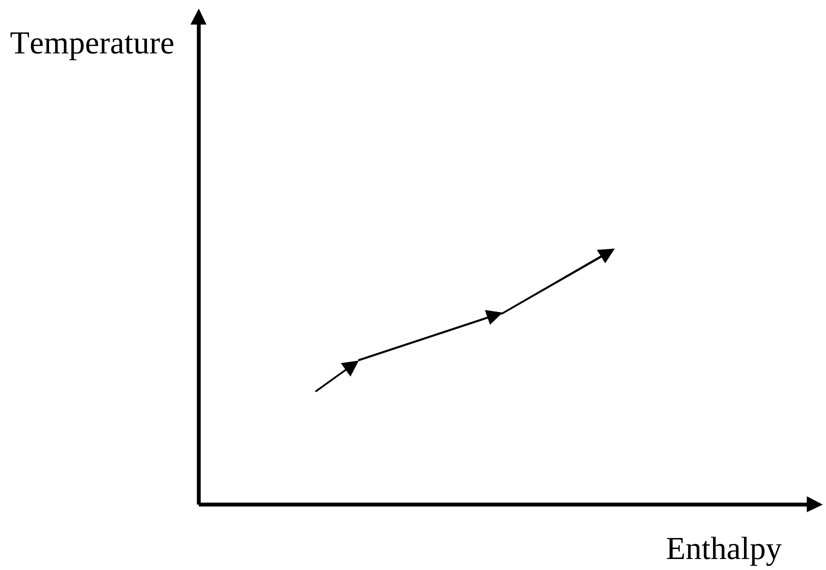


Figure 3.3: Cold composite line

Next, the hot and cold composite lines are placed on the same graph, and this can be seen in Figure 3.4.

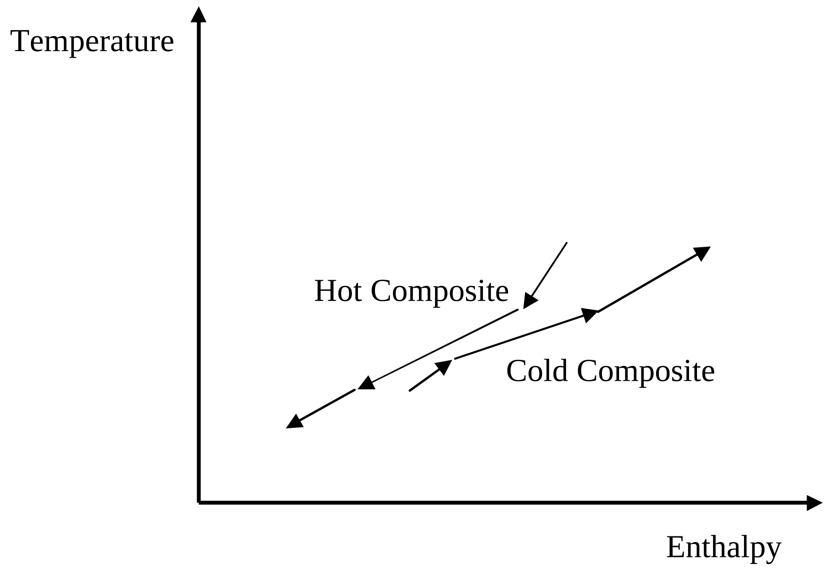


Figure 3.4: Hot and cold composite lines

The cold composite line can then be moved to the left or right until the composites touch with the cold composite lying completely beneath the hot composite. The region of vertical overlap corresponds to the energy that could theoretically be integrated. However, in order to achieve this energy transfer, infinitely large heat exchangers would be required. This is because at the point of contact between the composite lines there is no temperature difference, and therefore no driving force. To insure that heat transfer will occur without an unnecessarily large heat exchanger the cold composite line is adjusted by a minimum temperature difference, DT_{min}. The adjusted cold composite line can be seen in Figure 3.5.

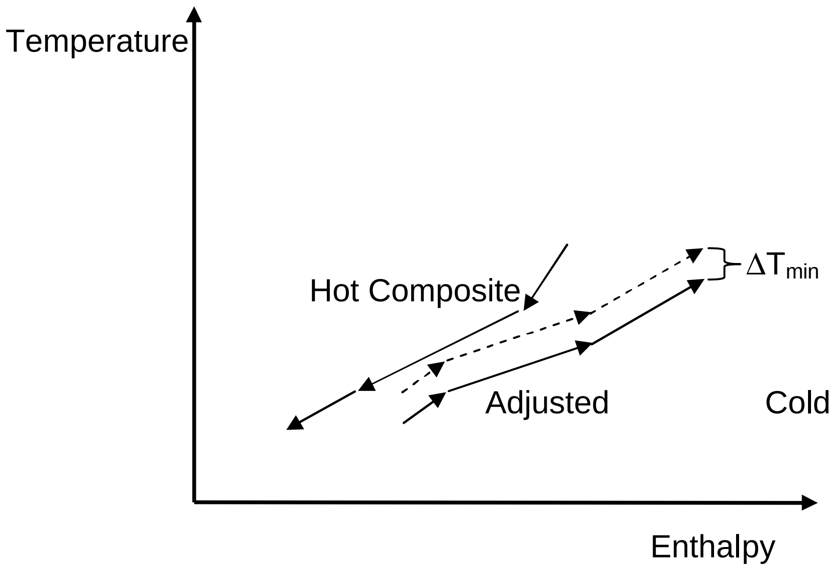


Figure 3.5: Shifted cold composite line

Next, as described before, the cold composite line can be moved to the right or left until the composite lines touch. The point where the lines touch is referred to as the "Thermal Pinch Point" (Umeda et al., 1979). The pinch point indicates the limit of feasible energy integration within the process; which is determined as the region of overlap between the hot and cold composite streams. A complete pinch diagram with an adjusted and shifted cold composite line can be seen in Figure 3.6.

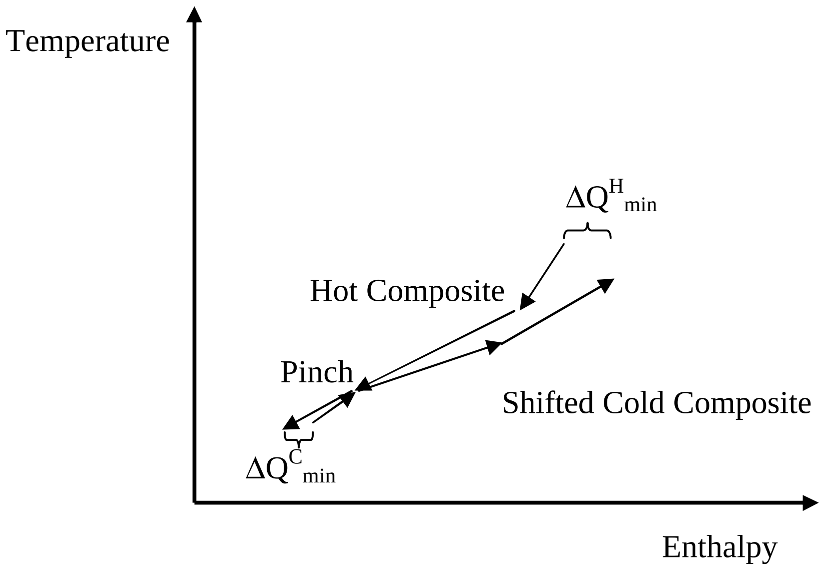


Figure 3.6: Pinch diagram

In addition to providing the amount of feasibly integrated heat transfer within a process, the pinch diagram also provides the minimum heating and cooling duty. The region on the cold composite that has no hot composite directly above is the minimum heating duty, DQ^{H}_{min}; while the region on the hot composite that has no cold composite directly below is the minimum cooling duty, DQ^{C}_{min} (Hohmann, 1971).

Temperature Interval Method

While a graphical approach provides insights and an understanding of the process it also has its limitations. As the problem becomes increasingly large, the development of the pinch diagram becomes increasingly tedious. In this instance a mathematical approach becomes desirable. The “Temperature Interval Method” provides an algebraic approach that performs the same duties as the pinch diagram by determining the pinch location and the minimum heating and cooling duties (Linnhoff and Fowler, 1978).

To begin the temperature interval method a temperature interval diagram is constructed. Consider the same four streams, H1, H2, C3 and C4, discussed in the previous section. A pair of vertical axes are constructed with the left axis indicating temperature and the right axis indicating temperature minus a DT_{min}. Each hot stream is then plotted against the left axis from its respective T_{supply} to T_{target}. Similarly, on the right axis the cold streams are plotted from their respective T_{supply} to T_{target}. An example of this diagram can be seen in Figure 3.7.

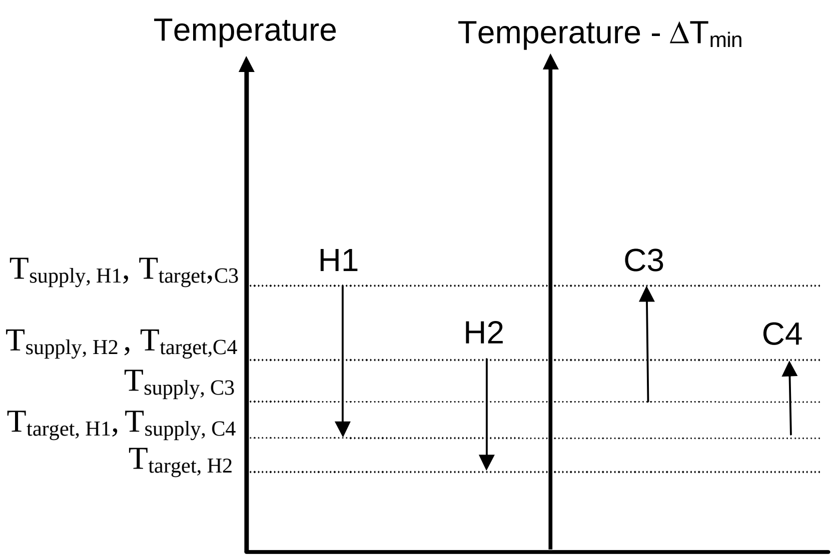
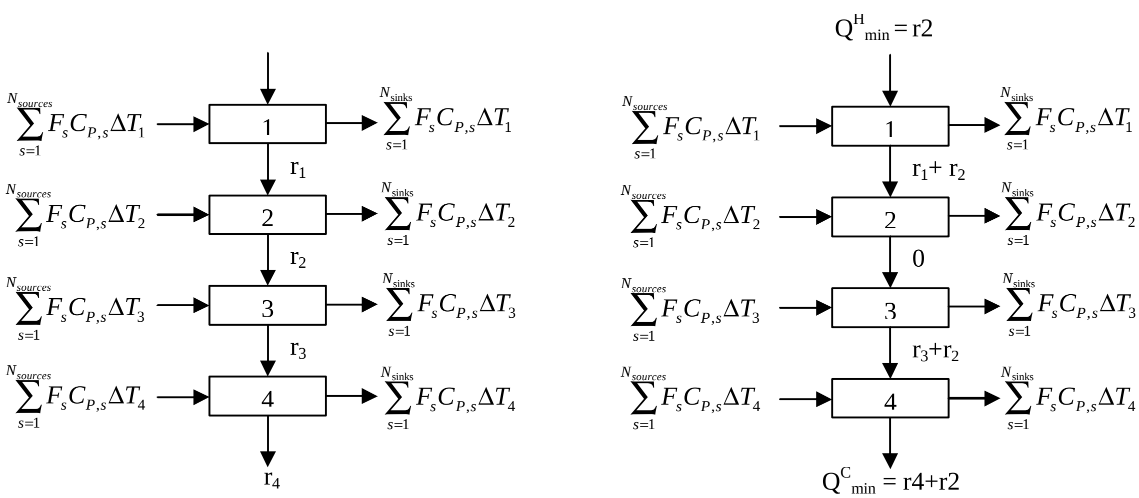


Figure 3.7: Temperature interval diagram

To define intervals within the diagram, horizontal lines are drawn at all supply and target temperatures. Then, feasible heat transfer can occur within any interval. Additionally, heat transfer can occur between an upper interval and any lower interval. For example, H1 can transfer heat to C3 in the first interval or to C3 or C4 in either of the next to lower intervals. To determine the pinch location and heating/cooling duties, energy balances are performed on each interval.

To perform an interval energy balance, the flow rate and the heat capacity of each source is multiplied by the temperature difference of the interval and summed for all sources in that interval; this is the energy available from the sources in this interval. A similar calculation is done for the sinks in the same interval; this is the energy needed by the sinks in this interval. Then, these calculations are carried out for all intervals. For the top interval, the energy available from the sources is subtracted from the energy needed by the sinks with the difference being passed down to the next interval. In the next interval, the energy passed down from the above interval is added to the available energy in that interval and subtracted from the sink energy needs with the difference again being passed down to the next interval. This calculation is repeated until all interval balances have been performed.

Then, the energy being passed down from interval to interval is examined. Negative values indicate an overall energy deficit in the preceding interval and means energy is being transferred from a lower temperature interval to a higher temperature interval, which is thermodynamically infeasible. To correct this, the most negative value being passed down the cascade is added to the top of the first interval and the balances are recalculated. The energy added to the top interval is the minimum heating duty; while the energy being passed out of the final interval is the minimum cooling duty. Furthermore, the interval in which no energy is transferred between constitutes the thermodynamic pinch location. Cascade diagrams illustrating the initial and final balances of Figure 3.7 can be seen in Figure 3.8:



*r_2 is defined as the most negative residual

Figure 3.8: Cascade diagram

where *s* refers to streams and *r* represents the residual energy from the preceding interval.

Grand Composite Curve

Another graphical approach in energy integration is known as the grand composite curve or GCC (Linnhoff et al., 1982). The GCC provides the same information as the previous two approaches, but it presents the information in a slightly different fashion. The advantage the grand composite curve has over the other two approaches is that it lends itself to multiple process analysis techniques.

The construction of the GCC can be done from either the pinch diagram or the cascade diagram; however, the cascade diagram is simpler to explain. From the final cascade diagram represented in Figure 3.8, consider the heating/cooling duties as well as the residual energies being passed between intervals. This information is plotted on a temperature versus enthalpy diagram using the average temperatures between intervals. The GCC for Figure 3.8 can be seen in Figure 3.9.

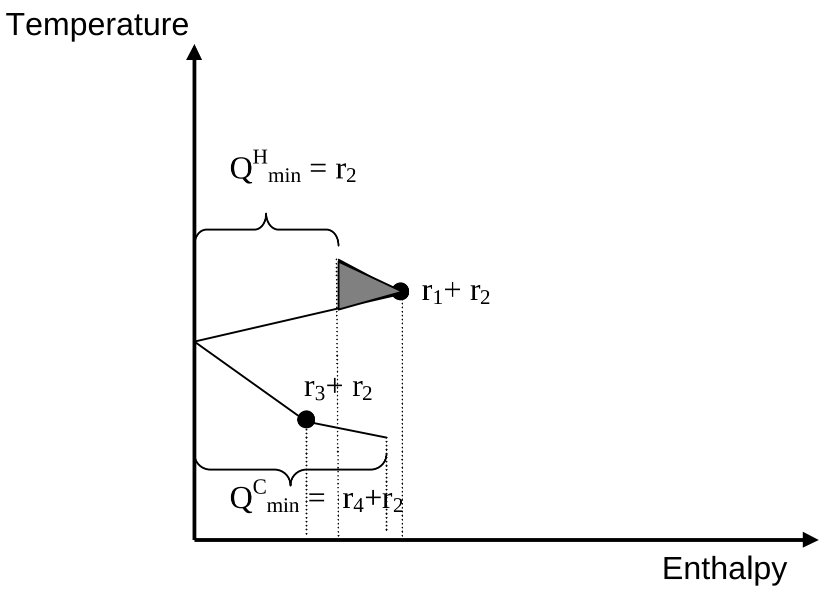


Figure 3.9: Grand composite curve

The gaps at the top and the bottom of the diagram represent the minimum heating and cooling duty. Furthermore, the pinch location occurs at the point where the plot touches the vertical temperature axis. Finally, intra-process heat transfer is identified by pockets, in Figure 3.9 a pocket is identified by the grey region. The GCC is particularly useful in determining the level and amount of heating and cooling required within the system.

The techniques discussed up to this point have generally been applicable to single processes. Multi-process techniques for determining heating and cooling duties have been developed; however, they also deal with cogeneration targeting and therefore, will be discussed in the cogeneration section of the literature review.

Mass Integration

The focus of mass integration is to achieve specific mass objectives associated with a process. Some examples of mass objectives could be, reducing waste water discharge, recovering raw materials from product or waste streams, recovering products from waste streams, etc. In order to accomplish this, mass integration focuses on screening mass separating agents (MSAs) and synthesizing mass exchange networks to recycle and recover material within a process. Similar to the thermal pinch diagram and the cascade diagram presented in the energy integration review, mass integration has analogous techniques. These techniques are very similar to those previously presented, and therefore, only the graphical source sink diagram will be reviewed, as a variation of it will be utilized during the case study in Chapter VI.

The source sink diagram was developed by (El-Halwagi and Spriggs, 1996) and is a useful technique for determining direct recycle opportunities within a process. An example of the source sink diagram can be seen in Figure 3.10:

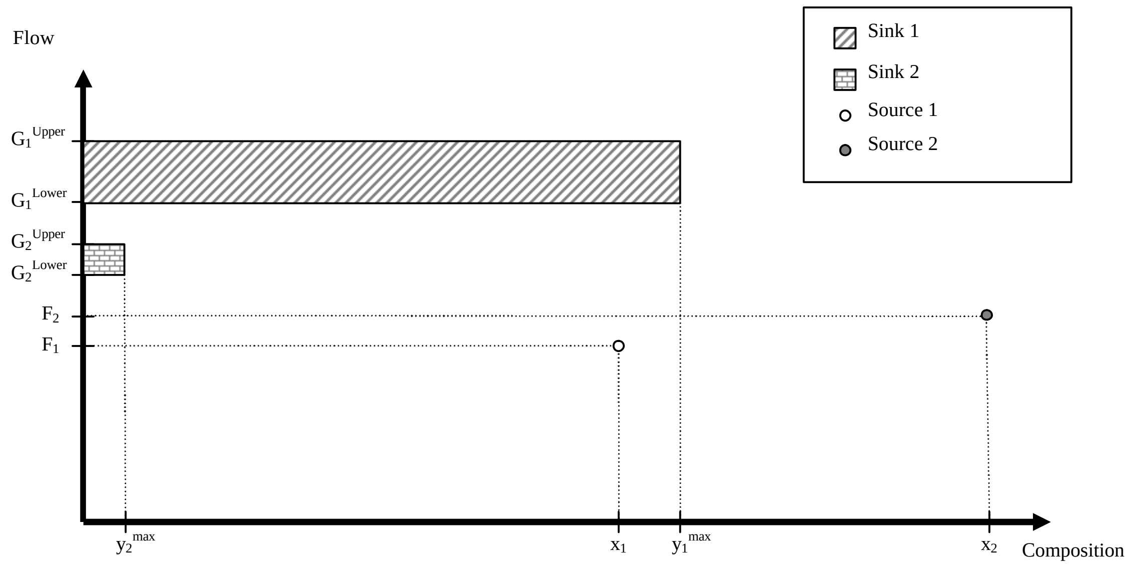


Figure 3.10: Source sink diagram

where G represents the flow rate of a sink, F represents the flow rate of sources, and y and x are the compositions of sinks and sources respectively. Figure 3.10 uses bounds on composition and flow rate to create regions to represent sinks. Meanwhile, sources have fixed flow rates and compositions, and are therefore represented by points. Then, lever arm principles are used to determine which sources, or mixtures of sources, can be recycled to which sinks.

For example, source 1 can be directly recycled to sink 1; however, source 1 does not contain a high enough flow rate to satisfy the demand of sink 1. Since source 1 is not at the upper composition limit of sink 1, source 1 can be mixed with source 2 in such a proportion to achieve a mixture that lies at the lower right corner of sink 1's feasibility region. By utilizing the shortest arm principle (sources with the shortest lever arm are recycled first), sources can be systematically mixed and recycled until all direct recycle opportunities are explored. Additionally, the source sink diagram provides insights into what level of interception is needed in order to recycle a potential source to a sink.

Property Integration

The field of property integration, unlike mass and energy integration, is only in its infancy; as such, the amount of literature on the subject matter is limited. The primary work in the area of property integration revolves around the concept of clusters to track properties (Shelley and El-Halwagi, 2000). Unlike mass and energy, properties are not conserved and therefore, in order to track them throughout a process the concept of clusters has been introduced.

Principles of Clusters

The main aspect of component-less design is the idea of using clusters to track properties. Properties alone are not conserved quantities; in order to track them, properties are transformed through mixing rules into dimensionless quantities (clusters) that allow both intra-stream and inter-stream conservation. Intra-stream conservation states that the summation of clusters within a stream is equal to a constant and is shown in equation 3.1:

$$\sum_{i=1}^{N_{prop}} C_{i.,s} = 1 \qquad (3.1)$$

where $C_{i,s}$ is the cluster of property i in stream s, and N_{prop} is the number of properties of interest within the process. For three properties the concept of clusters can be illustrated graphically on a ternary diagram. Figure 3.11 represents intra-stream conservation within a ternary diagram.

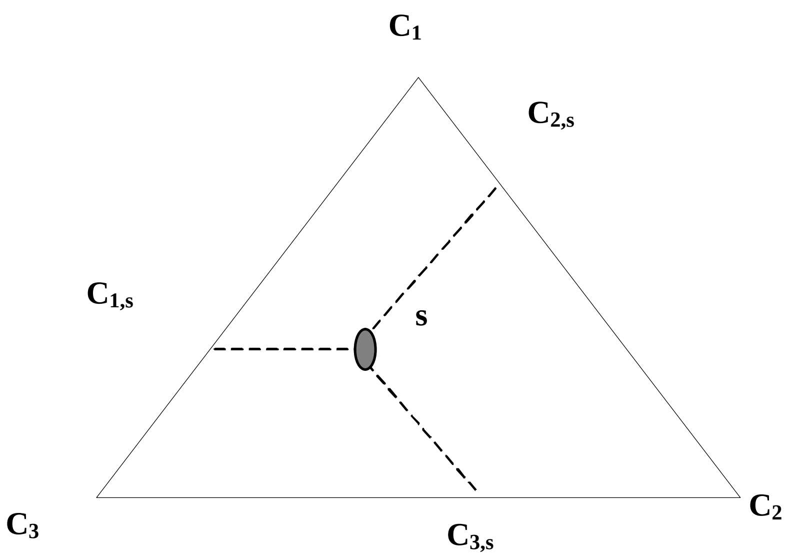


Figure 3.11: Intra-stream conservation

Another important criterion is inter-stream conservation which states that when two or more streams are mixed the resulting mixture clusters can be determined by standard additive rules (lever arm principle). This can be represented mathematically in equation 3.2:

$$\overline{C}_i = \sum_{s=1}^{N_{sources}} b_s C_{i,s} \qquad (3.2)$$

where $\overline{C}_i$ is the mixture cluster, b_s is the fractional contribution of stream s and $N_{sources}$ is the number of streams being mixed. As with intra-stream conservation, the additive rule can be represented graphically for three clusters. The graphical representation of the lever arm principle is shown in Figure 3.12.

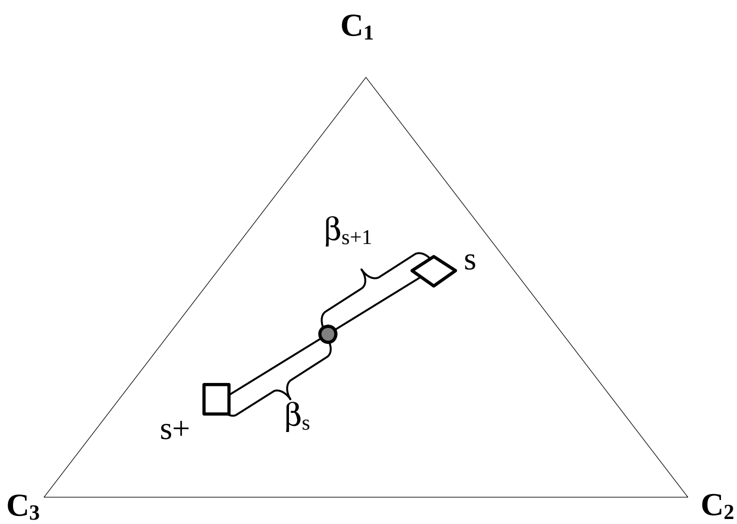


Figure 3.12: Inter-stream conservation

Having discussed the basic principles of clusters it is now important to briefly discuss the derivation of clusters from properties.

Derivation of Clusters

The derivation of clusters is applied to the class of properties that exhibit the following mixing rule form seen in equation 3.3:

$$y(\overline{P}) = \sum_{s=1}^{N_s} x_s y(P_s) \tag{3.3}$$

where y is the property operator, $\overline{P}$ is the mixture property, P_s is the property of stream s and x_s is the fractional contribution of stream s. An example of a property with one such mixing rule is density, shown in equation 3.4:

$$\frac{1}{\overline{r}} = \sum_{s=1}^{N_s} x_s \frac{1}{r_s} \tag{3.4}$$

where r is density and the property operator is $\frac{1}{r}$.

To begin the derivation of clusters, the mixing rule operators are first made dimensionless by using arbitrarily chosen reference values. The reference values can be any number, but are usually chosen to keep the magnitudes of the dimensionless quantities similar. The dimensionless quantity of property i is presented in equation 3.5:

$$\Omega_i = \frac{y(P_i)}{y(P_i^{ref})} \tag{3.5}$$

where W_i is the dimensionless quantity of property i, and P_i^{ref} is the arbitrarily chosen reference of property i. Next, the augmented property index or AUP is defined as the summation of all the W values for a given stream, shown in equation 3.6.

$$AUP_s = \sum_{i=1}^{N_P} \Omega_{i,s} \tag{3.6}$$

Finally, a cluster *i* is defined in equation 3.7:

$$C_{i,s} = \frac{\Omega_{i,s}}{AUP_s} \tag{3.7}$$

where $C_{i,s}$ is the cluster of property *i* in stream *s*. Equation 3.7 guarantees that intra-stream conservation is maintained. Clusters can then be utilized to track properties throughout a process in a similar fashion to mass or energy.

Optimization of properties using clusters has been limited to three properties and graphical approaches using ternary diagrams (Shelley and El-Halwagi, 2000). The primary use of this approach is for the development of recycling strategies or resource allocation. Additionally, the graphical nature provides insights into how properties can be modified to improve a process. Expansion of property integration through mathematical techniques will be discussed later in Chapter VII.

Waste Heat Recovery

Waste heat recovery is a topic gaining increased popularity as companies struggle to improve performance and cut costs. Waste heat is a broad term that can be used to categorize numerous industrial streams. For instance, the exhaust gases from gas turbines and furnaces can be considered sources of waste heat. Similarly, condenser cooling water and condensate streams can also be categorized as sources of waste heat. Therefore, in order to appropriately utilize waste heat sources they must first be characterized. Several key characteristics to determine the best approach for utilizing waste heat are temperature range, phase, amount, makeup, availability and location (Olszewski, 1980). The temperature range determines where the waste heat might be best applied as well as the technology that might be used. For instance, a high temperature source such as a gas turbine exhaust might be used to generate steam in a waste heat boiler. Similarly, the other characteristics also help determine how and where the waste heat source can be used.

Additionally, there are sources of potential waste heat within a process such as spent solvents or lubricants, wood wastes, or polymeric wastes. These wastes possess considerable potential energy that can be released through combustion in a furnace. Again, the wide range of materials that can be considered as potential waste heat sources require characterization, similar to the list for waste heat sources, to properly be utilized. A primary concern with incineration is the environmental hazards associated with the combustion products. For example, the incineration of a wood waste would not likely present much of an environmental concern. Meanwhile, the combustion of a spent lubricant may produce several combustion gases that require substantial treatment before being released into the environment. Additionally, the ash produced may require special disposal.

With the numerous sources of waste heat available in an industrial process many technologies have emerged to utilize this energy. Some of the more common technologies available are heat recovery heat exchangers, heat pumps and incinerators.

The term, heat recovery heat exchanger covers a wide spectrum of equipment. Since the focus of this dissertation is on the optimization of utility system it is appropriate to focus on the heat recovery heat exchanger that is most applicable, the waste heat boiler (WHB) or heat recovery steam generator (HRSG).

The waste heat boiler is a device that transfers the energy from high temperature exhaust gases to water to produce steam. There are three main classes of WHBs: unfired, auxiliary fired and furnace fired systems (Ganapathy, 1991). The unfired HRSG typically utilizes 430ºC – 540ºC waste streams and has a gas to steam ratio of 5.5 to 7. The auxiliary fired WHB passes the exhaust gas through a burner prior to entering the boiler. As a result of the supplementary firing, the waste stream enters the boiler at temperatures of 540ºC - 930ºC and has a gas to steam ratio of 2.5 to 5.5. Finally, the furnace fired HRSG, fires the exhaust gas to its adiabatic combustion temperature based on the oxygen present in the exhaust stream. The furnace fired HRSG has the highest inlet gas temperature at 930ºC - 2000ºC and also the lowest gas to steam ratio at 1.2 to 2.5.

Heat pumps and incinerators are also commonly used technologies for recovering heat. However, heat pumps are used to extract energy from low level heat sources and through the input of mechanical energy transfer it to higher level heat sinks. The applicability of such a device in a steam utility system is minimal and therefore is only mentioned here for completeness. Incinerators, on the other hand, can be directly utilized for the production of steam. However, because of the numerous complications associated with incineration such as, high and low level corrosion and combustion product treatment they will not be considered in this dissertation.

Heat Pipe Technology

The advent of new technologies always poses the possibility to improve existing systems. A heat pipe is a technology that possesses the potential to substantially increase the amount of energy that is integrated within a plant because a heat pipe transfers heat nearly isothermally. Therefore, using heat pipes in place of standard heat exchangers decreases the driving force required, and subsequently allows more energy to be transferred between streams.

While heat pipes are not a new technology, they are not a technology that has been readily employed in the process industry. The heat pipe was first conceived by Gaugler in 1944 in an attempt to solve a refrigeration problem for the General Motors Corporation (Dunn and Reay, 1994). However, the first prototype was not developed until 1964. The first heat pipe prototypes were built by Grover and others at the Los Alamos National Laboratory for use by NASA in satellites. Unfortunately, the high cost and prohibitively difficult process of manufacturing heat pipes prevented the technology from gaining rapid wide-scale terrestrial popularity. Fortunately, the potential benefits of heat pipes, along with improved manufacturing processes have led to an insurgence of research and availability of the technology. Therefore, the use of heat pipes in heat exchange networks is being explored within this dissertation. As such, prior to developing any techniques for utilizing heat pipes, a basic understanding of heat pipes must be established.

A heat pipe is a heat transport device using evaporation and condensation to transport high rates of heat nearly isothermally. The basic construction of a heat pipe is a sealed chamber containing a non-porous outer shell, porous inner shell (the wick), and a heat transport fluid. The heat transport fluid exists in both the liquid and vapor phases within the pipe. The liquid resides in the wick, and the vapor occupies the hollow inside of the pipe. While there are many different designs of heat pipes, the simplest design can be seen in Figure 3.13.

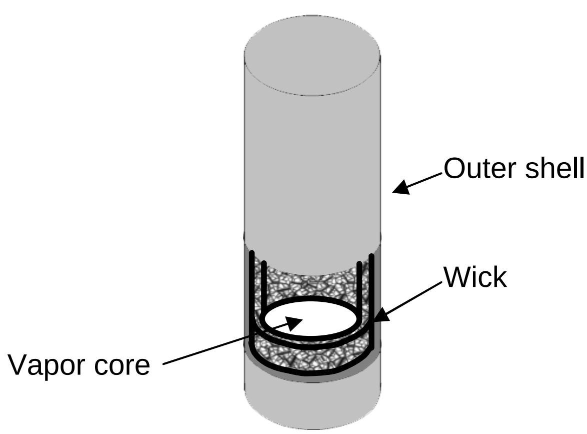


Figure 3.13: Capillary driven heat pipe

There are three main sections of a heat pipe: the evaporator, adiabatic, and condenser sections. The evaporator section (one end of the pipe) is in contact with a heat source, which causes the fluid in this section to evaporate. The vapor moves to the cooler condenser section through the vapor core, carrying with it the absorbed heat. The vapor then condenses in the condensing section (the other end of the pipe), and the liquid returns to the evaporator section by flowing back through the wick. The liquid returns through the wick by capillary pressure and gravity if the pipe is oriented properly. Finally, the adiabatic section is the middle portion of the heat pipe where very little vapor condenses.

Having described the operation of a heat pipe it becomes clear that in addition to the nearly isothermal heat transfer, heat pipes present an additional advantage over traditional heat exchangers. In a traditional heat exchanger, the fluids transferring energy are contained within the same unit. Therefore, it is dangerous to transfer energy between certain materials, for instance two materials that may react. In a heat pipe heat exchanger, the fluids transferring energy can be contained in separate units that are connected by a heat pipe. This energy transfer bridge greatly reduces the dangers associated with transferring energy between incompatible materials; which greatly alleviates constraints associated with pairing streams during the formation of a heat exchange network. While there is considerable information regarding the design and operation of heat pipes; the knowledge that heat pipes transport energy nearly isothermally, and that heat pipes allow the exchange of energy indirectly is sufficient for the techniques being developed within this dissertation.

Cogeneration

Cogeneration is the simultaneous production of two or more forms of useful energy. As applied to the process industry, this typically involves the production of heat and electricity for use within a plant. When conditions allow the simultaneous production of heat and electricity, plants should explore the potential of implementing a cogeneration system for several reasons: increased fuel efficiency, reduced operating expenses and reduced pollution. As such, the identification and quantification of cogeneration opportunities within the process industry has become a topic of increasing interest. For the purpose of this literature review, focus will be placed on cogeneration systems involving steam systems. Several methods for targeting cogeneration potential and establishing viable cogeneration networks for steam systems have been identified.

Steam Turbines

Prior to examining the various methods of targeting cogeneration potential, it is important to briefly discuss the primary unit involved in steam cogeneration, the steam turbine. Steam turbines are used in cogeneration networks because they produce two forms of useful energy. High pressure steam is let down producing a lower quality steam which can be used for heating purposes while simultaneously producing shaft work.

Steam turbines can be classified in several ways. However, for the purpose of this dissertation it is convenient to classify turbines based on whether they condense the vapor being expanded, a condensing turbine, or if they simply eject it at a lower pressure, a backpressure turbine or extraction turbine. A backpressure turbine lets down to only one pressure level. Meanwhile, an extraction turbine is more complex and has the ability to let vapor down to multiple pressure levels.

A turbine operates by accepting a vapor stream currently at a high pressure and letting it down to a lower pressure, or even condensing the vapor. The energy associated with the pressure change is converted into mechanical energy through the turbine in the form of shaft work. The shaft work can then be used in several fashions to provide useful work to the process. Typically, the shaft work is used to run a generator that produces electricity. However, the shaft work can also be used to run motors in units such as pumps or compressors.

Exergy Analysis

The first advance in cogeneration targeting and network formulation occurred by coupling the concept of exergy with existing graphical energy integration techniques. Exergy is the measure of useful energy available in a given source. This concept was added to the "Total Site Source Sink Profile," an energy integration technique that examines multiple processes simultaneously through the use of grand composite curves (Dhole and Linnhoff, 1992).

The total site source sink profile examines multiple processes at once by constructing overall composite source and sink profiles through the individual process GCCs. To begin, the grand composite curve pockets, as discussed earlier, are removed from the diagrams to account for intra-process integration. Next, the source portions of the GCCs are shifted down by ½ DT_{min}, while the sink portions are shifted up by ½ DT_{min}. This shifting insures feasible heat transfer between processes. Next, the source portions of all the GCCs are combined into a total site source composite. Similarly, the sink portions of all the GCCs are combined into a total site sink profile. The resulting composite curves are plotted on a temperature enthalpy diagram, an example of which is presented in Figure 3.14.

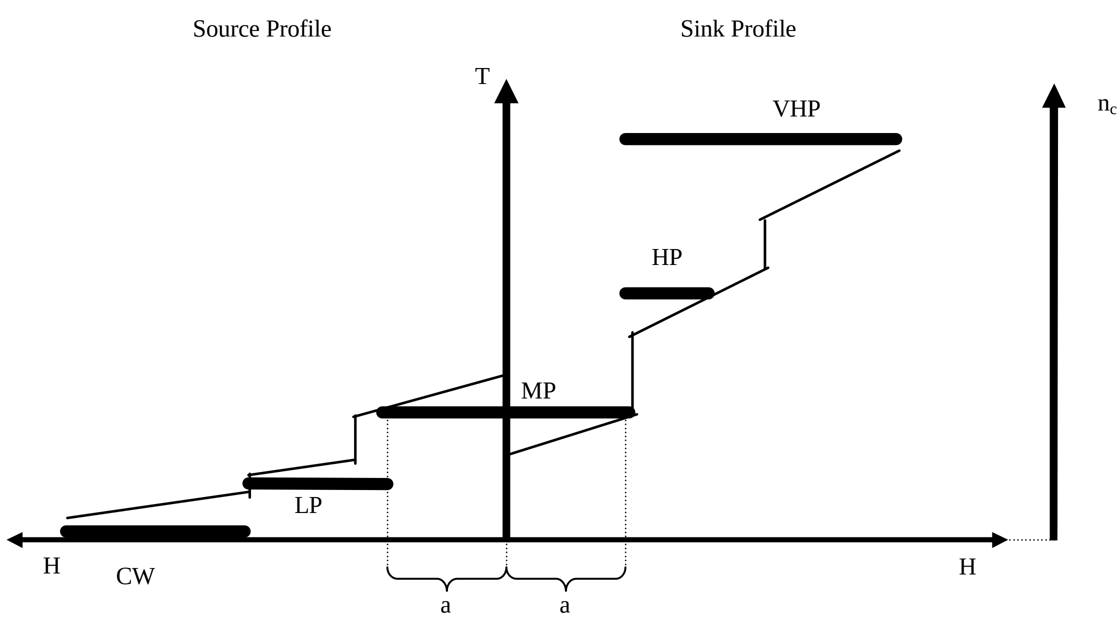


Figure 3.14: Total site source sink profile

In addition to the source and sink profiles, the steam/cooling water utility system can be included on the diagram which allows cogeneration targeting and utility integration to be performed. For instance, in Figure 3.14 the MP header shows that an equal amount of MP steam can be generated from the sources as is needed by the sink. Additionally, a portion of the VHP steam can be let down to HP steam and the LP steam generated by the sources can be condensed. The cogeneration potential of these expansions can be predicted by including a secondary vertical access with the Carnot efficiency. Then, the area between header levels, using the Carnot axis, is proportional to the cogeneration potential.

TH-Shaftwork Model

The next advance in cogeneration targeting and network formulation came with the TH-Shaftwork targeting model (Raissi, 1994). Raissi's model is based off an observation first made by (Salisbury, 1942). That is, the specific enthalpy at the turbine outlet minus the specific enthalpy of saturated water is relatively constant regardless of the outlet conditions. From this, and the observation that specific power can be approximated through a linear function of the outlet saturation temperature, the TH-Shaftwork target was developed (Raissi, 1994). The TH-Shaftwork target is based off of the equation below:

$$W = \frac{e}{q} \cdot (T_{in}^{sat} - T_{out}^{sat}) \cdot Q \tag{3.8}$$

where W is the overall power output, e is the power coefficient, q is the constant observed by Salisbury, T_{in}^{sat} and T_{out}^{sat} are the saturation temperatures at the inlet and outlet conditions of the turbine and Q is the heat load to be supplied by the turbine. From the above equation it is clear that power output is proportional to the area a turbine would occupy on a temperature-enthalpy diagram. By applying this technique to a graphical energy integration technique like the Total Site Profile technique previously discussed, the cogeneration potential of a plant can be determined. Furthermore, viable cogeneration networks can be designed through visual inspection. However, the method has several limitations. First, the observation of Salisbury is only valid for high turbine efficiencies (>0.7) and low turbine inlet pressures (< 100 bar). Secondly, the method does not work for turbines in series, or complex turbines. Finally, the method relies on saturation temperatures rather than actual header temperatures.

Turbine Hardware Model

The final method in cogeneration targeting and network formulation worth noting is the Turbine Hardware (TH) Model (Mavromatis, 1996). The TH Model is based on the Willans line and utilizes typical maximum efficiency plots and rules of thumb to target cogeneration potential. The TH Model also incorporates complex turbines by modeling them as sets of simpler turbines. While the TH model is considerably more accurate than the previous methods discussed, its limitation is its complexity. In order to accurately model a system, several parameters must be estimated through linear regression; which requires considerable data about the types of turbines being used.

CHAPTER IV

HEAT PIPE ENHANCEMENTS OF HENs

The incorporation of heat pipes into heat exchange networks presents the potential to substantially improve the amount of integration within a process. Furthermore, heat pipes allow a safe way to pair streams within a HEN that normally could not be paired due to safety concerns because of the indirect method of heat transfer. With the advantages of using heat pipes clear, it becomes necessary to determine if and where using heat pipes is appropriate; because, while heat pipes are more prevalent in industry today, they are still considered a specialty item and therefore more costly than a comparable standard heat exchanger. This chapter will provide a method to determine the minimal heating and cooling target when using heat pipes in a process. Then, a systematic procedure will be developed that will show where and how many heat pipes will be needed to achieve the aforementioned targets. Finally, a case study will be solved to show the applicability of the developed techniques.

Problem Statement

The problem to be addressed within this chapter can be stated as follows: given a process containing a heat exchange network with certain heating and cooling demands, target to what extent heat pipe technology can improve the exisiting heating and cooling demands, and determine how and where heat pipe technology should be used to accomplish the aforementioned target.

Heat Pipe Minimum Heating and Cooling Demands

The ability to quickly and accurately determine the minimum heating and cooling demands of a process using heat pipes is detrimental to the further development of procedures regarding the implementation of heat pipes into HENs. Fortunately, there are well established techniques used with standard heat exchangers that can be easily adapted to target the minimum heating and cooling demands of a process when heat pipes are employed. While several techniques exist in energy integration that will work for the overall targeting task, the temperature interval method coupled with the cascade diagram will be illustrated here since it is the basis for the technique to be developed later on in this chapter.

As discussed in the literature review in Chapter III, the temperature interval diagram (TID) plots hot and cold streams from their supply to their target temperatures on two distinct axes separated by a DT_{min}. Then, the diagram is broken into temperature intervals and the energy available or needed in each interval is transferred to the cascade diagram. Finally, energy balances are performed over each interval on the cascade diagram, which subsequently determines the thermal pinch location and the minimum heating requirement of the process. The minimum heating requirement is then added to the top of the cascade, and the resulting adjusted cascade diagram determines the minimum cooling requirement.

In order to determine the minimum heating and cooling requirements of a process when heat pipe technology is employed, it is convenient to simply determine the heating and cooling targets if heat pipes were the sole means of transferring energy. Therefore, on the TID rather than using the standard DT_{min} of 10ºC, a lower DT_{min} can be employed. Since heat pipes transfer energy nearly isothermally, an acceptable DT_{min} to accurately predict the performance of a heat pipe is 2ºC. It is difficult to show how a different DT_{min} will affect the generic TID and cascade diagram (shown in Figures 3.7 and 3.8); therefore, the differences will be elucidated during the case study at the end of this chapter.

Although the targets determined using the abovementioned method are most likely achievable by primarily using standard heat exchangers with heat pipe technology being employed sparingly for key heat transfers, the targets determined are guaranteed to be optimal for the technology available. Since heat pipe technology is not yet an off-the-shelf technology, it is prohibitively expensive to simply place heat pipes everywhere. Therefore, the upcoming section will develop a procedure to systematically determine where employing heat pipes will be most beneficial to a process.

Iterative Cascade Approach

To determine the ideal locations to use heat pipes within a heat exchange network a systematic procedure based off the cascade diagram has been developed. The procedure begins by first constructing a standard TID (10ºC DT_{min}) and also a heat pipe technology only TID (2ºC DT_{min}). Then, cascade diagrams are constructed for both TIDs and the minimum heating and cooling utilities are determined for both scenarios, as well as, the thermal pinch points. The 2ºC DT_{min} cascade provides the targets which will determine when the iterative procedure, about to be described, will end. Meanwhile, the 10ºC DT_{min} cascade provides the starting point for the iterative procedure.

Prior to discussing the iterative procedure it is useful to briefly convey the rational behind the approach. The rational behind this procedure is as follows, in a standard heat exchange network the thermal pinch point is the thermodynamically limiting point within the network. Therefore, other than physically changing a stream's flow rate or temperature within the network the only way of alleviating a pinch point is by decreasing the driving force required to transfer energy. Therefore, the pinch location is the ideal point to add a heat pipe, which will lower the driving force needed for efficient heat transfer. However, by altering the driving force around the initial pinch, a new pinch location may develop within the process. Subsequently, heat pipes can be added to further remove the new bottlenecks as they arise until the overall targets determined from the above methodology are reached. When the 2ºC DT_{min} cascade targets are achieved, the further addition of heat pipes will no longer achieve any benefit and the procedure can be terminated.

As mentioned earlier, the 10ºC DT_{min} TID and cascade are the starting point for the iterations and can be seen in Figures 4.1 and 4.2. The initial and revised cascade diagrams are shown and it is clear that the minimum heating and cooling utilities are r_2 and r_4+r_2 respectively, and the thermal pinch point occurs between intervals 2 and 3. Therefore, the addition of a heat pipe is warranted to transfer energy over the temperature range between intervals 2 and 3. To accomplish this, a new TID is developed. The new TID maintains the standard 10° DT_{min} between the hot and cold stream axes. However, over the interval of interest identified from the first cascade diagram, the DT_{min} is allowed to shift to mimic the addition of a heat pipe.

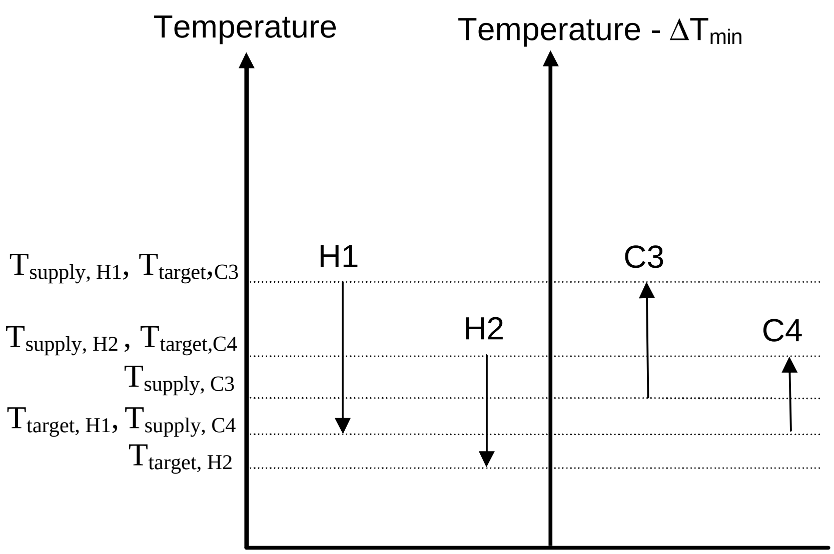
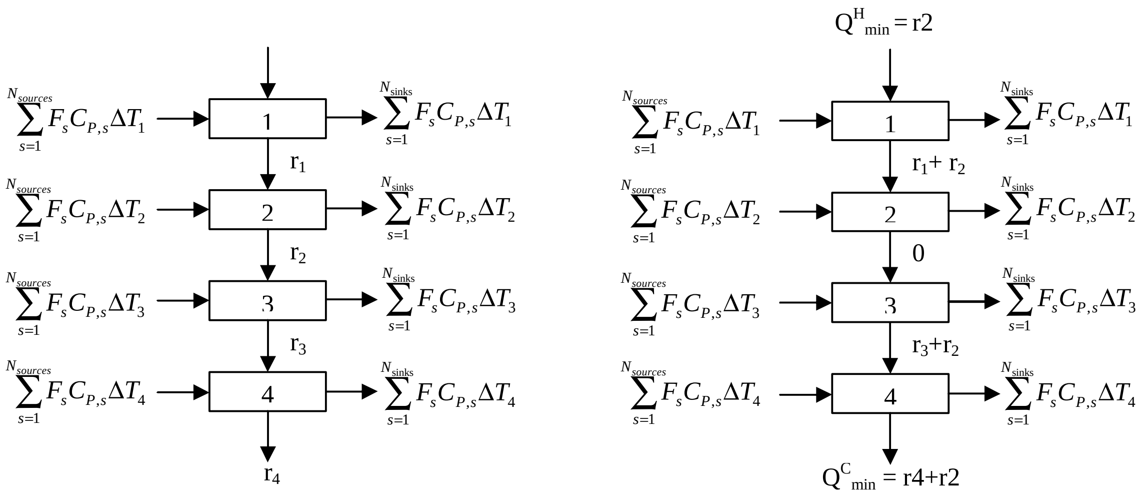


Figure 4.1: Generic TID



*r_2 is defined as the most negative residual

Figure 4.2: Initial and final cascade diagrams for a process

The resulting TID to accommodate a heat pipe heat exchanger between intervals 2 and 3 can be seen in Figure 4.3.

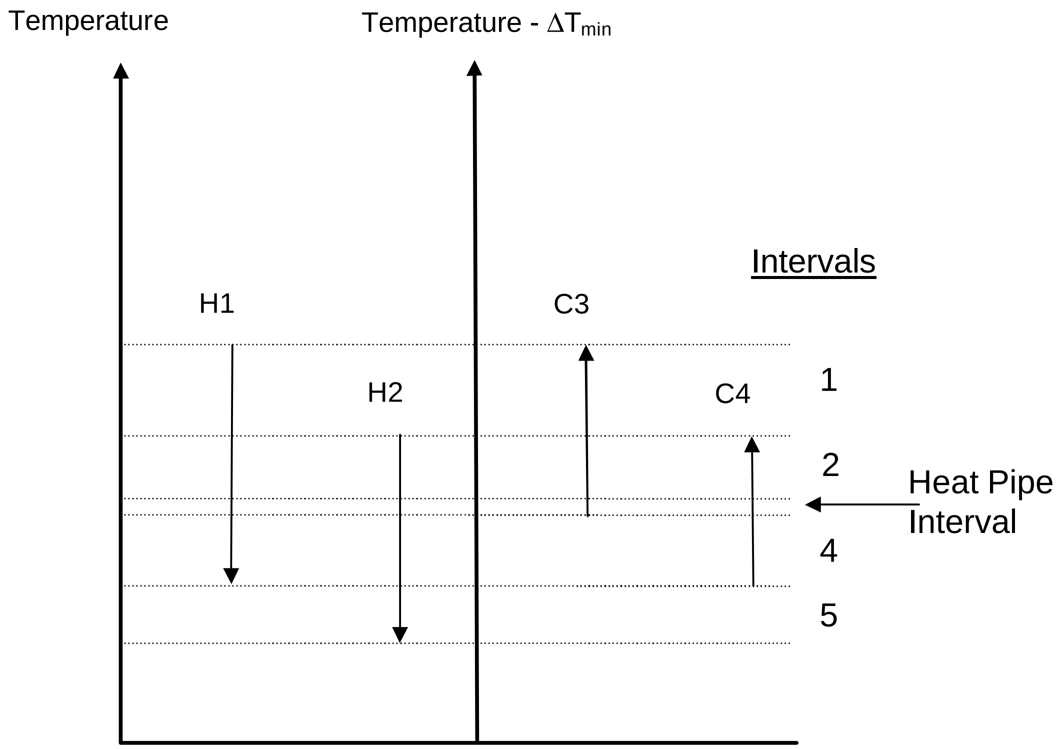


Figure 4.3: TID after first iteration

Comparing Figures 4.1 and 4.3 the obvious difference is that a new interval has appeared between where intervals 2 and 3 were. This new interval represents a heat pipe being used to decrease the driving force necessary for efficient heat transfer from a 10ºC DT_{min} to a 2ºC DT_{min}. As a result of this region of decreased driving force, a less apparent distinction occurs between Figures 4.1 and 4.3. In a standard TID the driving force throughout the entire graph remains constant; therefore, the temperature differences in each interval are the same for both the hot and cold axes. However, in the modified TID in Figure 4.3, the shrinking of the DT_{min} in the heat pipe region results in slightly different temperature differences in the intervals directly above and below the heat pipe interval for the hot and cold side. As a result, the hot and cold sides must use independent *DT* scales for each interval analysis.

After constructing the modified TID, the energy available or required in each interval is determined and transferred to a cascade diagram. The cascade diagram is solved as before, by performing energy balances over the intervals and passing the residual energy down the cascade. Then, as before, the most negative residual is added to the top of the diagram and the balance is performed again to determine the cooling target. If the heating and cooling targets of the revised cascade are equal to those predicted by the 2ºC DT_{min} TID and cascade the iterations stop. However, if the targets are higher than those predicted, the new pinch location is determined from the revised cascade and the procedure is repeated. To clarify and show the applicability of the iterative method described above a case study will be solved in the following section.

Case Study

To illustrate the usefulness of incorporating heat pipe technology into a heat exchange network a simple case study has been solved. Consider a process containing four hot streams, denoted by H, that require cooling and four cold streams, denoted by C, that require heating. Information regarding the flow rate (F), heat capacity (C_p), supply temperature (T_{supply}) and target temperature (T_{target}) of these streams can be found in Table 4.1.

Table 4.1: Heat pipe case study stream data

	$F \cdot C_p$ (kJ/h ºC)	T_{supply} ºC	T_{target} ºC
H1	0.5	650	150
H2	2.0	550	500
H3	1.3	500	250
H4	0.9	400	160
C1	0.9	490	640
C2	1.5	360	490
C3	1.3	130	320
C4	1.0	210	520

With this information the standard TID and cascade diagram can be created using a 10ºC DT_{min}. The TID and adjusted cascade diagram for the 10ºC DT_{min} can be seen in Figure 4.4. From the adjusted cascade diagram it is clear that the minimum heating and cooling targets are 60 kJ/h and 136 kJ/h respectively. Additionally, the thermal pinch point is located between intervals 4 and 5, which is equivalent to the temperature range of 390 – 400ºC. The pinch location will be the starting point for the iterations. However, prior to beginning the iterative process the 2ºC DT_{min} TID and cascade diagram should be constructed to determine a stopping point for the iterations.

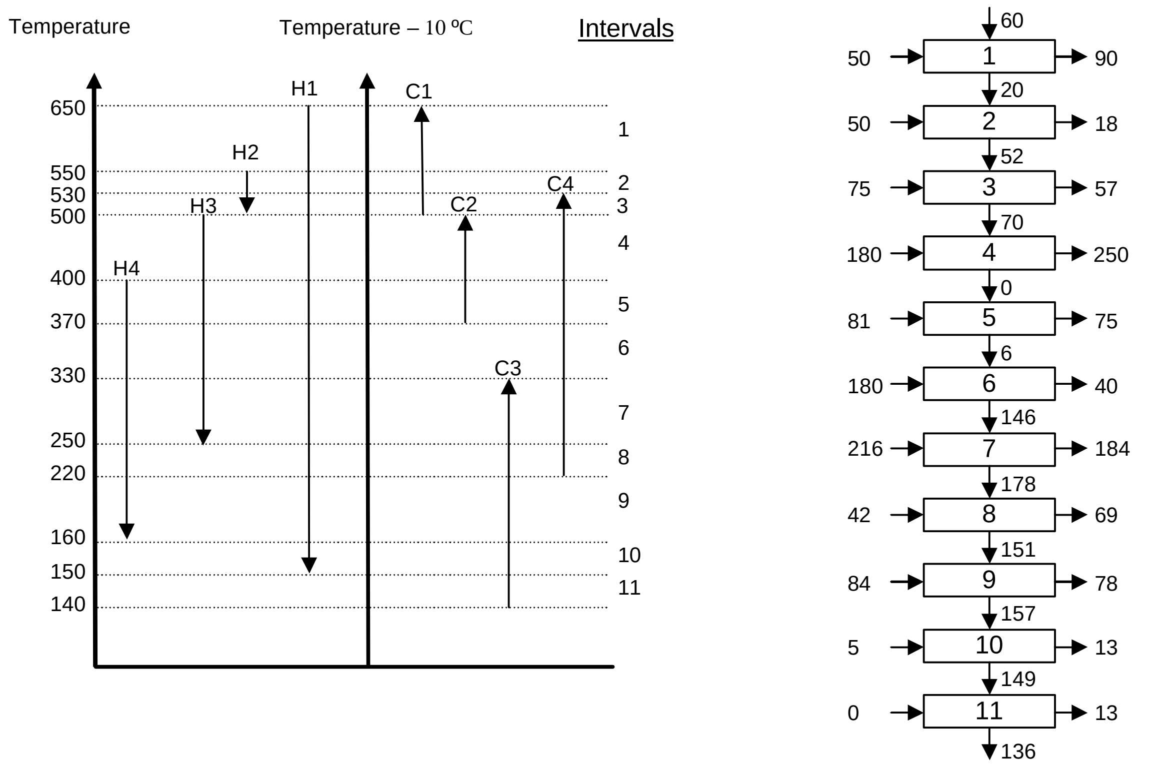


Figure 4.4: TID and adjusted cascade diagram for 10ºC ΔT_{min} case

Using a 2ºC DT_{min}, the heat pipe only TID and adjusted cascade diagram can be created and are shown in Figure 4.5. From the adjusted cascade diagram in Figure 4.5 it is clear that using only heat pipes, the minimum heating and cooling loads required become 40 kJ/h and 44 kJ/h respectively. This is a considerable reduction, 33.3% reduction in heating and 67.6% reduction in cooling, over the nominal heating and cooling targets of 60 kJ/h and 136 kJ/h. Additionally, the thermal pinch occurs between the 6th and 7th interval, which translates to a temperature range of 398-400ºC.

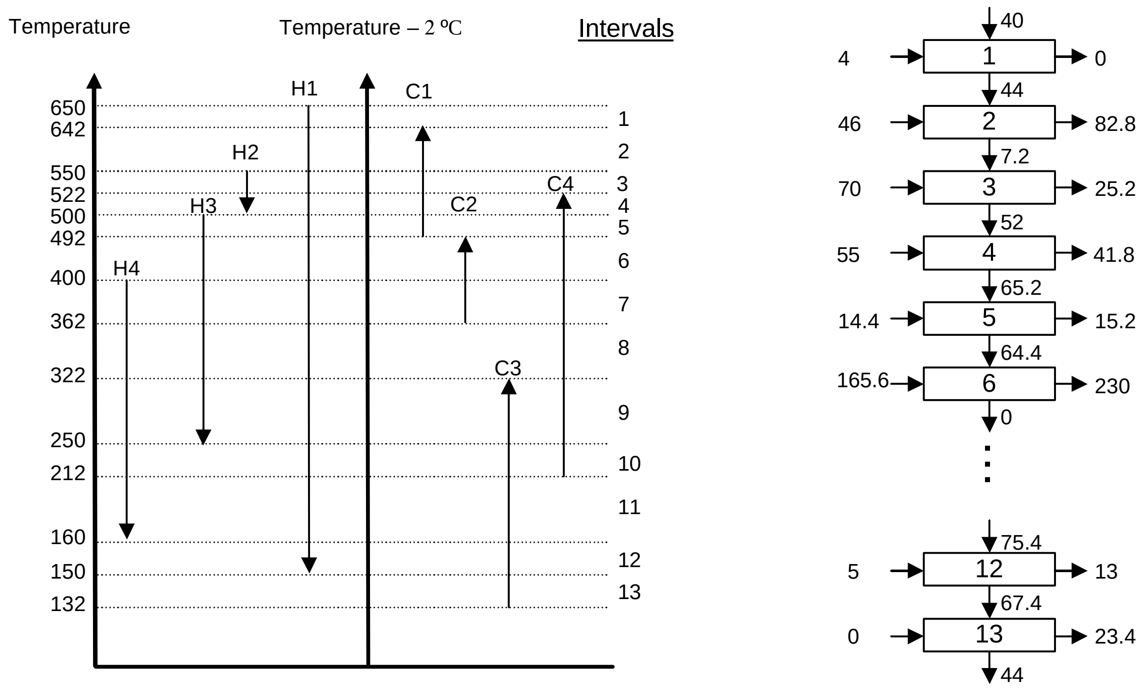


Figure 4.5: TID and adjusted cascade diagram for 2ºC ΔT_{min} case

Having established a stopping point in the iterations, the data obtained regarding the pinch location from Figure 4.4 can be used to construct a revised TID and cascade diagram. The revised TID and cascade diagram can be seen in Figure 4.6. On the revised TID, as described above, there is no longer a constant secondary axis. This is illustrated in intervals 4, 5 and 6 where the heat pipe has distorted the otherwise constant 10ºC difference. The adjusted cascade after this first iteration shows that the heating and cooling target have decreased considerably to 54 kJ/h and 58 kJ/h respectively. While these targets are considerably lower than the nominal case, they do not represent the optimal targets, and therefore a second iteration must be performed. Noting that the new pinch location occurs at the interface between intervals 6 and 7, a temperature range of 360-370ºC, the procedure can be repeated and another heat pipe can be added.

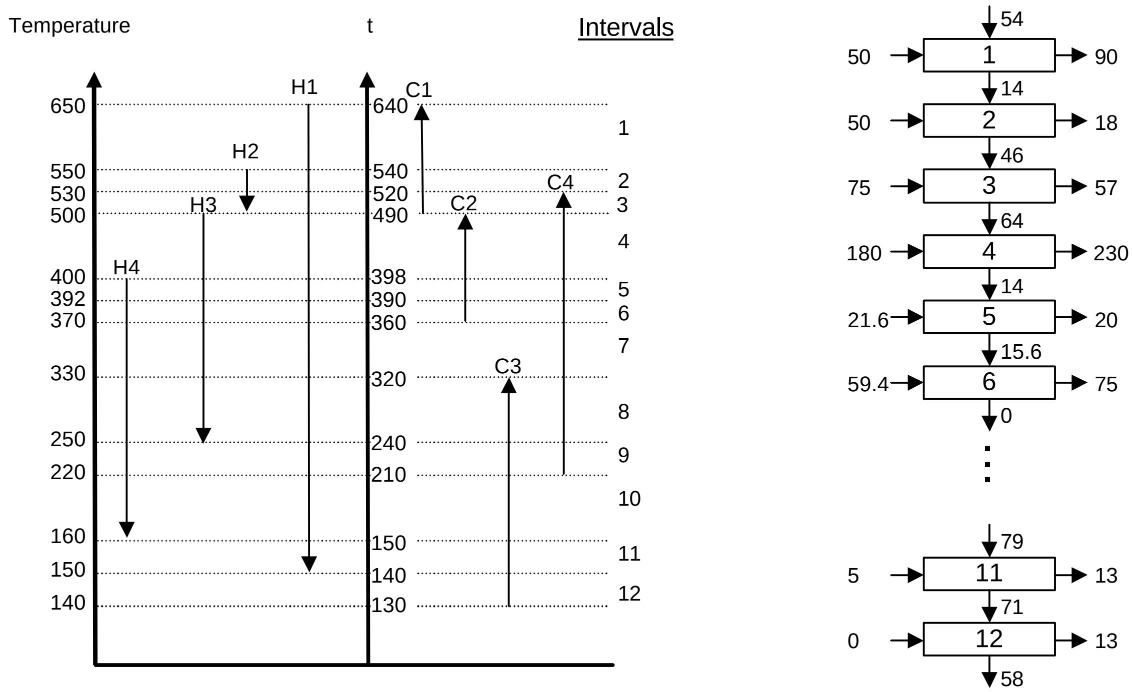


Figure 4.6: TID and adjusted cascade diagram for case study iteration 1

Adjusting the TID from iteration 1, to incorporate a lower driving force in the temperature region from 360-370ºC, results in the following TID and cascade diagrams shown in Figure 4.7. The second iteration has resulted in the optimal heating and cooling targets of 40 kJ/h and 44 kJ/h. Therefore, further addition of heat pipes cannot reduce the heating and cooling targets any further and the procedure is terminated. Subsequently, heat pipe technology was only required in the temperature region between

360-400ºC to achieve the optimal targets rather than throughout the entire network. The final cascade also indicates that the process in now thermodynamically limited at two pinch locations, in between intervals 1 and 2 as well as intervals 4 and 5.

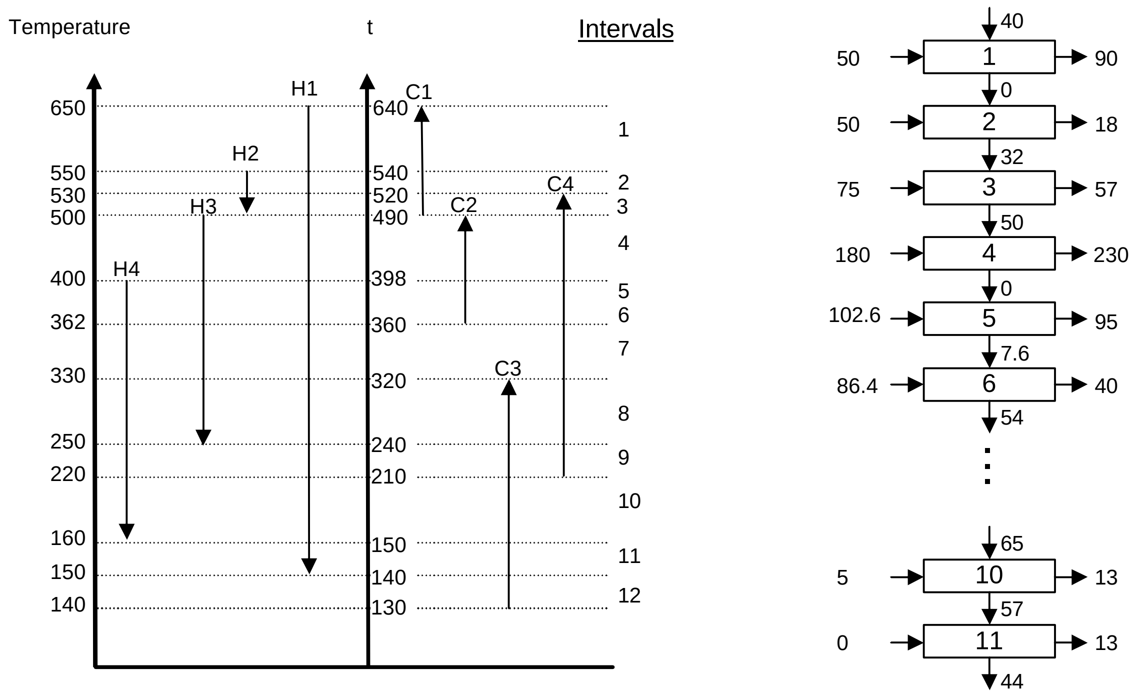


Figure 4.7: TID and adjusted cascade diagram for case study iteration 2

CHAPTER V

UTILITY SYSTEM OPTIMIZATION

The optimization of utility systems requires that both mass and energy objectives be optimized. Typically, fuel is burned to generate steam which is then let down through either throttling valves or turbines before being sent to various processes. Additionally, processes within the plant may generate steam which is added to the header system. The allocation of the resources within a utility system therefore revolves around the generation and routing of steam. Therefore, cogeneration plays a pivotal role in optimizing a utility system.

Problem Statement

The problem to be addressed within this chapter can be stated as follows: given a process that has been optimized with mass and heat integration techniques in terms of the usage of heating and live steam, by incorporating waste heat determine a target for the maximum cogeneration potential and minimum external fuel needs for steam production of the process as well as a steam allocation strategy to accomplish the aforementioned targets.

Traditional Cogeneration Targeting

The traditional method for determining the cogeneration potential of a steam turbine is through the use of a Mollier diagram represented in Figure 5.1.

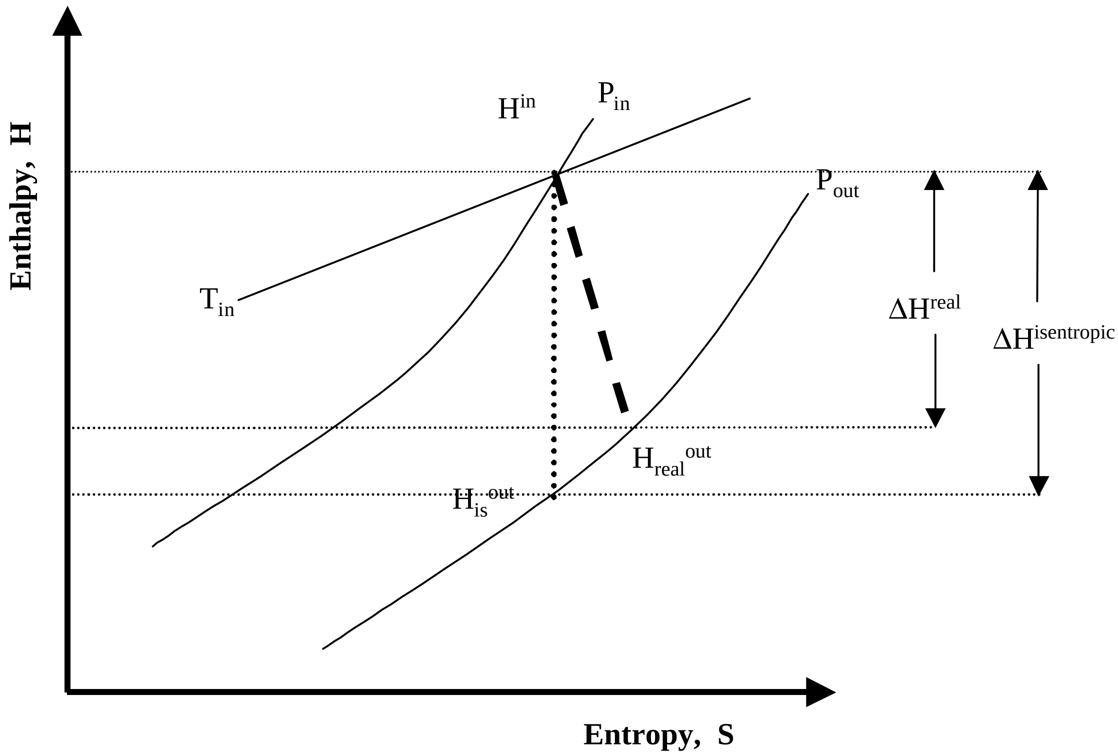


Figure 5.1: Mollier diagram

Typically, for a turbine, the inlet pressure and temperature are known as well as the outlet pressure. From this information, the isentropic enthalpy change in the turbine can be determined as:

$$\Delta H^{isentropic} = H^{in} - H_{is}^{out} \tag{5.1}$$

where $DH^{isentropic}$ is the specific isentropic enthalpy change in the turbine, H^{in} is the specific enthalpy of the steam at the inlet temperature and pressure of the turbine and H_{is}^{out} is the specific isentropic enthalpy at the outlet pressure of the turbine. However, due to mechanical and entropy losses the actual enthalpy change in the turbine is less than predicted from equation 5.1. To account for losses, an isentropic efficiency term is employed and can be defined as follows:

$$h_{is} = \frac{\Delta H^{real}}{\Delta H^{isentropic}} \tag{5.2}$$

where h_{is} is the isentropic efficiency and DH^{real} is the actual specific enthalpy difference across the turbine. By combining equations 5.1 and 5.2 and solving for the actual enthalpy change in the turbine, the specific work produced by the turbine can be determined and is shown below:

$$w = \Delta H^{real} = h_{is}\left(H^{in} - H_{is}^{out}\right) \tag{5.3}$$

where w is the specific work. Then to determine the power produced by the turbine the mass flow rate of steam being passed through the turbine is multiplied by equation 5.3. The power produced from the turbine is shown in equation 5.4:

$$W = \dot{m} h_{is}\left(H^{in} - H_{is}^{out}\right) \tag{5.4}$$

where W is the power produced from the turbine and $\dot{m}$ is the mass flow rate of steam passing through the turbine.

Concept of Extractable Energy

Although the Mollier diagram is a practical method of determining the cogeneration potential of a turbine, it is cumbersome because it requires the determination of the isentropic enthalpy of the turbine at the outlet pressure. A more convenient approach for determining the cogeneration potential of a turbine would utilize the actual outlet temperature and pressure of the turbine. Because turbines are placed in steam systems between headers, the inlet and outlet temperature and pressures are known. Therefore, the extractable power concept is based off of the header level that the turbine is being outlet to, rather than the isentropic conditions at the outlet pressure. This difference can be illustrated on the Mollier diagram in Figure 5.2.

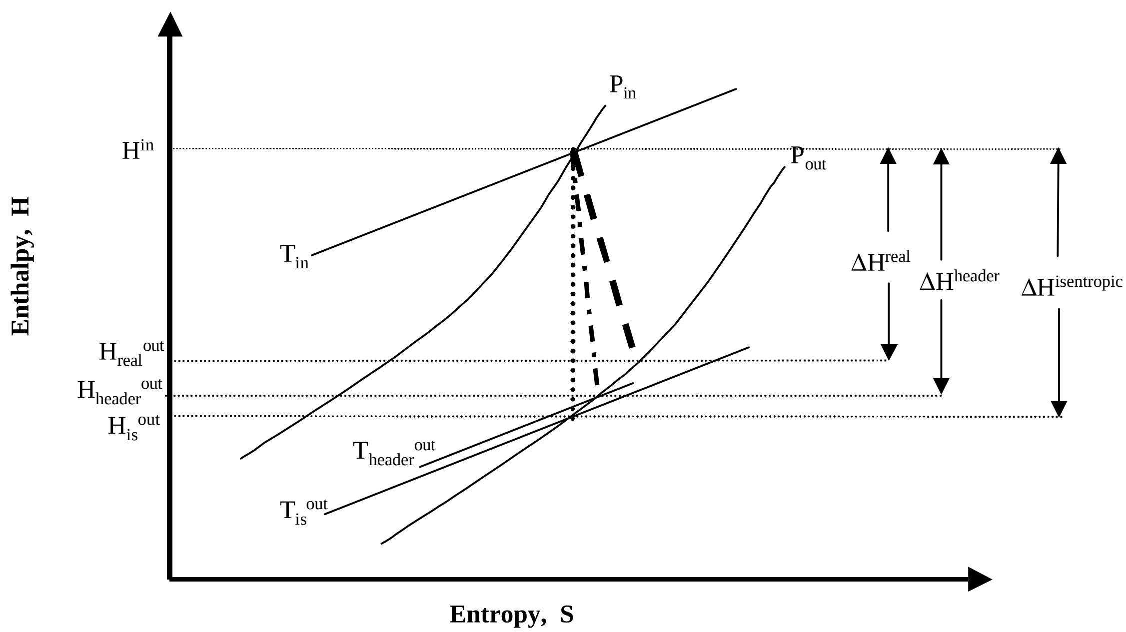


Figure 5.2: Mollier diagram with header and isentropic outlet conditions

From Figure 5.2 the enthalpy difference between the turbine inlet and outlet header is:

$$\Delta H^{header} = H^{in} - H^{out}_{header} \tag{5.5}$$

where DH^{header} is the specific enthalpy difference between the turbine inlet and outlet header and H^{out}_{header} is the enthalpy at the outlet header temperature and pressure. Similar to the isentropic case, an efficiency term can be incorporated to relate the header difference to the actual enthalpy difference that occurs. This expression can be seen in equation 5.6:

$$h_{header} = \frac{\Delta H^{real}}{\Delta H^{header}} \tag{5.6}$$

where h_{header} is the efficiency of the system. By combining equations 5.5 and 5.6 and solving for DH^{real}, the following expression can be generated for the specific power produced by a turbine.

$$w = \Delta H^{real} = h_{header}\left(H^{in} - H^{out}_{header}\right) \tag{5.7}$$

Similar to the isentropic procedure, the actual power generated from the turbine is then determined by multiplying the specific power by the mass flow rate of steam passing through the turbine, the resulting expression is seen in equation 5.8.

$$W = \dot{m} h_{header}\left(H^{in} - H^{out}_{header}\right) \tag{5.8}$$

Now, in order to simplify the expression, it is convenient to define the concept of extractable energy which is shown in equation 5.9:

$$e = hH \tag{5.9}$$

where e is the extractable energy, h is an efficiency term and H is the specific enthalpy at a given set of conditions. Then, the power generation expression can be rewritten as follows.

$$W = \dot{m}\left(e^{in} - e^{out}_{header}\right) \tag{5.10}$$

By combining the mass flow rate with the extractable energy terms, the power generated by the turbine takes a convenient form as the difference between the inlet and outlet extractable power:

$$W = E^{in} - E_{header}^{out} \tag{5.11}$$

where E is defined as the extractable power at a given header condition.

Equation 5.11 provides the basis for a novel graphical technique that allows the cogeneration potential of a steam utility system, as well as a method for developing feasible turbine networks to accomplish the aforementioned targets. The development of this graphical technique begins with analyzing a general steam utility system

Header Balances

Typically, in a plant there will be steam demands at various pressure levels for heating requirements. Additionally, there may be steam demands for processes other than heating e.g. steam blanketing, steam stripping, etc. Furthermore, there may be hot processes that require cooling and generate steam in order to accommodate this need, or there may be processes that generate steam as a byproduct of a reaction. The steam generated and required by these processes will be allocated through a system of steam headers. Usually, there are several pressure levels in a header system that are often denoted by the acronyms VHP, HP MP and LP, which stand for very high pressure, high pressure, medium pressure and low pressure respectively. A characteristic header system can be seen in Figure 5.3.

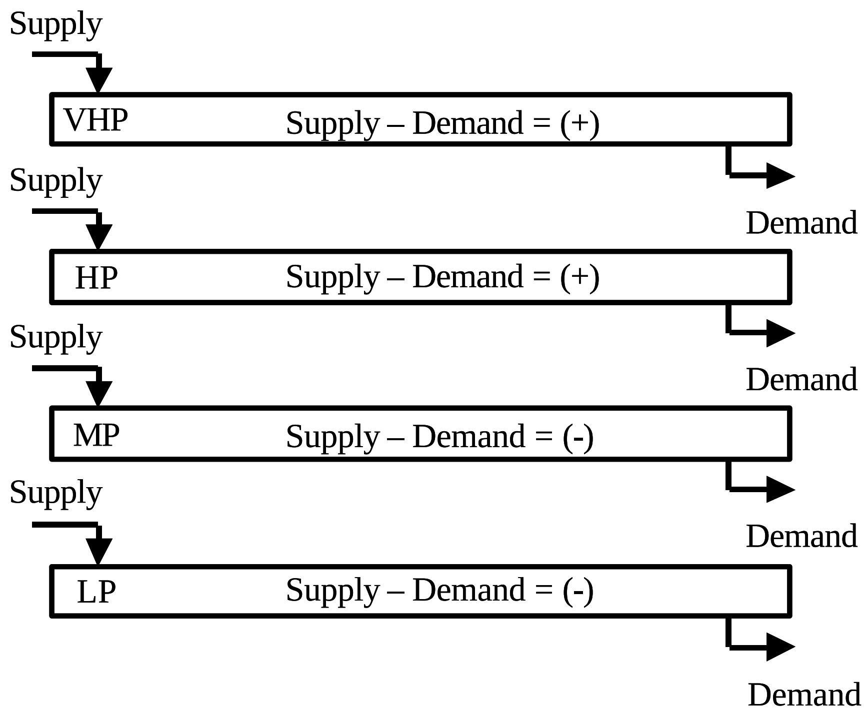


Figure 5.3: Typical steam header system

Each header level has steam being supplied to it, and steam demands it must satisfy. By performing a balance around each header level it can be determined if there is a surplus or deficit of steam at the header lever. Figure 5.3 represents a case where there is a surplus of steam at the VHP and HP levels, while there is a deficit of steam at the MP and LP levels. In order to satisfy the steam deficits in the MP and LP levels, steam must be let down from the surplus headers. The knowledge of the utility system, coupled with a header balance provides the information necessary to develop a graphical cogeneration targeting technique using equation 5.11.

Within a steam header system the temperature and pressure of each header will be known. With this information, the specific enthalpy of steam at each header level can be determined through numerous methods. Utilizing a steam header balance the mass flow rates of steam needed at the surplus and deficit levels can also be determined. Then, by combining the specific enthalpy at each header level with its associated surplus or deficit steam mass flow rate and an appropriate efficiency term the extractable power at each header level can be determined. Then, the magnitude of the extractable power is plotted versus the steam mass flow rate for each surplus header in ascending order of pressure levels (making the surplus composite line), with a similar curve being constructed with the deficit headers (making the deficit composite line).

Composite Curve Construction

To illustrate the construction of the surplus and deficit composite, consider the header system shown in Figure 5.3; where the magnitude of extractable power at the VHP, HP, MP and LP levels will be E1, E2, E3 and E4, and the mass flow rates will be M1, M2, M3 and M4 respectively. First, consider the surplus VHP and HP headers which are ranked in order of ascending pressure levels, that is, HP first and VHP second. The surplus composite line can be seen in Figure 5.4.

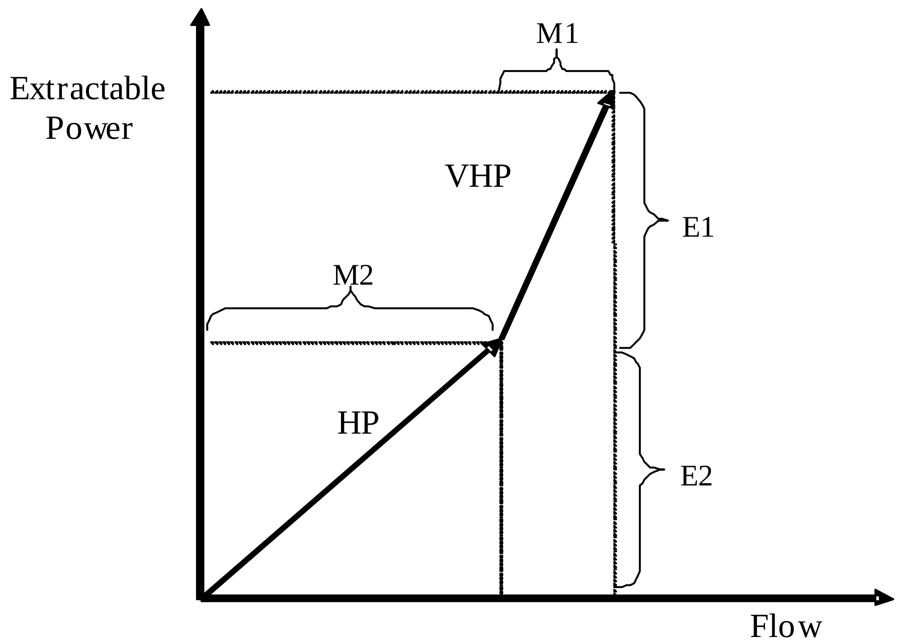


Figure 5.4: Extractable power surplus composite line

In a similar fashion, the deficit composite line can also be constructed on the same graph by plotting the LP and then MP deficit headers. The addition of the deficit composite line can be seen in Figure 5.5.

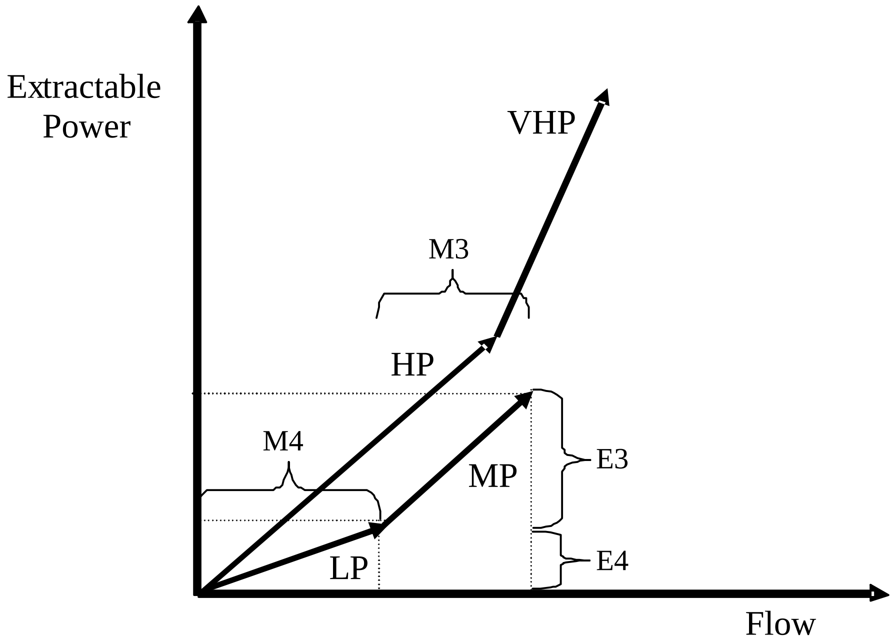


Figure 5.5: Extractable power surplus and deficit composite lines

After constructing the surplus and deficit lines, the cogeneration potential of the system is easily determined by shifting the deficit composite line to the right and up until it is directly below the uppermost region of the surplus line. The shifting of the deficit line is possible because both the extractable power and the mass flow rate are relative quantities; as long as the shape and magnitude of the line stays constant the line can be moved anywhere on the graph. Figure 5.6 shows the appropriately shifted deficit composite line.

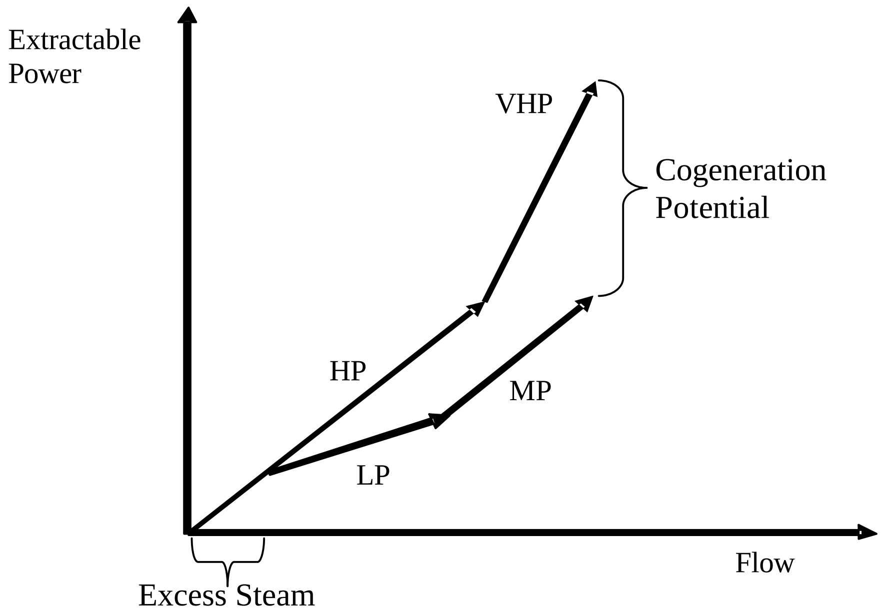


Figure 5.6: Shifted Extractable power versus flow diagram

The gap between the surplus and deficit line determines the cogeneration potential of the system. Furthermore, the region for which there is no deficit line below the surplus line indicates the amount of excess steam within the process. The excess steam can either be let down through a condensing turbine to increase the cogeneration of the site, or the steam production can be reduced accordingly to save fuel. In order to insure that the cogeneration target generated is feasible, higher pressure level surplus headers must be above lower pressure level deficit headers. In Figure 5.6, this criterion is satisfied because both surplus headers' pressures are above the deficit headers' pressures. However, had there been a deficit in the HP header and a surplus in the deficit header then shifting the deficit line as before could have resulted in an infeasible region where a lower pressure level was being let down to a higher pressure level. A scenario of this nature can be seen in Figure 5.7.

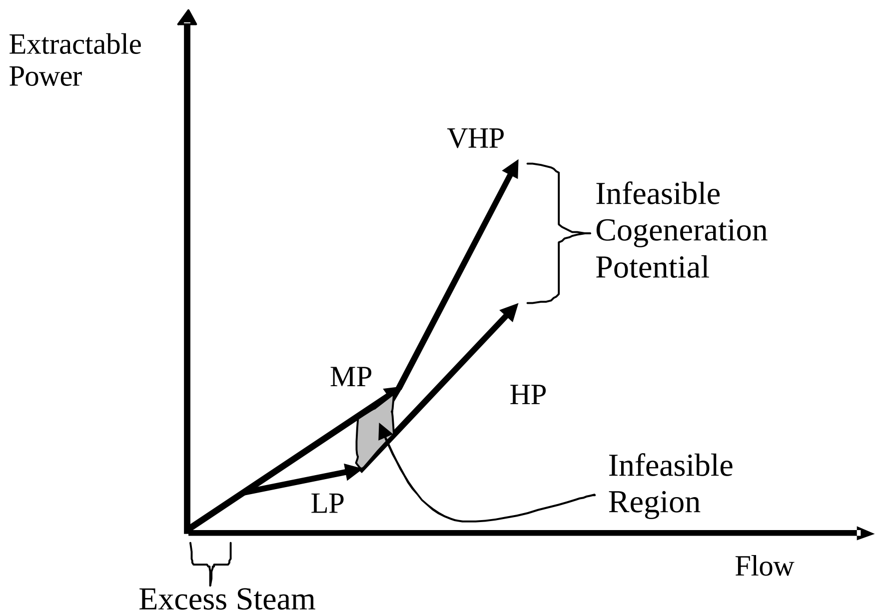


Figure 5.7: Infeasible cogeneration target

In a scenario such as the one shown in Figure 5.7, the deficit composite line can be split into multiple deficit header lines. Then, each deficit header line can be individually shifted to insure feasibility and target for cogeneration potential. The separated deficit composite line can be seen in Figure 5.8.

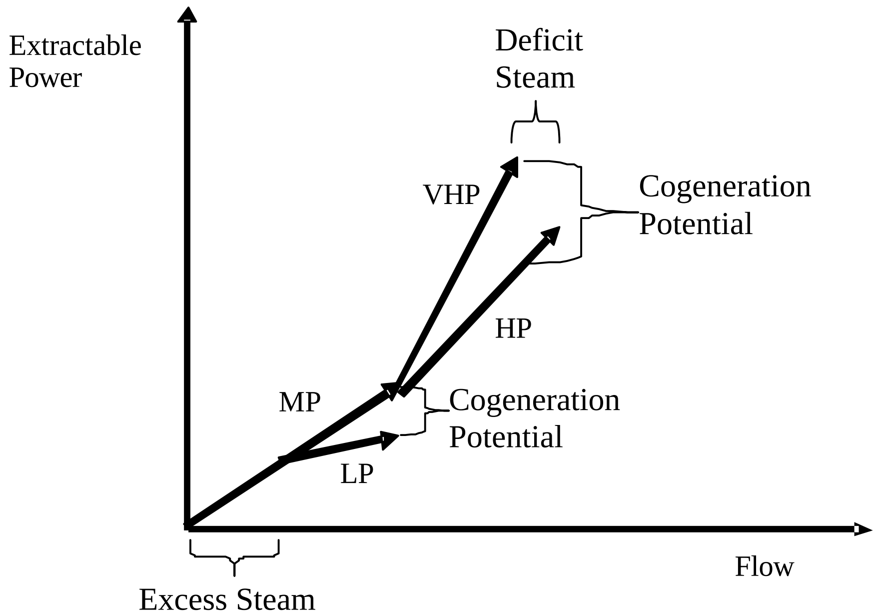


Figure 5.8: Shifted deficit header lines

In Figure 5.8, the cogeneration potential is the summation of the gaps between the surplus and deficit line. The excess steam is still determined from the region of the MP surplus composite that has no deficit line below. However, in this scenario there is a portion of the HP deficit line that has no surplus line above it; which indicates that there is a need for steam at or above the HP level. This will have to be generated in the boiler system.

Determining Feasible Turbine Networks

In addition to targeting the cogeneration potential of a steam system, it is also important to generate a feasible turbine network to achieve that target. The graphical approach outlined for targeting cogeneration potential also allows the development of feasible turbine networks. Referring back to the case illustrated by Figure 5.6, steam can be let down from a header at a higher pressure to a header at a lower pressure. Therefore, by inspection, it is clear that the VHP surplus lies directly above a portion of the MP deficit header. Additionally, the HP surplus header lies above a portion of the MP deficit header and entirely above the LP deficit header. Subsequently, a total of three turbines can be used to achieve the target with the potential of a fourth condensing turbine to let down the excess steam. On the extractable power diagram, this can be represented by breaking up the deficit composite line into several lines each representing a feasible pairing between headers. To illustrate this consider Figure 5.9, the feasible pairing of Figure 5.6, along with a miniature header system including turbine network.

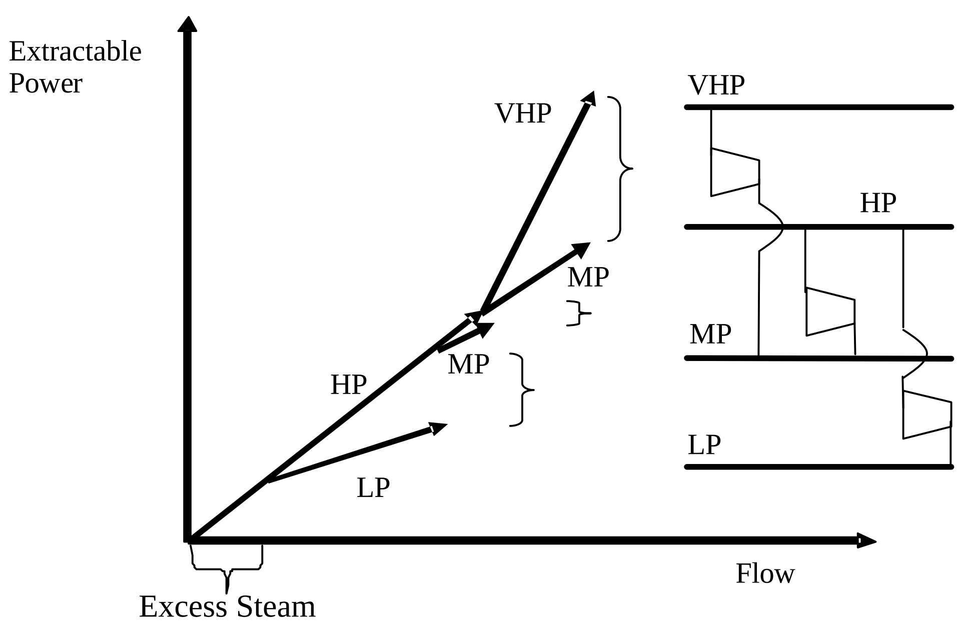


Figure 5.9: Graphical illustration of feasible turbine network

The network represented in Figure 5.9 is only one potential network, for instance rather than a turbine from the HP to MP and a turbine from the HP to LP headers, one extraction turbine could be used to accommodate both the MP and LP demands from the HP header. The ideal network can be determined by performing an economic analysis of the feasible networks. Furthermore, an economic analysis will be needed to determine if the optional condensing turbine is more beneficial than reducing the HP steam being generated.

Methodology

The concept of extractable power can be incorporated after traditional process integration techniques are used to target the cogeneration potential of a plant while providing viable turbine configurations to achieve the determined target. A general methodology for implementing the concept of extractable power can be seen in Figure 5.10.

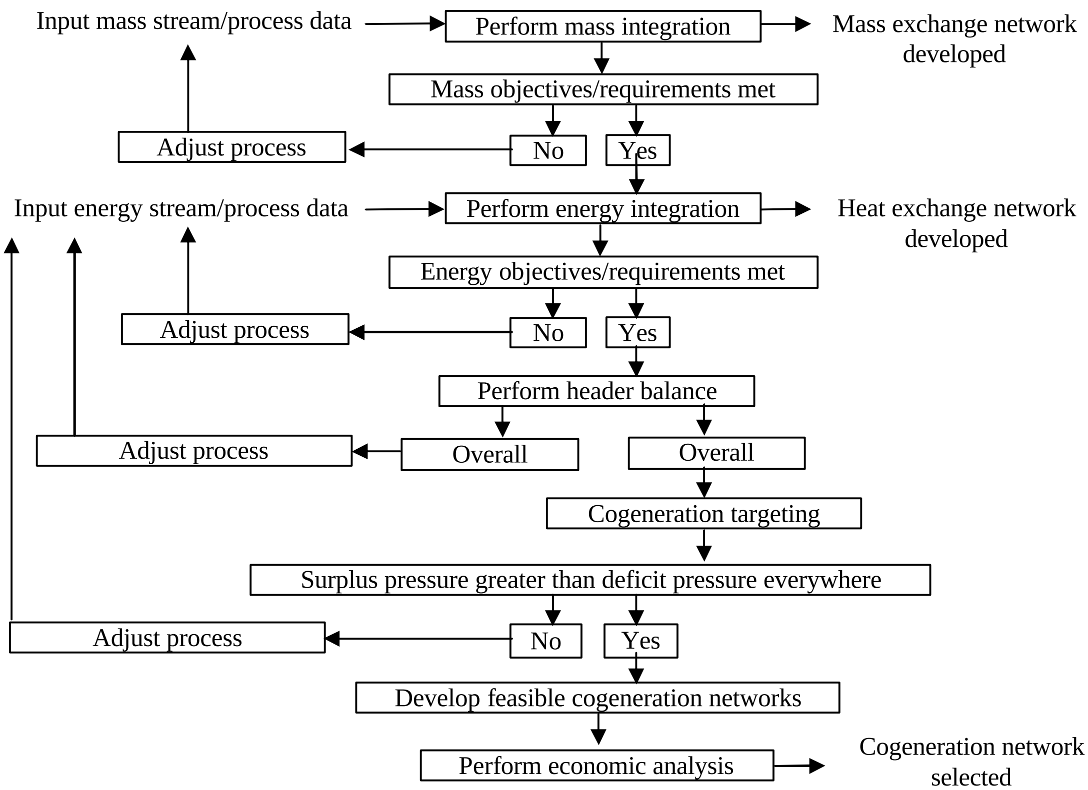


Figure 5.10: Cogeneration methodology

First, traditional mass and energy integration techniques are employed to optimize the steam demand and generation within a process. Next, a header balance is performed and the extractable power and steam surplus/deficits are determined. Then, the surplus and deficit composite curves are generated and the deficit line is shifted. If the surplus pressure is greater than the deficit pressure everywhere then network configurations can be developed and analyzed. Also, excess steam can be reduced or condensed to produce additional power. If the surplus pressure is not greater than the deficit pressure everywhere then the deficit line is decomposed and reshifted until the pressures are feasible. If there is not an overall steam deficit then network configurations can be developed and analyzed. If there is an overall steam deficit, then additional steam must be generated and a header balance must be performed again. Using this methodology, the cogeneration potential and a feasible turbine network can be developed for a given steam utility system.

As stated earlier, the incorporation of waste heat would be addressed as it pertained to improving utility systems. The incorporation of waste heat falls into the mass integration, energy integration and header balance phases and therefore will be briefly discussed here.

Waste Heat Utilization

Traditional mass and energy integration techniques can be used to incorporate waste heat into the utility system. However, the sources of waste heat must be properly identified in order to incorporate them. As mentioned earlier, incineration is a technology that can convert waste products, through combustion, into energy that can produce steam. Mass integration techniques would be used to examine the potential of incineration technologies. However, it was also pointed out that incineration of waste material produces several problems and therefore would not be explored as an option to improve utility systems. Meanwhile, utilizing high temperature exhaust gases was determined to be a very viable option of improving steam utility systems. Subsequently, sources of waste heat must be identified and screened as candidate HRSG inlets.

To identify sources of waste heat the process must be examined and all waste exhaust streams must be identified. After identifying the potential sources, they must then be screened based on temperature level, composition and quantity primarily. The waste streams should then be incorporated into the HEN analysis. By using the waste streams to heat process cold streams, the amount of steam required from the boilers will be decreased. After developing the HEN, any excess waste streams that were not used due to an abundance of hot sources, or an inability to safely pair them with process cold streams should be screened for use in HRSGs.

After incorporating of the waste streams into the HEN, the determination of how to use the remaining waste exhaust streams must wait until the header balance has been completed. If there is an overall deficit of steam then the use of the waste exhausts should be considered in auxiliary fired or furnace fired WHBs to produce high level steam to correct the deficit. However, if there is an overall surplus of steam then unfired HRSGs should be considered to improve cogeneration potential.

When screening the waste exhaust streams preference should go to streams with the potential to produce higher pressure steam. Furthermore, streams with higher flow rates should be considered ahead of lower flow rate streams. Any potential steam production by HRSG should be put through an economic analysis to determine if the steam production/cogeneration benefits outweigh the cost of the HRSG installation and operation.

Caste Study

To show the applicability of the proposed graphical approach for targeting cogeneration potential, a case study will be solved that contains heating and process steam needs and demands, as well as an existing steam header system. The process contains eight streams, two hot streams (H1 and H2) and two cold streams (C1 and C2), with the following pertinent data shown in Table 5.1:

Table 5.1: Process stream data

Stream	FCp (MMBtu/h ºF)	T_{supply} (ºF)	T_{target} (ºF)
H1	0.5	650	150
H2	2.0	550	500
C1	0.9	490	640
C2	1.5	360	490

Additionally, the process already contains a steam header system with four levels: VHP, HP, MP and LP. The temperature and pressure of these steam headers can be seen in Table 5.2.

Table 5.2: Steam header data

Header	Pressure (psia)	Temperature (ºF)
VHP	600	800
HP	160	600
MP	80	400
LP	60	300

Finally, the process contains live steam generation and demands at the four steam levels, this information is listed in Table 5.3.

Table 5.3: Process live steam demands and generation

Live Steam	Supply (MMBtu/h)	Demand (MMBtu/h)
VHP	218	9
HP	183	14
MP	25	160
LP	35	106

Since the focus of this research is on energy, the information provided in Table 5.3 has already been optimized using mass integration techniques.

In addition, the process contains a gas turbine that is used for on-site energy production. The gas turbine has an exhaust that is at 750 ºF and a flow rate of 90,000 lb/h with a composition of 0.75 N_2 0.07 H_2O, 0.15 O_2 and 0.03 CO_2 on a volume basis [9]. Because of location it is not convenient to incorporate the exhaust into any HEN and therefore, the stream is being considered for use in an HRSG.

For the research conducted on cogeneration a numerical approximation was used to determine the isentropic and standard enthalpies based on the temperatures and pressures of interest. This formulation can be seen in Appendix A1. Unfortunately, a reference could not be found for this formulation and therefore, Appendix A2 contains a table comparing the calculated enthalpies with those from a steam table.

Having obtained the pertinent information concerning the process the first step is to perform mass and energy integration on the system. As previously mentioned, the mass integration has already been performed, so only energy integration needs to be performed. The details concerning the energy integration of the process are inconsequential for this case study; therefore, the results are presented in the grand composite curve (GCC) shown in Figure 5.11.

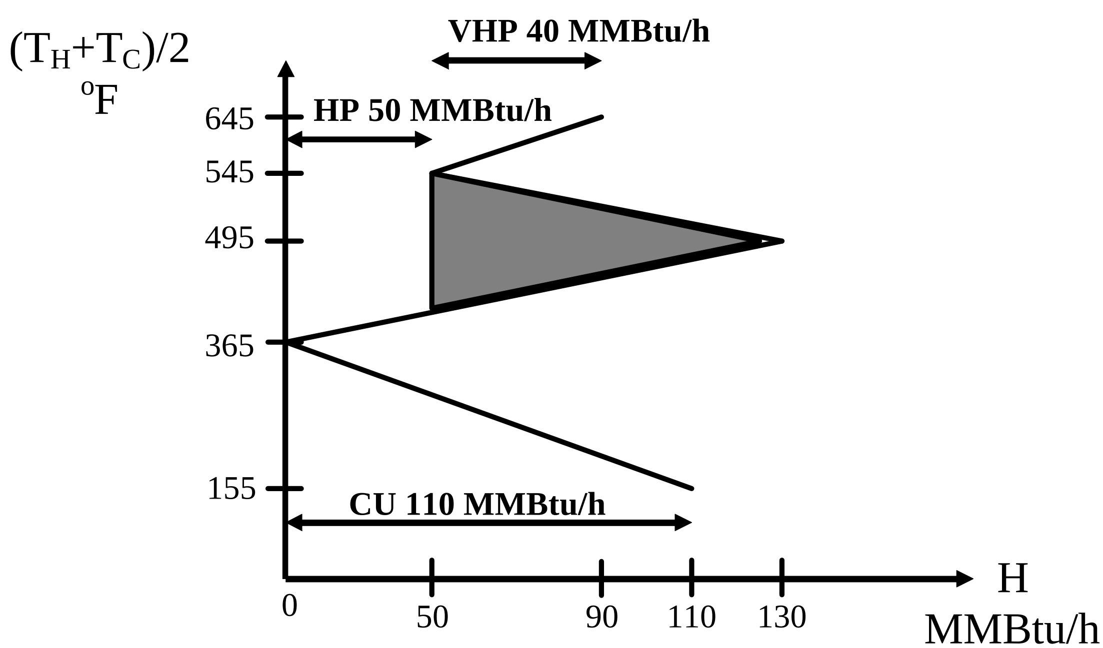


Figure 5.11: Process grand composite curve

From the GCC it is apparent that there is a heating demand for approximately 50 MMBtu/h and 40 MMBtu/h of HP and VHP steam respectively. Additionally, there is a net cooling need of 110 MMBtu/h. By combining the steam heating information with the live steam data from Table 5.3 a header balance can be performed similar to that described in Figure 5.3. The overall header balance can be seen in Table 5.4.

Table 5.4: Steam header balance

Header	Pressure (psia)	Supply (MMBtu/h)	Demand (MMBtu/h)
VHP	600	218	49
HP	160	183	64
MP	80	25	160
LP	60	35	106

By utilizing the header pressure and temperature data in Table 5.2, the data in Table 5.4 can be converted into surplus and deficit steam flow rates. Furthermore, utilizing the header data and the surplus/deficit steam flow rates in conjunction with equations 5.9 and 5.10 the extractable power for each header can be calculated. For the purpose of this case study a standard efficiency of 70% was used. Table 5.5 shows the surplus and deficit steam flow rates and the associated extractable power at each header level.

Table 5.5: Surplus/deficit steam flow rates and extractable power

Surplus Header	Pressure (psia)	Flow rate (lb/h)	E (MMBtu/h)
VHP	600	119519	118.3
HP	160	89844	83.5
Deficit Headers			
MP	80	110119	94.8
LP	60	60015	49.6

Table 5.5 shows an overall surplus of steam in the process with the VHP and HP headers being surplus headers and the MP and LP headers being deficit headers. Because there is an overall surplus of steam in the process the gas turbine exhaust can be used in an unfired HRSG to produce HP steam. Since the stream is at the low end of the temperature range for an unfired HRSG, from the literature review, a conservative gas to steam ratio of 7.5 is used to estimate the amount of steam produced. Using this ration the 90,000 lb/h of exhaust gas should produce approximately 12,000lb/h of HP steam. This information can be added to the data in Table 5.5, and the new surplus/deficit steam flow rates can be seen in Table 5.6.

Table 5.6: Revised surplus/deficit table

Surplus Header	Pressure (psia)	Flow rate (lb/h)	E (MMBtu/h)
VHP	600	119519	118.3
HP	160	101844	83.5
Deficit Headers			
MP	80	110119	94.8
LP	60	60015	49.6

With the information in Table 5.6 the extractable power versus flow rate plot, previously illustrated in Figure 5.5, can be constructed and is shown in Figure 5.12.

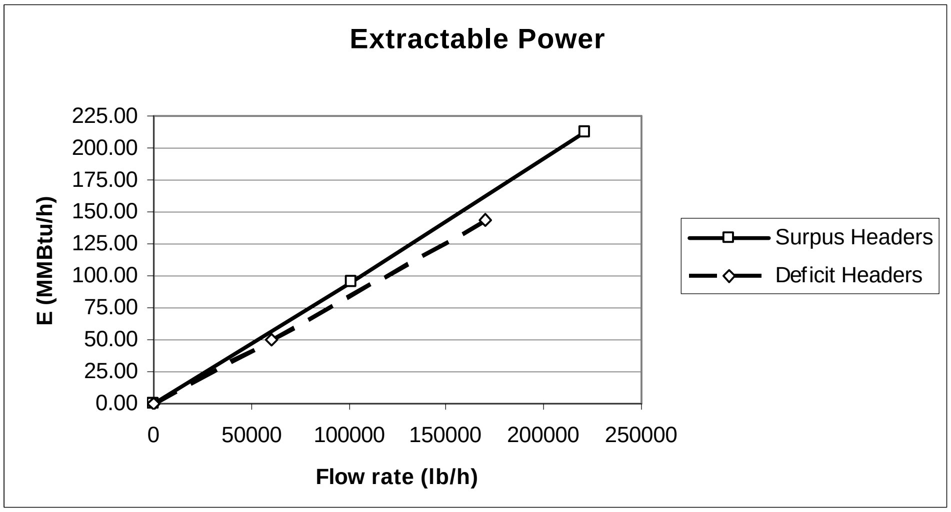


Figure 5.12: Unshifted extractable power versus flow rate plot

By shifting the deficit composite line to the right and up the cogeneration target can be determined as well as the excess steam present within the process. Figure 5.13 shows the shifted extractable power plot.

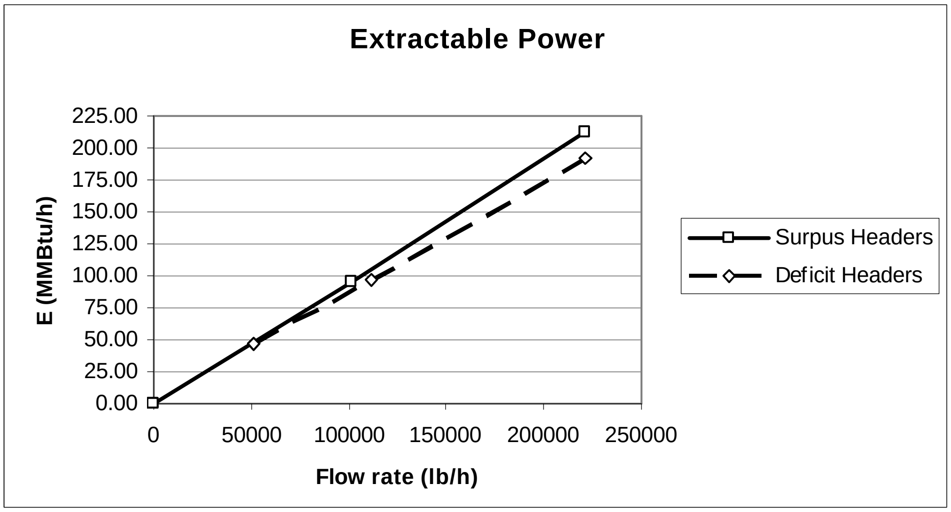


Figure 5.13: Shifted extractable power versus flow rate plot

From Figure 5.13, the cogeneration target is approximately 20.9 MMBtu/h, and there is an excess of approximately 51,000 lb/h of steam being generated within the process. The excess steam in this case should be let down through a condensing turbine because it primarily comes from live steam or steam produced in the HRSG, i.e. it is generated within the process as a byproduct or required for non-heating purposes.

A feasible turbine configuration to generate the target predicted can be achieved by letting steam down from each surplus header to the deficit header directly below on Figure 5.13. Subsequently, for this case study three turbines: one form VHP to MP, one from VHP to LP and one from HP to LP can be used to achieve the cogeneration target. Additionally, it has been determined that a fourth turbine, condensing type, should be added to the system to capitalize on the excess steam generated in the system.

CHAPTER VI

PROPERTY INTERCEPTION NETWORKS

Many process integration problems are not component dependent. For instance, solvents are typically chosen based on their solubility, vapor pressure, environmental and health impacts, etc., and not on the chemical makeup of the solvent. Therefore, it seems reasonable that when attempting to optimize a process that primarily has solvent based objectives, property based integration strategies should be employed. There are other instances where properties provide advantages over chemical constituents such as mixtures with nearly infinite components. For example, a petroleum blend has hundreds or thousands of chemicals. If a few key properties of interest could be tracked, the computational savings would be tremendous compared to the thousands of mass balances needed to accomplish the same task. This chapter focuses on developing techniques to recycle and recover effluent streams based on properties.

Through the use of property mixing rules, it is possible to adapt traditional mass integration techniques to work for properties. Furthermore, the incorporation of mathematical programming techniques allows feasible property interception networks to be developed from property mixing rules. This negates the need to transform properties into clusters as discussed in the literature review. Additionally, the use of programming techniques will allow the expansion from three key properties to numerous key properties.

Problem Statement

The overall problem to be addressed in this chapter can be stated as follows: "Given a process with certain sources (streams), sinks (units), and interception devices along with the associated properties, flow rates and constraints, it is desired to develop an optimization based procedure that identifies strategies for allocation and interception of sources, sinks and interceptors so as to optimize a desirable process objective (e.g. minimum usage of fresh resources, minimum cost of interception, or maximum utilization of process resources) while satisfying the physical and property constraints of the sinks."

Development of Property Interception Networks

To develop a generalized approach for designing optimal property interception networks first the method of tracking properties must be clearly defined. Then, a robust program must be formulated to account for a wide range of scenarios including the mixing, separation and recycling of sources within the interception network. Additionally, the interception technologies must be allowed to arrange in any parallel or series configuration with the option of using a single technology multiple times. Finally, the model must be validated with an applicable case study.

Property Mixing Rules

Initially, it is important to establish the class of properties for which the proposed techniques are applicable. Consider the property mixing rule seen in Equation 6.1:

$$y(\overline{P}) = \sum_{s=1}^{N_s} x_s y(P_s) \tag{6.1}$$

where y is the property operator, $\overline{P}$ is the mixture property, P_s is the property of stream s and x_s is the fractional contribution of stream s. The form of this equation results in several constraints on the properties. First, the order the sources are mixed is independent of the resulting mixture properties. That is, if a source A is mixed with B then the resulting mixture property will be the same had source B been mixed with A. Assuming the contributions of each source in both instances are the same. Furthermore, adding more or less of a source does not altar the mixing rule. Additionally, mixing A with B and C results in the same solution as mixing A with a mixture of B and C given the same proportions. Finally, if A and B have the same property, then the resulting mixture will also have that property.

Having established the applicable requirements a property of interest must meet it is now appropriate to proceed to the program formulation. By utilizing the property operator many traditional mass integration approaches can be adapted to work for properties. An example of this will be shown in the case study at the end of this chapter.

Program Formulation of Property Interception Networks

In order to develop the program it is convenient to visualize a generic representation of a property interception network. Consider the allocation diagram shown in Figure 6.1.

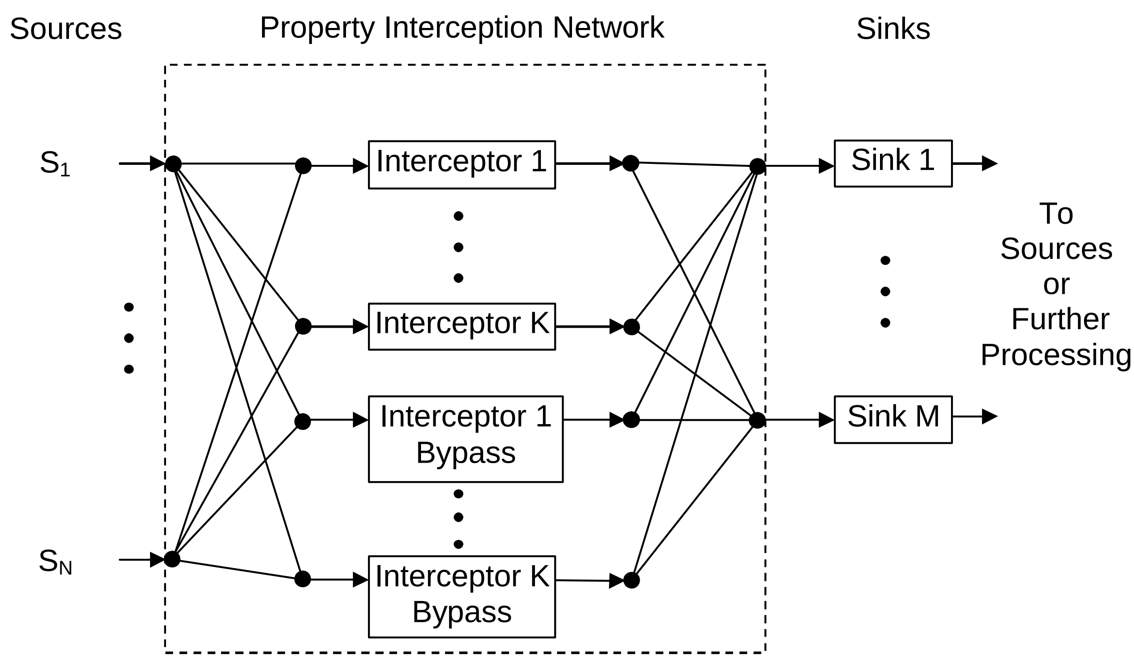


Figure 6.1: Generic source sink allocation with interception network

Within the process, each source has the opportunity to split and go to any interception technology, or bypass the interception technologies and proceed directly to a sink. The bypasses in the formulation will be represented as interceptors that do not alter the streams that enter them. The sources allocated to an interception technology must mix prior to interception, and then the mixed stream is treated. After treatment, the outlet streams, as well as the bypassed streams, are split and allocated to the sinks within the process. To account for recycling, several “empty sinks” are placed within the process whose unaltered outlets become sources. In addition to the allocation, certain requirements concerning inlet and outlet property constraints must be obeyed as well as overall outlet property constraints.

The formulation of this program is illustrated in the following equations. First, the objective of the formulation is to minimize the cost associated with the PIN and is seen in Equation 6.2.

$$Min = \sum_{k=1}^{N_{\text{int}}} Cost_k I_k \tag{6.2}$$

where $Cost_k$ is the cost associated with interception technology k, I_k is a binary integer that takes the value of 1 if technology k is used and 0 if technology k is not used, and N_{int} is the total number of interception technologies.

Next, flow balances are performed around all of the initial splitters, as seen in equation 6.3:

$$F_s = \sum_{k=1}^{N_{int}} F_{s,k} \qquad s=\{1,...,N_{sources}\} \tag{6.3}$$

where F_s is the flow rate of source s, $F_{s,k}$ refers to the flow rate of source s to the mixer for interceptor k, and $N_{sources}$ is the total number of sources. The mixers require both flow and property balances as shown in equation 6.4 and 6.5:

$$K_k = \sum_{s=1}^{N_{sources}} F_{s,k} \qquad k=\{1,...,N_{int}\} \tag{6.4}$$

$$K_k y_i(P_{i,k}) = \sum_{s=1}^{N_{sourcess}} F_{s,k} y_i(P_{i,s}^{source}) \qquad k=\{1,...,N_{int}\},\ i=\{1,\ldots,N_{prop}\} \tag{6.5}$$

where K_k is the flow rate to interceptor k, $\psi_i(P_{i,k})$ is the operator of property i entering interceptor k, $\psi_i(P_{i,s}^{source})$ is the operator of property i of source s, and N_{prop} is the total number of properties of interest.

Next, the interception devices will require modeling to relate the inlet flow rate and properties to the intercepted flow rate and properties. Because the models will be technology dependent, it is impossible to list universal equations that will relate the flow rate and properties of the inlet to the outlet.

After interception, the second round of splitters will require a flow balance shown in equation 6.6:

$$K_k^{\text{int}} = \sum_{j=1}^{N_{\text{sinks}}} K_{k,j} \qquad k=\{1,...,N_{int}\} \tag{6.6}$$

where K_k^{int} refers to the intercepted flow rate out of unit k, $K_{k,,j}$ is the flow rate of interceptor k to sink j, and N_{sinks} is the total number of sinks.

Before the intercepted splits can be sent to a sink they must be mixed, and as such require both a flow rate and property balances shown in equations 6.7 and 6.8:

$$G_j = \sum_{k=1}^{N_{\text{int}}} K_{k,j} \qquad j=\{1,...,N_{sinks}\} \tag{6.7}$$

$$G_j \psi_i(P_{i,j}^{sink}) = \sum_{k=1}^{N_{int}} K_{k,j} \psi_i(P_{i,k}^{\text{int}}) \qquad j=\{1,...,N_{sinks}\},\ i=\{1,\dots,N_{prop}\} \tag{6.8}$$

where G_j is the flow rate to sink *j*, $y_i(P_{i,j}^{sink})$ is the operator of property *i* going to sink *j*, and $y_i(P_{i,k}^{\text{int}})$ is the intercepted operator of property *i* from interceptor *k*.

The process sinks will have both flow rate and property constraints shown in equations 6.9 and 6.10:

$$G_j^{lower} \le G_j \le G_j^{upper} \qquad j=\{1,...,N_{sinks}\} \tag{6.9}$$

$$y_i(P_{i,j}^{lower}) \le y_i(P_{i,j}^{sink}) \le y_i(P_{i,j}^{upper}) \qquad j=\{1,...,N_{sinks}\},\ i=\{1,\ldots,N_{prop}\} \tag{6.10}$$

where G_j^{lower} and G_j^{upper} are the lower and upper flow rate constraints on sink *j*, and $y_i(P_{i,j}^{lower})$ and $y_i(P_{i,j}^{upper})$ are the lower and upper constraints on the operators of property *i* for sink *j*. For the "empty sinks" these constraints will be nonexistent.

Finally, all the variables in this formulation will require nonnegativity constraints illustrated in equations 6.11 through 6.19:

$$F_s \ge 0 \qquad s=\{1,\ldots,N_{sources}\} \tag{6.11}$$

$$F_{s,k} \ge 0 \qquad s=\{1,\ldots,N_{sources}\},\ k=\{1,\ldots,N_{int}\} \tag{6.12}$$

$$K_k \ge 0 \qquad k=\{1,\ldots,N_{int}\} \tag{6.13}$$

$$K_{k,j} \ge 0 \qquad k=\{1,\ldots,N_{int}\},\ j=\{1,\ldots,N_{sinks}\} \tag{6.14}$$

$$G_j \ge 0 \qquad j=\{1,\ldots,N_{sinks}\} \tag{6.15}$$

$$y_i(P_{i,s}^{source}) \ge 0 \qquad i=\{1,\ldots,N_{prop}\},\ s=\{1,\ldots,N_{sources}\} \tag{6.16}$$

$$y_i(P_{i,k}) \ge 0 \qquad i=\{1,\ldots,N_{prop}\},\ k=\{1,\ldots,N_{int}\} \tag{6.17}$$

$$y_i(P_{i,k}^{int}) \geq 0 \qquad i=\{1,\ldots,N_{prop}\},\ k=\{1,\ldots,N_{int}\} \tag{6.18}$$

$$y_i(P_{i,j}^{sink}) \geq 0 \qquad i=\{1,\ldots,N_{prop}\},\ j=\{1,\ldots,N_{sinks}\} \tag{6.19}$$

This formulation, along with the addition of scenario specific constraints will generate a solution to achieve the specific objectives of the interception network. However the following formulation is clearly a mixed integer non-linear program (MINLP) and as such, it may be prohibitively difficult to find a global solution to the problem. To guarantee a global solution, several simplifications can be made in the model formulation that transform the program into a linear program (LP).

Program Linearization

First, the cost function in equation 6.2 can be replaced with the following expression seen in equation 20:

$$Min = \sum_{k=1}^{N_{int}} Cost_k F_k \tag{6.20}$$

where $Cost_k$ is now the cost per unit flow of interceptor *k* rather than the cost per unit as before, and F_k remains the flow rate to interceptor *k*. This new expression removes all binary integers from the formulation and linearizes the cost function.

The next step in linearizing the formulation is to develop simplified models for the interception devices. For the purpose of this dissertation, it will be assumed that the flow rate entering and leaving an interception device will remain constant as shown in equation 6.21.

$$F_k^{int} = F_k \qquad k=\{1,...,N_{int}\} \tag{6.21}$$

The property relationship between the inlet and outlet of an interception device will be represented by a linear expression that employs a removal factor that can be seen in equation 6.22:

$$y_i(P_{i,k}^{int}) = h_{i,k} P_{i,k} \qquad i=\{1,\ldots,N_{prop}\},\ k=\{1,...,N_{int}\} \tag{6.22}$$

where $h_{i,k}$ is the removal factor of property i for interceptor k.

Finally, the operation of mixing within the formulation results in bilinear terms due to the nature of the property mixing rule. To alleviate this problem, the interception network can be modeled so that only the streams entering the process sinks require mixing. To clarify this reformulation, a simple example containing one interceptor, one interceptor bypass, one process sink and one process source is shown in Figure 6.2.

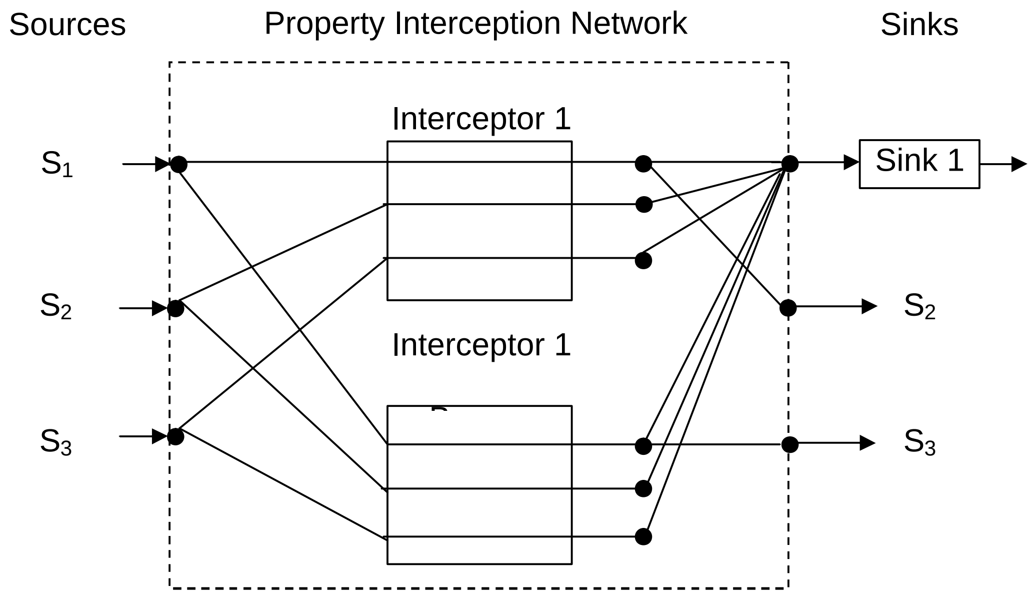


Figure 6.2: Simplified PIN reformulation

In Figure 6.2 rather than mixing the streams as before, the streams are tracked individually throughout the process. The result of this reformulation is that equations 6.4 and 6.5 are no longer needed. In addition, an extra index is needed to track the streams in equations 6.6, 6,7, and 6.8 which can be shown in equations 6.23, 6.24 and 6.25 respectively.

$$K_{k,u}^{\text{int}} = \sum_{j=1}^{N_{\sin ks}} K_{k,j,u} \qquad k=\{1,...,N_{int}\},\ u=\{1,\ldots,N_{sub}\} \tag{6.23}$$

$$G_j = \sum_{k=1}^{N_{\text{int}}} \sum_{u=1}^{N_{sub}} K_{k,j,u} \qquad j=\{1,...,N_{sinks}\} \tag{6.24}$$

$$G_j y_i(\overline{P}_{i,j}) = \sum_{k=1}^{N_{int}} \sum_{u=1}^{N_{sub}} K_{k,j,u} y_i(P_{i,k,u}^{\text{int}}) \qquad j=\{1,...,N_{sinks}\},\ i=\{1,\ldots,N_{prop}\} \tag{6.25}$$

where u denotes the extra index used to track the unmixed streams and N_{sub} is the total number of unmixed streams per source.

After interception, the streams are split and sent to the process sinks or recycled back as a new source. The new sources are then tracked throughout the process and eventually also either go to a process sink or are recycled back as new sources. This process will repeat itself indefinitely, and therefore requires a user decision to terminate the process. In the example above, the original source, S1, is only allowed to recycle through the process once. Therefore, after the first cycle through the process, S1 creates S2 and S3. Then, when S2 and S3 leave the interceptor/bypass the only option for them is to go directly to sink 1, thus stopping the propagation of sources. By tracking the unmixed streams and defining the interceptor models as stated above, most of the bilinear terms have been decomposed so that the property of a stream can be determined prior to solving the formulation. This can be explained better from the following generic formulations indicated the original and modified programs. Originally, the problem could be stated as follows:

$$min = Cost_k(K_k, P_{i,k}, P_{i,k}^{int}) * I_k$$

s.t.

$$h(F_s, F_{s,k}, K_k, K_{k,j}, G_j, P_{i,s}^{source}, P_{i,k}, P_{i,k}^{int}, P_{i,j}^{sink})=0$$

$$g(F_s, F_{s,k}, K_k, K_{k,j}, G_j, P_{i,s}^{source}, P_{i,k}, P_{i,k}^{int}, P_{i,j}^{sink})<=0$$

where h and g represent functions in terms of the process variables F_s, $F_{s,k}$, K_k, $K_{k,j}$,G_j, $P_{i,s}^{source}$, $P_{i,k}$, $P_{i,k}^{int}$, $P_{i,j}^{sink}$. With the modifications made the problem can be restated as follows.

$min = Cost_k(K_k, h_{i,k})$

s.t.

$h_1(P_{i,k}, P_{i,k}^{int})=0$

$h_2(F_s, F_{s,k}, K_k, K_{k,j}, G_j, P_{i,s}^{source}, P_{i,k}, P_{i,k}^{int}, P_{i,j}^{sink})=0$

$g(F_s, F_{s,k}, K_k, K_{k,j}, G_j, P_{i,s}^{source}, P_{i,k}, P_{i,k}^{int}, P_{i,j}^{sink})<=0$

Since the number of unknowns in h_1 is equal to the number of constraints, the expressions in h_1 can be solved algebraically. This results in h_2 and g taking linear forms in terms of the process variables.

This formulation has removed all unknown bilinear terms except the mixing of intercepted/bypassed sources to sinks. To remove this bilinearity the sink flow rate, rather than being allowed to vary from some upper to lower bound, is fixed at some average value. This effectively removes the remaining bilinear terms present in the formulation.

There are several downsides to this reformulation. First, a choice must be made as to how many times a source is allowed to recycle within the process which limits the robustness of the formulation. However, by choosing a reasonable number of recycling loops this choice is not unrealistic. The other downside to this formulation is that the actual program that needs to be written becomes considerably larger than the more compact MINLP.

By using the simplifying assumptions discussed above the MINLP formulation can be reduced to an LP formulation which can be solved globally. To show the applicability of this LP formulation, a case study from a textile dyeing facility will be solved.

Textile Case Study

The textile industry produces a considerable amount of effluent waste that is constrained by properties. The general approach to treatment has been to treat all of the effluents at once in an aeration basin or similar technology which reduces many of the undesirable properties such as biological oxygen demand, chemical oxygen demand, suspended solids, etc. However, the current approach has a limited effect on the effluent color resulting in highly colored discharge. Historically, regulations concerning this were lax or nonexistent and as a result the problem was ignored. However, concern over aesthetic pollution coupled with recent findings suggesting highly colored discharges adversely affect the aquatic life has caused companies and legislators to take action. As such the objective of this case study is to design a property interception network to recover effluents where possible and reduce the overall color of the effluents being sent to the aeration basin.

Consider the textile dyeing process illustrated in Figure 6.3. Cotton fabric is sent through three stages, dyeing, soapy rinsing and rinsing, before the fabric is sent to finishing. Additionally within the process, there is a boiler that generates steam for various processes and produces a sulfur-rich off gas. The effluents from the dyeing and rinsing stages are full of color from dye which is measured by the American Dye Manufacturers Index, ADMI. The ADMI gives a reference of how much color is present compared to a colorless reference, clean water. Within this process two objectives were established, reduction of the overall effluent waste to 300 ADMI and a reduction of SO_2 in the off gas to 25 ppm.

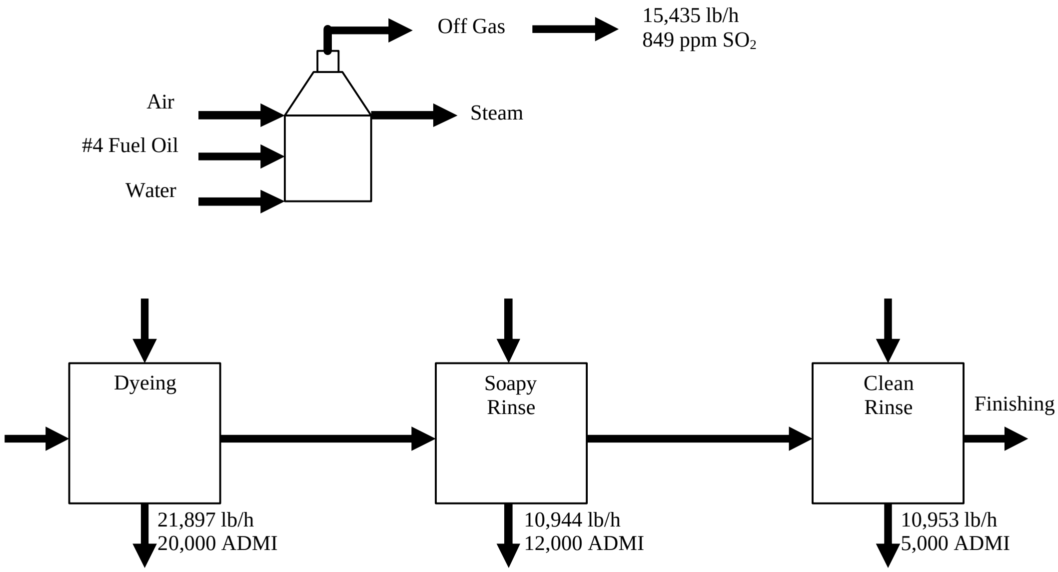


Figure 6.3: Textile dyeing process

To achieve the objectives set forth several technologies are available: absorption for SO_2 reduction, and reverse osmosis, and alum coagulation for color removal.

To begin the case study, the color mixing rule must first be determined and it is as follows:

$$\overline{ADMI}^{0.606} = \sum_{s=1}^{N_s} x_s ADMI_s^{0.606} \tag{6.26}$$

where s refers to the source. Next, recycling opportunities must be assessed to decrease the overall effluent being discharged prior to treatment. It has been determined that the absorption unit for treating the SO_2 can accept recycled effluent up to a color level of 7000 ADMI, and the soapy rinse inlet can be replaced partially with recovered clean rinse effluent up to a level of 300 ADMI and flow rates between 10,944 lb/h and 11,500 lb/h without adversely affecting the soapy rinse stage.

The first step in optimizing this process is to determine the needed flow rate to reduce the SO_2 content in the off gas. To do this a mass pinch diagram is constructed using Henry's law for absorption of SO_2 in water (Geankopolis, 1994). The water was assumed to have no initial SO_2 and was capable of accepting 1000 ppm. Figure 6.4 shows the resulting mass pinch diagram.

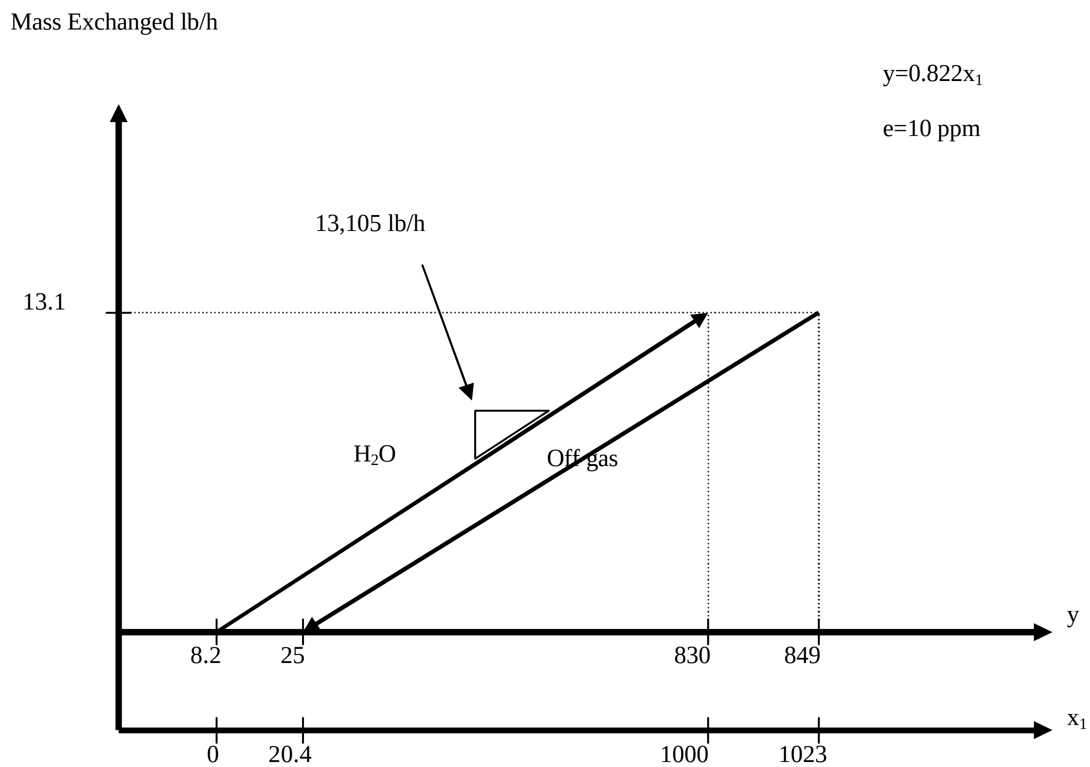


Figure 6.4: Mass pinch diagram for absorption unit

From the slope of the water line, the mass flow rate of water required is determined to be approximately 13,105 lb/h. With this information coupled with the color and flow rate constraints given above, the optimal recycling strategy can be determined with a modified version of the source sink diagram [1]. The recycling strategy to be shown here could have been directly incorporated in the program formulation for the PIN. However, to illustrate the extension of mass integration techniques to the property domain this aspect of the probem was decomposed and solved graphically.

Rather than plotting the sources and sinks on a flow rate composition diagram, a flow rate operator diagram is used. The modified source sink diagram is shown in Figure 6.5.

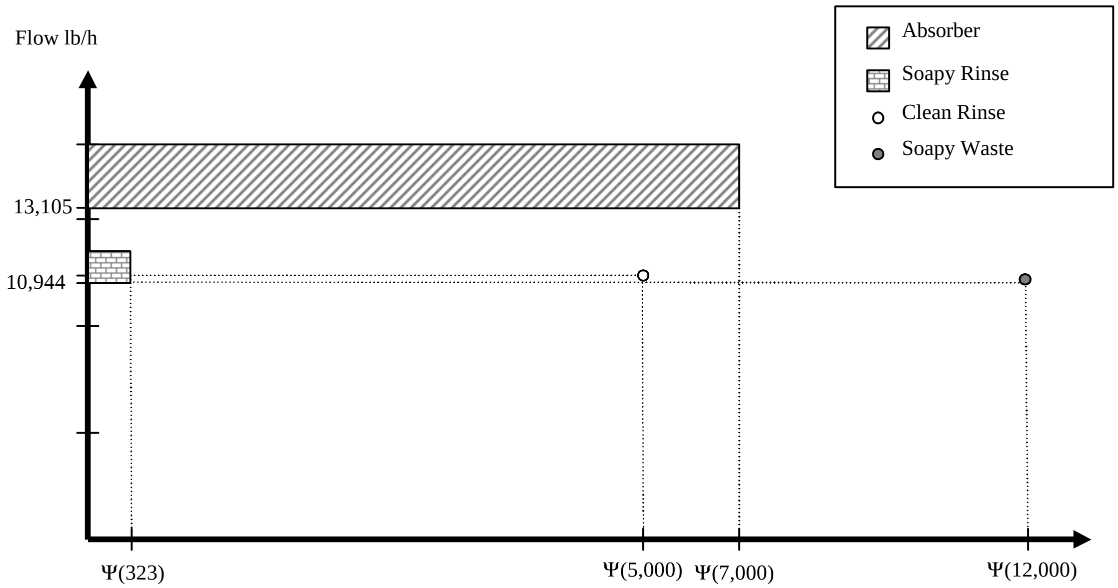


Figure 6.5: Modified source sink diagram

Then, in a similar fashion to mass integration a lever arm principle, and shortest arm rule is used to determine the recycling strategy. Therefore, the Ψ(5000), or clean rinse effluent and the Ψ(12000), or soapy rinse effluent can be combined and the resulting mixture will just meet the lower right hand corner of the absorber sink. The resulting mixture requires 8,872 lb/h clean rinse and 4,233 lb/h soapy rinse. The remaining clean rinse can then be combined with fresh soapy rinse, not pictured but it would be located on the vertical axis, to just meet the demands of the soapy rinse unit in its lower right hand corner. The resulting mixture is 2,081 lb/h of clean rinse and 8,864 lb/h of fresh soapy rinse. The resulting flow sheet, after recycling, can be seen in Figure 6.6.

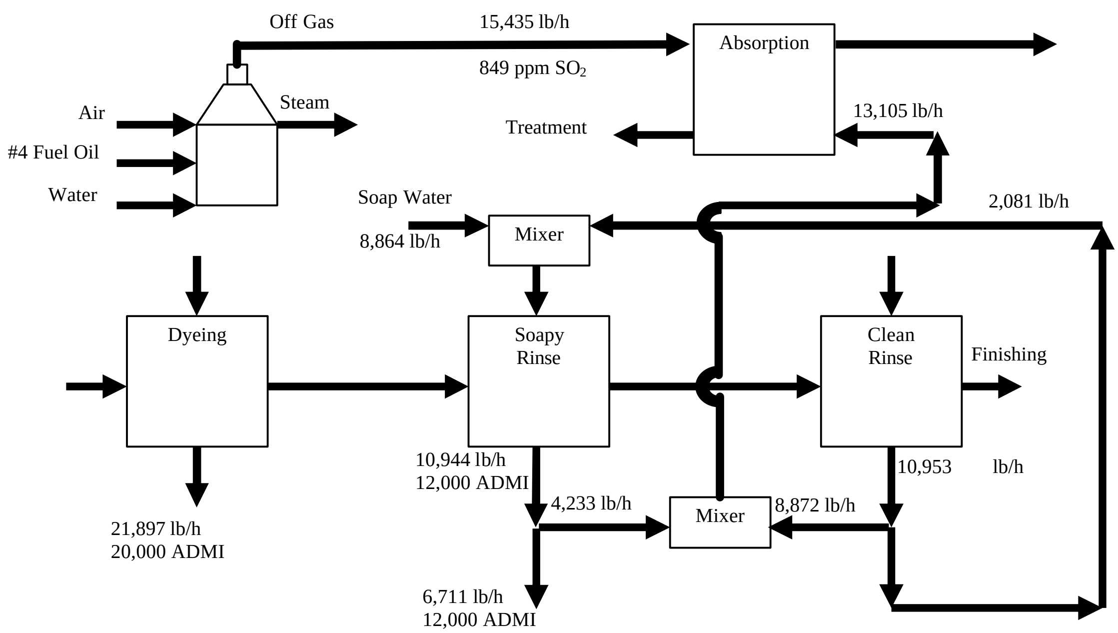


Figure 6.6: Revised textile dyeing process with recycling

Reexamining the flow sheet it is now clear that there are two color laden effluent streams, the dyeing effluent and the soapy rinse effluent. The water discharge out of the absorption unit, although colorful contains sulfur and therefore, is sent to a different treatment facility. Having determined the sources and the intercepting technologies the formulation of the property interception network (PIN) can begin utilizing the LP formulation laid out earlier in this chapter.

The following information was used during the solution of the problem using LINGO optimization software. The costs of the interception devices were assumed to be \$1.5/lb/h and \$5/lb/h for alum and reverse osmosis respectively. In addition, the removal efficiencies for the technologies can be seen in Table 6.1. For this case study it was assumed that sources were allowed to go through the process twice therefore allowing two technologies to be used in series.

Table 6.1: Interception technology removal efficiency (Environmental Protection Service, 1982)

Technology	Removal Efficiency
Alum Coagulation	0.72
Reverse Osmosis	0.95

With the given information along with the source data provided in the revised flow sheet, the interception network in Figure 6.7 was devised.

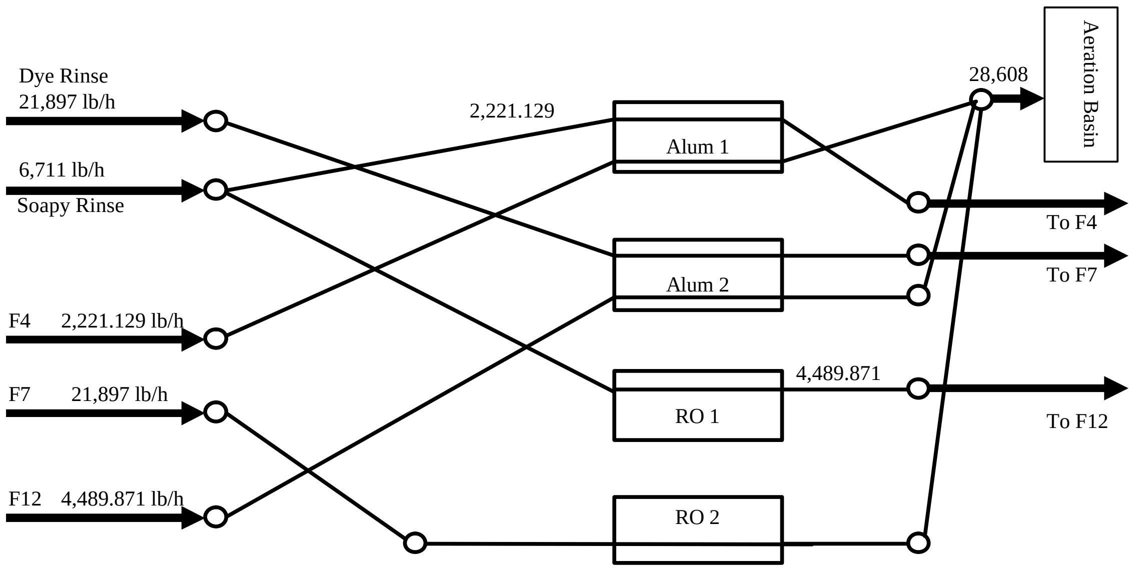


Figure 6.7: Optimized property interception network

The global solution associated with the optimized network was approximately $178,178 and involved four interception devices, both alum units and both reverse osmosis units however, no bypass units were used. Because similar units are considered to have the same removal efficiency and cost, the above formulation could actually be reduced to two units, one larger alum unit and one larger reverse osmosis unit. The entire program formulation that was used to develop this solution as well as the program output can be seen in Appendix B1 and B2. The solution time was negligible, less than 1 minute on a Pentium 4 based laptop. As expected the resulting effluent achieved exactly the 300 ADMI specification. Unfortunately, the case study solved in this chapter was adapted from several case studies in the literature, therefore it is difficult to draw comparisons. The main point of similarity is that the case studies in the literature (DPPEA, 1998) all contain at least two units to accomplish the color removal task which is similar to the formulation above.

CHAPTER VII

CONCLUSIONS

This dissertation has focused on advancing the field of process integration through developing techniques to enhance resource conservation and allocation. Several techniques have been developed to optimize steam utility systems and recover property constrained wastes. To enhance steam utility systems three concepts were explored: targeting steam cogeneration potential and designing feasible cogeneration networks while minimizing fuel requirements, identifying and exploiting sources of waste heat, and incorporating heat pipes into heat exchange networks. As a result, an iterative cascade procedure was developed that identified the optimal location to utilize heat pipe technology in heat exchange networks. Additionally, the concept of extractable power was introduced for the targeting and development of cogeneration networks while minimizing fuel usage. Furthermore, a methodology was developed to identify and utilize waste heat within a process. Finally, case studies were solved to illustrate the ease and applicability of the abovementioned techniques.

To improve the recovery of property constrained effluents the adaptation of established mass integration techniques for property objectives was explored. Furthermore, a generic MINLP was formulated to generate property interception networks to recover property constrained effluents. Additionally, the MINLP formulation was simplified for certain cases to allow an LP formulation to guarantee global solutions, and a case study was solved with this reformulation.

CHAPTER VIII

FUTURE WORK

There are three primary aspects of this dissertation that can be expanded upon in the future. First, the expansion to unsteady state operation could be explored in both the cogeneration targeting and network design as well as in the development of property interception networks. In addition to unsteady state operation, scheduling issues could also be addressed in both the aforementioned areas. Secondly, considerable work can be done in developing methods to simultaneously solve the problems associated with mass, energy and cogeneration rather than working one problem at a time. Finally, there is a considerable amount of work that can be done in modeling units based on properties. In particular, the modeling of reactive systems should receive considerable attention.

REFERENCES

Dhole V.R. and Linnhoff, B. (1992). Total site targets for fuel, co-generation, emissions, and cooling, *Comp. Chem. Eng.*, **17**, S101-S109.

Division of Pollution Prevention and Environmental Assistance. (1998). *Color Reduction and Removal Seminar*, DPPEA.

Dunn P.D. and Reay, D.A. (1994). *Heat Pipes 4th ed.*,Elsevier Science Ltd, Oxford.

El-Halwagi, M.M. (1997). *Pollution Prevention Through Process Integration Systematic Design Tools*, Academic Press, New York.

El-Halwagi, M.M. and Spriggs, H.D. (1996). An integrated approach to cost and energy efficient pollution prevention, *Proceedings Fifth World Congress of Chemical Engineering*, AIChE, Vol III, 344-349.

Environmental Protection Service. (1982). *Survey of Textile Wet Processing and Pollution Abatement Technology*, Minister of Supply and Services Canada, Ontario.

Ganapathy, V. (1991). *Waste Heat Boiler Deskbook*, The Fairmont Press, Lilburn, GA..

Geankoplis, C.J. (1994). *Transport Processes and Unit Operations 3rd ed.*, Prentice Hall Paramus, NJ.

Hohmann, E.C. (1971). Optimum Networks for Heat Exchange, Ph.D. Thesis, University of Southern California, Los Angeles, CA.

Linnhoff, B., and Flower, J.R. (1978). Synthesis of heat exchange networks: part 1 – systematic generation of heat exchanger networks, *AIChE J.*, **24(4)**, 633-642.

Linnhoff, B., Townsend, D.W., Boland, D., Hewitt, G.F., Thomas, B.E.A., Guy, A.R., and Marsland, R.H. (1982). *User Guide on Process Integration for the Efficient Use of Energy*, ICHemE Press, Rugby, Warwickshire, UK.

Mavromatis, S.P. (1996). Conceptual Desing and Operation of Industrial Steam Turbine Networks, Ph.D. Dissertation, University of Manchester Institute of Science and Technology, Manchester, UK

Olszewski, M. (1980). *Utilization of Reject Heat*, Marcel Dekker Inc., New York

Raissi, K. (1994). Total Site Integration. Ph.D. Dissertation, University of Manchester Institute of Science and Technology, Manchester, UK.

Salisbury, J.K. (1942). The steam turbine regenerative cycle- an analytical approach, *ASME Trans*., **64**, 231-245.

Shelley, M.D. and El-Halwagi, M.M. (2000). Compont-less design of recovery and allocation systems: a functionality-based clustering approach, *Comp*. *Chem*. *Eng*., **24**, 2081-2091.

Umeda, T., Itoh, J., and Shiroka, K. (1979). A thermodynamic approach to the synthesis of heat integration systems in chemical processes, *Comp*. *Chem*. *Eng*., **3**, 273-282.

APPENDICES

A1- Numerical approximation for steam enthalpies

YI=ln(PI)

XI=1.0750-0.12286*YI-0.0014143*YI^2+0.0000027405*YI^3

TSATI=(705.47-459.67*XI)/(1+XI)

RSATI=TSATI+459.67

TRI=TI+459.67

Z=705.47-TSATI

HSATI=859.2+45.354*Z^0.5-1.5713*Z+0.005416*Z^1.5

SSATI=1.2707+0.82886*XI-0.38025*XI^2+0.20749*XI^3

TAUI=ln(TRI/TSATI)

LMTI=(TRI-RSATI)/TAUI

SI=1.98793-0.084015*YI+0.39408*TAUI+0.08119*TAUI^2+0.00010649*YI^2+

0.008029*YI*TAUI^2+0.0075381*TAUI*YI^2-0.009056*TAUI^2*YI^2

HI=HSATI+LMTI*(SI-SSATI)

*where PI and TI are the pressure and temperature inputs required in psia and fahrenhite

** HSATI, SSATI and TSATI are the saturated enthalpy (Btu/lb), entropy (Btu/lb F) and temperature (F) at PI

***SI and HI are the entropy (Btu/lb F) and enthalpy (Btu/lb) at the respective PI and TI

A2 – Validation of numerical approximation

Table A.1: Validation of numerical steam calculations

P (psia)	T (F)	H Calculated (Btu/lb)	Steam Table H (Btu/lb)	% Difference
800	800	1402	1399	0.20
800	700	1339	1339	-0.02
800	650	1306	1307	-0.06
800	600	1272	1271	0.06
800	520	1215	1201	1.12
600	700	1354	1352	0.16
600	650	1323	1322	0.06
600	600	1291	1290	0.02
600	500	1223	1216	0.57
500	600	1300	1299	0.03
500	560	1274	1274	0.03
500	520	1248	1246	0.13
500	480	1221	1216	0.43
400	600	1308	1307	0.06
400	500	1246	1245	0.04
400	460	1220	1217	0.25
300	520	1269	1270	-0.04
300	460	1232	1232	0.00
300	420	1207	1205	0.18
200	500	1268	1269	-0.06
200	400	1210	1210	-0.04
100	400	1226	1227	-0.10
100	340	1193	1194	-0.07
50	350	1210	1210	0.00
50	300	1185	1184	0.03
25	300	1192	1190	0.14

B1 – LINGO program for textile case study

MODEL:

!Textile Case Study LP formulation;

!There were 4 technologies (2 alum and 2 RO units) and 4 technology bypasses the technologies and there bypasses were designated by s, t, u, v, w, x, y and z;

!s - alum 1;

!t - alum 1 bypass;

!u - alum 2;

!v - alum 2 bypass;

!w - RO 1;

!x - RO1 bypass;

!y - RO2;

!z - RO2 bypass;

!there were 18 sources labelled 1-18, with 1 and 2 being dye and soap respectively, the remainder are recycle sources;

!f denotes source;

!k denotes interceptor;

!g denotes sink;

!h denotes operator property;

!Objective Function;

```
Min=cost1*(fs1+fs2+fs3+fs4+fs5+fs6+fs7+fs8+fs9+fs10+fs11+fs12+fs13+fs14+fs15+fs
16+fs17+fs18+fu1+fu2+fu3+fu4+fu5+fu6+fu7+fu8+fu9+fu10+fu11+fu12+fu13+fu14+f
u15+fu16+fu17+fu18)+cost2*(fw1+fw2+fw3+fw4+fw5+fw6+fw7+fw8+fw9+fw10+fw
11+fw12+fw13+fw14+fw15+fw16+fw17+fw18+fy1+fy2+fy3+fy4+fy5+fy6+fy7+fy8+f
y9+fy10+fy11+fy12+fy13+fy14+fy15+fy16+fy17+fy18);
!First set of splitters;
f1=fs1+ft1+fu1+fv1+fw1+fx1+fy1+fz1;
f2=fs2+ft2+fu2+fv2+fw2+fx2+fy2+fz2;
f3=fs3+ft3+fu3+fv3+fw3+fx3+fy3+fz3;
f4=fs4+ft4+fu4+fv4+fw4+fx4+fy4+fz4;
f5=fs5+ft5+fu5+fv5+fw5+fx5+fy5+fz5;
f6=fs6+ft6+fu6+fv6+fw6+fx6+fy6+fz6;
f7=fs7+ft7+fu7+fv7+fw7+fx7+fy7+fz7;
f8=fs8+ft8+fu8+fv8+fw8+fx8+fy8+fz8;
f9=fs9+ft9+fu9+fv9+fw9+fx9+fy9+fz9;
f10=fs10+ft10+fu10+fv10+fw10+fx10+fy10+fz10;
f11=fs11+ft11+fu11+fv11+fw11+fx11+fy11+fz11;
f12=fs12+ft12+fu12+fv12+fw12+fx12+fy12+fz12;
f13=fs13+ft13+fu13+fv13+fw13+fx13+fy13+fz13;
f14=fs14+ft14+fu14+fv14+fw14+fx14+fy14+fz14;
f15=fs15+ft15+fu15+fv15+fw15+fx15+fy15+fz15;
f16=fs16+ft16+fu16+fv16+fw16+fx16+fy16+fz16;
```

```
f17=fs17+ft17+fu17+fv17+fw17+fx17+fy17+fz17;

f18=fs18+ft18+fu18+fv18+fw18+fx18+fy18+fz18;

!Interception technologies;

ks1=fs1;

ks2=fs2;

ks3=fs3;

ks4=fs4;

ks5=fs5;

ks6=fs6;

ks7=fs7;

ks8=fs8;

ks9=fs9;

ks10=fs10;

ks11=fs11;

ks12=fs12;

ks13=fs13;

ks14=fs14;

ks15=fs15;

ks16=fs16;

ks17=fs17;

ks18=fs18;
```

```
hs1=e1*h1;
hs2=e1*h2;
hs3=e1*h3;
hs4=e1*h4;
hs5=e1*h5;
hs6=e1*h6;
hs7=e1*h7;
hs8=e1*h8;
hs9=e1*h9;
hs10=e1*h10;
hs11=e1*h11;
hs12=e1*h12;
hs13=e1*h13;
hs14=e1*h14;
hs15=e1*h15;
hs16=e1*h16;
hs17=e1*h17;
hs18=e1*h18;
kt1=ft1;
kt2=ft2;
kt3=ft3;
kt4=ft4;
```

```
kt5=ft5;
kt6=ft6;
kt7=ft7;
kt8=ft8;
kt9=ft9;
kt10=ft10;
kt11=ft11;
kt12=ft12;
kt13=ft13;
kt14=ft14;
kt15=ft15;
kt16=ft16;
kt17=ft17;
kt18=ft18;
ht1=e2*h1;
ht2=e2*h2;
ht3=e2*h3;
ht4=e2*h4;
ht5=e2*h5;
ht6=e2*h6;
ht7=e2*h7;
ht8=e2*h8;
```

```
ht9=e2*h9;
ht10=e2*h10;
ht11=e2*h11;
ht12=e2*h12;
ht13=e2*h13;
ht14=e2*h14;
ht15=e2*h15;
ht16=e2*h16;
ht17=e2*h17;
ht18=e2*h18;
ku1=fu1;
ku2=fu2;
ku3=fu3;
ku4=fu4;
ku5=fu5;
ku6=fu6;
ku7=fu7;
ku8=fu8;
ku9=fu9;
ku10=fu10;
ku11=fu11;
ku12=fu12;
```

```
ku13=fu13;
ku14=fu14;
ku15=fu15;
ku16=fu16;
ku17=fu17;
ku18=fu18;
hu1=e1*h1;
hu2=e1*h2;
hu3=e1*h3;
hu4=e1*h4;
hu5=e1*h5;
hu6=e1*h6;
hu7=e1*h7;
hu8=e1*h8;
hu9=e1*h9;
hu10=e1*h10;
hu11=e1*h11;
hu12=e1*h12;
hu13=e1*h13;
hu14=e1*h14;
hu15=e1*h15;
hu16=e1*h16;
```

```
hu17=e1*h17;
hu18=e1*h18;
kv1=fv1;
kv2=fv2;
kv3=fv3;
kv4=fv4;
kv5=fv5;
kv6=fv6;
kv7=fv7;
kv8=fv8;
kv9=fv9;
kv10=fv10;
kv11=fv11;
kv12=fv12;
kv13=fv13;
kv14=fv14;
kv15=fv15;
kv16=fv16;
kv17=fv17;
kv18=fv18;
hv1=e2*h1;
hv2=e2*h2;
```

```
hv3=e2*h3;
hv4=e2*h4;
hv5=e2*h5;
hv6=e2*h6;
hv7=e2*h7;
hv8=e2*h8;
hv9=e2*h9;
hv10=e2*h10;
hv11=e2*h11;
hv12=e2*h12;
hv13=e2*h13;
hv14=e2*h14;
hv15=e2*h15;
hv16=e2*h16;
hv17=e2*h17;
hv18=e2*h18;
kw1=fw1;
kw2=fw2;
kw3=fw3;
kw4=fw4;
kw5=fw5;
kw6=fw6;
```

```
kw7=fw7;
kw8=fw8;
kw9=fw9;
kw10=fw10;
kw11=fw11;
kw12=fw12;
kw13=fw13;
kw14=fw14;
kw15=fw15;
kw16=fw16;
kw17=fw17;
kw18=fw18;
hw1=e3*h1;
hw2=e3*h2;
hw3=e3*h3;
hw4=e3*h4;
hw5=e3*h5;
hw6=e3*h6;
hw7=e3*h7;
hw8=e3*h8;
hw9=e3*h9;
hw10=e3*h10;
```

```
hw11=e3*h11;
hw12=e3*h12;
hw13=e3*h13;
hw14=e3*h14;
hw15=e3*h15;
hw16=e3*h16;
hw17=e3*h17;
hw18=e3*h18;
kx1=fx1;
kx2=fx2;
kx3=fx3;
kx4=fx4;
kx5=fx5;
kx6=fx6;
kx7=fx7;
kx8=fx8;
kx9=fx9;
kx10=fx10;
kx11=fx11;
kx12=fx12;
kx13=fx13;
kx14=fx14;
```

```
kx15=fx15;
kx16=fx16;
kx17=fx17;
kx18=fx18;
hx1=e4*h1;
hx2=e4*h2;
hx3=e4*h3;
hx4=e4*h4;
hx5=e4*h5;
hx6=e4*h6;
hx7=e4*h7;
hx8=e4*h8;
hx9=e4*h9;
hx10=e4*h10;
hx11=e4*h11;
hx12=e4*h12;
hx13=e4*h13;
hx14=e4*h14;
hx15=e4*h15;
hx16=e4*h16;
hx17=e4*h17;
hx18=e4*h18;
```

```
ky1=fy1;
ky2=fy2;
ky3=fy3;
ky4=fy4;
ky5=fy5;
ky6=fy6;
ky7=fy7;
ky8=fy8;
ky9=fy9;
ky10=fy10;
ky11=fy11;
ky12=fy12;
ky13=fy13;
ky14=fy14;
ky15=fy15;
ky16=fy16;
ky17=fy17;
ky18=fy18;
hy1=e3*h1;
hy2=e3*h2;
hy3=e3*h3;
hy4=e3*h4;
```

```
hy5=e3*h5;
hy6=e3*h6;
hy7=e3*h7;
hy8=e3*h8;
hy9=e3*h9;
hy10=e3*h10;
hy11=e3*h11;
hy12=e3*h12;
hy13=e3*h13;
hy14=e3*h14;
hy15=e3*h15;
hy16=e3*h16;
hy17=e3*h17;
hy18=e3*h18;
kz1=fz1;
kz2=fz2;
kz3=fz3;
kz4=fz4;
kz5=fz5;
kz6=fz6;
kz7=fz7;
kz8=fz8;
```

```
kz9=fz9;

kz10=fz10;

kz11=fz11;

kz12=fz12;

kz13=fz13;

kz14=fz14;

kz15=fz15;

kz16=fz16;

kz17=fz17;

kz18=fz18;

hz1=e4*h1;

hz2=e4*h2;

hz3=e4*h3;

hz4=e4*h4;

hz5=e4*h5;

hz6=e4*h6;

hz7=e4*h7;

hz8=e4*h8;

hz9=e4*h9;

hz10=e4*h10;

hz11=e4*h11;

hz12=e4*h12;
```

```
hz13=e4*h13;

hz14=e4*h14;

hz15=e4*h15;

hz16=e4*h16;

hz17=e4*h17;

hz18=e4*h18;

!Second set of splitters;

ks1=gs11+gs12;

ks2=gs21+gs22;

ks3=gs31;

ks4=gs41;

ks5=gs51;

ks6=gs61;

ks7=gs71;

ks8=gs81;

ks9=gs91;

ks10=gs101;

ks11=gs111;

ks12=gs121;

ks13=gs131;

ks14=gs141;

ks15=gs151;
```

```
ks16=gs161;
ks17=gs171;
ks18=gs181;
kt1=gt11+gt12;
kt2=gt21+gt22;
kt3=gt31;
kt4=gt41;
kt5=gt51;
kt6=gt61;
kt7=gt71;
kt8=gt81;
kt9=gt91;
kt10=gt101;
kt11=gt111;
kt12=gt121;
kt13=gt131;
kt14=gt141;
kt15=gt151;
kt16=gt161;
kt17=gt171;
kt18=gt181;
ku1=gu11+gu12;
```

```
ku2=gu21+gu22;

ku3=gu31;

ku4=gu41;

ku5=gu51;

ku6=gu61;

ku7=gu71;

ku8=gu81;

ku9=gu91;

ku10=gu101;

ku11=gu111;

ku12=gu121;

ku13=gu131;

ku14=gu141;

ku15=gu151;

ku16=gu161;

ku17=gu171;

ku18=gu181;

kv1=gv11+gv12;

kv2=gv21+gv22;

kv3=gv31;

kv4=gv41;

kv5=gv51;
```

```
kv6=gv61;
kv7=gv71;
kv8=gv81;
kv9=gv91;
kv10=gv101;
kv11=gv111;
kv12=gv121;
kv13=gv131;
kv14=gv141;
kv15=gv151;
kv16=gv161;
kv17=gv171;
kv18=gv181;
kw1=gw11+gw12;
kw2=gw21+gw22;
kw3=gw31;
kw4=gw41;
kw5=gw51;
kw6=gw61;
kw7=gw71;
kw8=gw81;
kw9=gw91;
```

```
kw10=gw101;

kw11=gw111;

kw12=gw121;

kw13=gw131;

kw14=gw141;

kw15=gw151;

kw16=gw161;

kw17=gw171;

kw18=gw181;

kx1=gx11+gx12;

kx2=gx21+gx22;

kx3=gx31;

kx4=gx41;

kx5=gx51;

kx6=gx61;

kx7=gx71;

kx8=gx81;

kx9=gx91;

kx10=gx101;

kx11=gx111;

kx12=gx121;

kx13=gx131;
```

```
kx14=gx141;
kx15=gx151;
kx16=gx161;
kx17=gx171;
kx18=gx181;
ky1=gy11+gy12;
ky2=gy21+gy22;
ky3=gy31;
ky4=gy41;
ky5=gy51;
ky6=gy61;
ky7=gy71;
ky8=gy81;
ky9=gy91;
ky10=gy101;
ky11=gy111;
ky12=gy121;
ky13=gy131;
ky14=gy141;
ky15=gy151;
ky16=gy161;
ky17=gy171;
```

```
ky18=gy181;
kz1=gz11+gz12;
kz2=gz21+gz22;
kz3=gz31;
kz4=gz41;
kz5=gz51;
kz6=gz61;
kz7=gz71;
kz8=gz81;
kz9=gz91;
kz10=gz101;
kz11=gz111;
kz12=gz121;
kz13=gz131;
kz14=gz141;
kz15=gz151;
kz16=gz161;
kz17=gz171;
kz18=gz181;
!Process Sinks;
g1=gs11+gs21+gs31+gs41+gs51+gs61+gs71+gs81+gs91+gs101+gs111+gs121+gs131+
gs141+gs151+gs161+gs171+gs181+gt11+gt21+gt31+gt41+gt51+gt61+gt71+gt81+gt91
```

+gt101+gt111+gt121+gt131+gt141+gt151+gt161+gt171+gt181+gu11+gu21+gu31+gu4
1+gu51+gu61+gu71+gu81+gu91+gu101+gu111+gu121+gu131+gu141+gu151+gu161+
gu171+gu181+gv11+gv21+gv31+gv41+gv51+gv61+gv71+gv81+gv91+gv101+gv111+
gv121+gv131+gv141+gv151+gv161+gv171+gv181+gw11+gw21+gw31+gw41+gw51+
gw61+gw71+gw81+gw91+gw101+gw111+gw121+gw131+gw141+gw151+gw161+gw
171+gw181+gx11+gx21+gx31+gx41+gx51+gx61+gx71+gx81+gx91+gx101+gx111+gx
121+gx131+gx141+gx151+gx161+gx171+gx181+gy11+gy21+gy31+gy41+gy51+gy61
+gy71+gy81+gy91+gy101+gy111+gy121+gy131+gy141+gy151+gy161+gy171+gy181
+gz11+gz21+gz31+gz41+gz51+gz61+gz71+gz81+gz91+gz101+gz111+gz121+gz131+g
z141+gz151+gz161+gz171+gz181;

g1*hg1=gs11*hs1+gs21*hs2+gs31*hs3+gs41*hs4+gs51*hs5+gs61*hs6+gs71*hs7+gs8
1*hs8+gs91*hs9+gs101*hs10+gs111*hs11+gs121*hs12+gs131*hs13+gs141*hs14+gs1
51*hs15+gs161*hs16+gs171*hs17+gs181*hs18+gt11*ht1+gt21*ht2+gt31*ht3+gt41*ht
4+gt51*ht5+gt61*ht6+gt71*ht7+gt81*ht8+gt91*ht9+gt101*ht10+gt111*ht11+gt121*ht
12+gt131*ht13+gt141*ht14+gt151*ht15+gt161*ht16+gt171*ht17+gt181*ht18+gu11*h
u1+gu21*hu2+gu31*hu3+gu41*hu4+gu51*hu5+gu61*hu6+gu71*hu7+gu81*hu8+gu91
*hu9+gu101*hu10+gu111*hu11+gu121*hu12+gu131*hu13+gu141*hu14+gu151*hu15
+gu161*hu16+gu171*hu17+gu181*hu18+gv11*hv1+gv21*hv2+gv31*hv3+gv41*hv4+
gv51*hv5+gv61*hv6+gv71*hv7+gv81*hv8+gv91*hv9+gv101*hv10+gv111*hv11+gv1
21*hv12+gv131*hv13+gv141*hv14+gv151*hv15+gv161*hv16+gv171*hv17+gv181*h
v18+gw11*hw1+gw21*hw2+gw31*hw3+gw41*hw4+gw51*hw5+gw61*hw6+gw71*h
w7+gw81*hw8+gw91*hw9+gw101*hw10+gw111*hw11+gw121*hw12+gw131*hw13

```
+gw141*hw14+gw151*hw15+gw161*hw16+gw171*hw17+gw181*hw18+gx11*hx1+g
x21*hx2+gx31*hx3+gx41*hx4+gx51*hx5+gx61*hx6+gx71*hx7+gx81*hx8+gx91*hx9
+gx101*hx10+gx111*hx11+gx121*hx12+gx131*hx13+gx141*hx14+gx151*hx15+gx1
61*hx16+gx171*hx17+gx181*hx18+gy11*hy1+gy21*hy2+gy31*hy3+gy41*hy4+gy51
*hy5+gy61*hy6+gy71*hy7+gy81*hy8+gy91*hy9+gy101*hy10+gy111*hy11+gy121*h
y12+gy131*hy13+gy141*hy14+gy151*hy15+gy161*hy16+gy171*hy17+gy181*hy18+
gz11*hz1+gz21*hz2+gz31*hz3+gz41*hz4+gz51*hz5+gz61*hz6+gz71*hz7+gz81*hz8+
gz91*hz9+gz101*hz10+gz111*hz11+gz121*hz12+gz131*hz13+gz141*hz14+gz151*hz
15+gz161*hz16+gz171*hz17+gz181*hz18;
!Recycle sinks;
gs12=f3;
gs22=f4;
gt12=f5;
gt22=f6;
gu12=f7;
gu22=f8;
gv12=f9;
gv22=f10;
gw12=f11;
gw22=f12;
gx12=f13;
gx22=f14;
```

```
gy12=f15;
gy22=f16;
gz12=f17;
gz22=f18;
hs1=h3;
hs2=h4;
ht1=h5;
ht2=h6;
hu1=h7;
hu2=h8;
hv1=h9;
hv2=h10;
hw1=h11;
hw2=h12;
hx1=h13;
hx2=h14;
hy1=h15;
hy2=h16;
hz1=h17;
hz2=h18;
!Inequality Constraints;
hg1<=hoverall;
```

```
!Constants;

f1=21897;

f2=6711;

g1=f1+f2;

h1=404.04;

h2=296.47;

cost1=1.5;

cost2=5;

e1=0.462;

e2=1;

e3=0.163;

e4=1;

hoverall=31.706;

END
```

B2 – LINGO output from textile case study

Rows= 326 Vars= 465 No. integer vars= 0 (all are linear)

Nonzeros= 1150 Constraint nonz= 1074(929 are +- 1) Density=0.008

Smallest and largest elements in absolute value= 1.00000 28608.0

No. < : 1 No. =: 324 No. > : 0, Obj=MIN, GUBs <= 257

Single cols= 0

Optimal solution found at step: 63

Objective value: 178178.1

Variable	Value	Reduced Cost
COST1	1.500000	0.0000000E+00
FS1	0.0000000E+00	0.0000000E+00
FS2	2221.129	0.0000000E+00
FS3	0.0000000E+00	0.0000000E+00
FS4	2221.129	0.0000000E+00
FS5	0.0000000E+00	0.0000000E+00
FS6	0.0000000E+00	0.0000000E+00
FS7	0.0000000E+00	0.0000000E+00
FS8	0.0000000E+00	0.0000000E+00
FS9	0.0000000E+00	0.0000000E+00

FS10	0.0000000E+00	0.0000000E+00
FS11	0.0000000E+00	0.0000000E+00
FS12	0.0000000E+00	0.0000000E+00
FS13	0.0000000E+00	0.0000000E+00
FS14	0.0000000E+00	0.0000000E+00
FS15	0.0000000E+00	0.0000000E+00
FS16	0.0000000E+00	0.0000000E+00
FS17	0.0000000E+00	0.0000000E+00
FS18	0.0000000E+00	0.0000000E+00
FU1	21897.00	0.0000000E+00
FU2	0.0000000E+00	0.5960464E-07
FU3	0.0000000E+00	0.0000000E+00
FU4	0.0000000E+00	0.0000000E+00
FU5	0.0000000E+00	0.0000000E+00
FU6	0.0000000E+00	0.0000000E+00
FU7	0.0000000E+00	0.0000000E+00
FU8	0.0000000E+00	0.0000000E+00
FU9	0.0000000E+00	0.0000000E+00
FU10	0.0000000E+00	0.0000000E+00
FU11	0.0000000E+00	0.0000000E+00
FU12	4489.871	0.0000000E+00
FU13	0.0000000E+00	0.0000000E+00

FU14	0.0000000E+00	0.0000000E+00
FU15	0.0000000E+00	0.0000000E+00
FU16	0.0000000E+00	0.0000000E+00
FU17	0.0000000E+00	0.0000000E+00
FU18	0.0000000E+00	0.0000000E+00
COST2	5.000000	0.0000000E+00
FW1	0.0000000E+00	0.0000000E+00
FW2	4489.871	0.0000000E+00
FW3	0.0000000E+00	0.0000000E+00
FW4	0.0000000E+00	0.0000000E+00
FW5	0.0000000E+00	0.0000000E+00
FW6	0.0000000E+00	0.0000000E+00
FW7	0.0000000E+00	0.0000000E+00
FW8	0.0000000E+00	0.0000000E+00
FW9	0.0000000E+00	0.0000000E+00
FW10	0.0000000E+00	0.0000000E+00
FW11	0.0000000E+00	1.817104
FW12	0.0000000E+00	2.265151
FW13	0.0000000E+00	0.0000000E+00
FW14	0.0000000E+00	0.0000000E+00
FW15	0.0000000E+00	1.817104
FW16	0.0000000E+00	2.265151

FW17	0.0000000E+00	0.0000000E+00
FW18	0.0000000E+00	0.0000000E+00
FY1	0.0000000E+00	0.0000000E+00
FY2	0.0000000E+00	0.0000000E+00
FY3	0.0000000E+00	0.0000000E+00
FY4	0.0000000E+00	0.0000000E+00
FY5	0.0000000E+00	0.0000000E+00
FY6	0.0000000E+00	0.0000000E+00
FY7	21897.00	0.0000000E+00
FY8	0.0000000E+00	0.0000000E+00
FY9	0.0000000E+00	0.0000000E+00
FY10	0.0000000E+00	0.0000000E+00
FY11	0.0000000E+00	0.0000000E+00
FY12	0.0000000E+00	2.265151
FY13	0.0000000E+00	0.0000000E+00
FY14	0.0000000E+00	0.0000000E+00
FY15	0.0000000E+00	0.0000000E+00
FY16	0.0000000E+00	2.265151
FY17	0.0000000E+00	0.0000000E+00
FY18	0.0000000E+00	0.0000000E+00
F1	21897.00	0.0000000E+00
FT1	0.0000000E+00	0.0000000E+00

FV1	0.0000000E+00	0.0000000E+00
FX1	0.0000000E+00	0.0000000E+00
FZ1	-0.3637979E-11	0.0000000E+00
F2	6711.000	0.0000000E+00
FT2	0.0000000E+00	0.0000000E+00
FV2	0.0000000E+00	0.0000000E+00
FX2	0.0000000E+00	0.0000000E+00
FZ2	0.0000000E+00	0.0000000E+00
F3	0.0000000E+00	0.0000000E+00
FT3	0.0000000E+00	0.0000000E+00
FV3	0.0000000E+00	0.0000000E+00
FX3	0.0000000E+00	0.0000000E+00
FZ3	0.0000000E+00	0.0000000E+00
F4	2221.129	0.0000000E+00
FT4	0.0000000E+00	0.0000000E+00
FV4	0.0000000E+00	0.0000000E+00
FX4	0.0000000E+00	0.0000000E+00
FZ4	0.0000000E+00	0.0000000E+00
F5	0.0000000E+00	1.528087
FT5	0.0000000E+00	0.0000000E+00
FV5	0.0000000E+00	0.0000000E+00
FX5	0.0000000E+00	0.0000000E+00

FZ5	0.0000000E+00	0.0000000E+00
F6	0.0000000E+00	0.0000000E+00
FT6	0.0000000E+00	0.0000000E+00
FV6	0.0000000E+00	0.0000000E+00
FX6	0.0000000E+00	0.0000000E+00
FZ6	0.0000000E+00	0.0000000E+00
F7	21897.00	0.0000000E+00
FT7	0.0000000E+00	0.0000000E+00
FV7	0.0000000E+00	0.0000000E+00
FX7	0.0000000E+00	0.0000000E+00
FZ7	0.0000000E+00	0.0000000E+00
F8	0.0000000E+00	0.0000000E+00
FT8	0.0000000E+00	0.0000000E+00
FV8	0.0000000E+00	0.0000000E+00
FX8	0.0000000E+00	0.0000000E+00
FZ8	0.0000000E+00	0.0000000E+00
F9	0.0000000E+00	0.0000000E+00
FT9	0.0000000E+00	0.0000000E+00
FV9	0.0000000E+00	0.0000000E+00
FX9	0.0000000E+00	0.0000000E+00
FZ9	0.0000000E+00	0.0000000E+00
F10	0.0000000E+00	0.0000000E+00

FT10	0.0000000E+00	0.0000000E+00
FV10	0.0000000E+00	0.0000000E+00
FX10	0.0000000E+00	0.0000000E+00
FZ10	0.0000000E+00	0.0000000E+00
F11	0.0000000E+00	0.0000000E+00
FT11	0.0000000E+00	0.0000000E+00
FV11	0.0000000E+00	0.0000000E+00
FX11	0.0000000E+00	0.0000000E+00
FZ11	0.0000000E+00	0.0000000E+00
F12	4489.871	0.0000000E+00
FT12	0.0000000E+00	0.0000000E+00
FV12	0.0000000E+00	0.0000000E+00
FX12	0.0000000E+00	0.0000000E+00
FZ12	0.0000000E+00	0.0000000E+00
F13	0.0000000E+00	1.528087
FT13	0.0000000E+00	0.0000000E+00
FV13	0.0000000E+00	0.0000000E+00
FX13	0.0000000E+00	0.0000000E+00
FZ13	0.0000000E+00	0.0000000E+00
F14	0.0000000E+00	0.0000000E+00
FT14	0.0000000E+00	0.0000000E+00
FV14	0.0000000E+00	0.0000000E+00

FX14	0.0000000E+00	0.0000000E+00
FZ14	0.0000000E+00	0.0000000E+00
F15	0.0000000E+00	0.0000000E+00
FT15	0.0000000E+00	0.0000000E+00
FV15	0.0000000E+00	0.0000000E+00
FX15	0.0000000E+00	0.0000000E+00
FZ15	0.0000000E+00	0.0000000E+00
F16	0.0000000E+00	0.0000000E+00
FT16	0.0000000E+00	0.0000000E+00
FV16	0.0000000E+00	0.0000000E+00
FX16	0.0000000E+00	0.0000000E+00
FZ16	0.0000000E+00	0.0000000E+00
F17	-0.3637979E-11	0.0000000E+00
FT17	0.0000000E+00	0.0000000E+00
FV17	0.0000000E+00	0.0000000E+00
FX17	0.0000000E+00	0.0000000E+00
FZ17	0.0000000E+00	0.0000000E+00
F18	0.0000000E+00	0.0000000E+00
FT18	0.0000000E+00	0.0000000E+00
FV18	0.0000000E+00	0.0000000E+00
FX18	0.0000000E+00	0.0000000E+00
FZ18	0.0000000E+00	0.0000000E+00

KS1	0.0000000E+00	0.0000000E+00
KS2	2221.129	0.0000000E+00
KS3	0.0000000E+00	0.0000000E+00
KS4	2221.129	0.0000000E+00
KS5	0.0000000E+00	0.0000000E+00
KS6	0.0000000E+00	0.0000000E+00
KS7	0.0000000E+00	0.0000000E+00
KS8	0.0000000E+00	0.0000000E+00
KS9	0.0000000E+00	0.0000000E+00
KS10	0.0000000E+00	0.0000000E+00
KS11	0.0000000E+00	0.0000000E+00
KS12	0.0000000E+00	0.0000000E+00
KS13	0.0000000E+00	6.824515
KS14	0.0000000E+00	0.0000000E+00
KS15	0.0000000E+00	0.0000000E+00
KS16	0.0000000E+00	0.0000000E+00
KS17	0.0000000E+00	0.0000000E+00
KS18	0.0000000E+00	0.0000000E+00
HS1	186.6665	0.0000000E+00
E1	0.4620000	0.0000000E+00
H1	404.0400	0.0000000E+00
HS2	136.9691	0.0000000E+00

H2	296.4700	0.0000000E+00
HS3	86.23991	0.0000000E+00
H3	186.6665	0.0000000E+00
HS4	63.27974	0.0000000E+00
H4	136.9691	0.0000000E+00
HS5	186.6665	0.0000000E+00
H5	404.0400	0.0000000E+00
HS6	136.9691	0.0000000E+00
H6	296.4700	0.0000000E+00
HS7	86.23991	0.0000000E+00
H7	186.6665	0.0000000E+00
HS8	63.27974	0.0000000E+00
H8	136.9691	0.0000000E+00
HS9	186.6665	0.0000000E+00
H9	404.0400	0.0000000E+00
HS10	136.9691	0.0000000E+00
H10	296.4700	0.0000000E+00
HS11	30.42664	0.0000000E+00
H11	65.85852	0.0000000E+00
HS12	22.32597	0.0000000E+00
H12	48.32461	0.0000000E+00
HS13	186.6665	0.0000000E+00

H13	404.0400	0.0000000E+00
HS14	136.9691	0.0000000E+00
H14	296.4700	0.0000000E+00
HS15	30.42664	0.0000000E+00
H15	65.85852	0.0000000E+00
HS16	22.32597	0.0000000E+00
H16	48.32461	0.0000000E+00
HS17	186.6665	0.0000000E+00
H17	404.0400	0.0000000E+00
HS18	136.9691	0.0000000E+00
H18	296.4700	0.0000000E+00
KT1	0.0000000E+00	0.0000000E+00
KT2	0.0000000E+00	0.0000000E+00
KT3	0.0000000E+00	0.0000000E+00
KT4	0.0000000E+00	0.0000000E+00
KT5	0.0000000E+00	0.0000000E+00
KT6	0.0000000E+00	0.0000000E+00
KT7	0.0000000E+00	0.0000000E+00
KT8	0.0000000E+00	0.0000000E+00
KT9	0.0000000E+00	0.0000000E+00
KT10	0.0000000E+00	0.0000000E+00
KT11	0.0000000E+00	0.0000000E+00

KT12	0.0000000E+00	0.0000000E+00
KT13	0.0000000E+00	0.0000000E+00
KT14	0.0000000E+00	0.0000000E+00
KT15	0.0000000E+00	0.0000000E+00
KT16	0.0000000E+00	0.0000000E+00
KT17	0.0000000E+00	0.0000000E+00
KT18	0.0000000E+00	0.0000000E+00
HT1	404.0400	0.0000000E+00
E2	1.000000	0.0000000E+00
HT2	296.4700	0.0000000E+00
HT3	186.6665	0.0000000E+00
HT4	136.9691	0.0000000E+00
HT5	404.0400	0.0000000E+00
HT6	296.4700	0.0000000E+00
HT7	186.6665	0.0000000E+00
HT8	136.9691	0.0000000E+00
HT9	404.0400	0.0000000E+00
HT10	296.4700	0.0000000E+00
HT11	65.85852	0.0000000E+00
HT12	48.32461	0.0000000E+00
HT13	404.0400	0.0000000E+00
HT14	296.4700	0.0000000E+00

HT15	65.85852	0.0000000E+00
HT16	48.32461	0.0000000E+00
HT17	404.0400	0.0000000E+00
HT18	296.4700	0.0000000E+00
KU1	21897.00	0.0000000E+00
KU2	0.0000000E+00	0.0000000E+00
KU3	0.0000000E+00	0.0000000E+00
KU4	0.0000000E+00	0.0000000E+00
KU5	0.0000000E+00	0.0000000E+00
KU6	0.0000000E+00	0.0000000E+00
KU7	0.0000000E+00	0.0000000E+00
KU8	0.0000000E+00	0.0000000E+00
KU9	0.0000000E+00	0.0000000E+00
KU10	0.0000000E+00	0.0000000E+00
KU11	0.0000000E+00	0.0000000E+00
KU12	4489.871	0.0000000E+00
KU13	0.0000000E+00	0.0000000E+00
KU14	0.0000000E+00	0.0000000E+00
KU15	0.0000000E+00	0.0000000E+00
KU16	0.0000000E+00	0.0000000E+00
KU17	0.0000000E+00	0.0000000E+00
KU18	0.0000000E+00	0.0000000E+00

HU1	186.6665	0.0000000E+00
HU2	136.9691	0.0000000E+00
HU3	86.23991	0.0000000E+00
HU4	63.27974	0.0000000E+00
HU5	186.6665	0.0000000E+00
HU6	136.9691	0.0000000E+00
HU7	86.23991	0.0000000E+00
HU8	63.27974	0.0000000E+00
HU9	186.6665	0.0000000E+00
HU10	136.9691	0.0000000E+00
HU11	30.42664	0.0000000E+00
HU12	22.32597	0.0000000E+00
HU13	186.6665	0.0000000E+00
HU14	136.9691	0.0000000E+00
HU15	30.42664	0.0000000E+00
HU16	22.32597	0.0000000E+00
HU17	186.6665	0.0000000E+00
HU18	136.9691	0.0000000E+00
KV1	0.0000000E+00	0.0000000E+00
KV2	0.0000000E+00	0.0000000E+00
KV3	0.0000000E+00	0.0000000E+00
KV4	0.0000000E+00	0.0000000E+00

KV5	0.0000000E+00	0.0000000E+00
KV6	0.0000000E+00	0.0000000E+00
KV7	0.0000000E+00	0.0000000E+00
KV8	0.0000000E+00	0.0000000E+00
KV9	0.0000000E+00	0.0000000E+00
KV10	0.0000000E+00	0.0000000E+00
KV11	0.0000000E+00	0.0000000E+00
KV12	0.0000000E+00	0.0000000E+00
KV13	0.0000000E+00	0.0000000E+00
KV14	0.0000000E+00	0.0000000E+00
KV15	0.0000000E+00	0.0000000E+00
KV16	0.0000000E+00	0.0000000E+00
KV17	0.0000000E+00	0.0000000E+00
KV18	0.0000000E+00	0.0000000E+00
HV1	404.0400	0.0000000E+00
HV2	296.4700	0.0000000E+00
HV3	186.6665	0.0000000E+00
HV4	136.9691	0.0000000E+00
HV5	404.0400	0.0000000E+00
HV6	296.4700	0.0000000E+00
HV7	186.6665	0.0000000E+00
HV8	136.9691	0.0000000E+00

HV9	404.0400	0.0000000E+00
HV10	296.4700	0.0000000E+00
HV11	65.85852	0.0000000E+00
HV12	48.32461	0.0000000E+00
HV13	404.0400	0.0000000E+00
HV14	296.4700	0.0000000E+00
HV15	65.85852	0.0000000E+00
HV16	48.32461	0.0000000E+00
HV17	404.0400	0.0000000E+00
HV18	296.4700	0.0000000E+00
KW1	0.0000000E+00	0.0000000E+00
KW2	4489.871	0.0000000E+00
KW3	0.0000000E+00	0.0000000E+00
KW4	0.0000000E+00	0.0000000E+00
KW5	0.0000000E+00	0.0000000E+00
KW6	0.0000000E+00	0.0000000E+00
KW7	0.0000000E+00	0.0000000E+00
KW8	0.0000000E+00	0.0000000E+00
KW9	0.0000000E+00	0.0000000E+00
KW10	0.0000000E+00	0.0000000E+00
KW11	0.0000000E+00	0.0000000E+00
KW12	0.0000000E+00	0.0000000E+00

KW13	0.0000000E+00	0.0000000E+00
KW14	0.0000000E+00	0.0000000E+00
KW15	0.0000000E+00	0.0000000E+00
KW16	0.0000000E+00	0.0000000E+00
KW17	0.0000000E+00	0.0000000E+00
KW18	0.0000000E+00	0.0000000E+00
HW1	65.85852	0.0000000E+00
E3	0.1630000	0.0000000E+00
HW2	48.32461	0.0000000E+00
HW3	30.42664	0.0000000E+00
HW4	22.32597	0.0000000E+00
HW5	65.85852	0.0000000E+00
HW6	48.32461	0.0000000E+00
HW7	30.42664	0.0000000E+00
HW8	22.32597	0.0000000E+00
HW9	65.85852	0.0000000E+00
HW10	48.32461	0.0000000E+00
HW11	10.73494	0.0000000E+00
HW12	7.876911	0.0000000E+00
HW13	65.85852	0.0000000E+00
HW14	48.32461	0.0000000E+00
HW15	10.73494	0.0000000E+00

HW16	7.876911	0.0000000E+00
HW17	65.85852	0.0000000E+00
HW18	48.32461	0.0000000E+00
KX1	0.0000000E+00	0.0000000E+00
KX2	0.0000000E+00	0.0000000E+00
KX3	0.0000000E+00	0.0000000E+00
KX4	0.0000000E+00	0.0000000E+00
KX5	0.0000000E+00	0.0000000E+00
KX6	0.0000000E+00	0.0000000E+00
KX7	0.0000000E+00	0.0000000E+00
KX8	0.0000000E+00	0.0000000E+00
KX9	0.0000000E+00	0.0000000E+00
KX10	0.0000000E+00	0.0000000E+00
KX11	0.0000000E+00	0.0000000E+00
KX12	0.0000000E+00	0.0000000E+00
KX13	0.0000000E+00	0.0000000E+00
KX14	0.0000000E+00	0.0000000E+00
KX15	0.0000000E+00	0.0000000E+00
KX16	0.0000000E+00	0.0000000E+00
KX17	0.0000000E+00	0.0000000E+00
KX18	0.0000000E+00	0.0000000E+00
HX1	404.0400	0.0000000E+00

E4	1.000000	0.0000000E+00
HX2	296.4700	0.0000000E+00
HX3	186.6665	0.0000000E+00
HX4	136.9691	0.0000000E+00
HX5	404.0400	0.0000000E+00
HX6	296.4700	0.0000000E+00
HX7	186.6665	0.0000000E+00
HX8	136.9691	0.0000000E+00
HX9	404.0400	0.0000000E+00
HX10	296.4700	0.0000000E+00
HX11	65.85852	0.0000000E+00
HX12	48.32461	0.0000000E+00
HX13	404.0400	0.0000000E+00
HX14	296.4700	0.0000000E+00
HX15	65.85852	0.0000000E+00
HX16	48.32461	0.0000000E+00
HX17	404.0400	0.0000000E+00
HX18	296.4700	0.0000000E+00
KY1	0.0000000E+00	0.0000000E+00
KY2	0.0000000E+00	0.0000000E+00
KY3	0.0000000E+00	0.0000000E+00
KY4	0.0000000E+00	0.0000000E+00

KY5	0.0000000E+00	0.0000000E+00
KY6	0.0000000E+00	0.0000000E+00
KY7	21897.00	0.0000000E+00
KY8	0.0000000E+00	0.0000000E+00
KY9	0.0000000E+00	0.0000000E+00
KY10	0.0000000E+00	0.0000000E+00
KY11	0.0000000E+00	0.0000000E+00
KY12	0.0000000E+00	0.0000000E+00
KY13	0.0000000E+00	0.0000000E+00
KY14	0.0000000E+00	0.0000000E+00
KY15	0.0000000E+00	0.0000000E+00
KY16	0.0000000E+00	0.0000000E+00
KY17	0.0000000E+00	0.0000000E+00
KY18	0.0000000E+00	0.0000000E+00
HY1	65.85852	0.0000000E+00
HY2	48.32461	0.0000000E+00
HY3	30.42664	0.0000000E+00
HY4	22.32597	0.0000000E+00
HY5	65.85852	0.0000000E+00
HY6	48.32461	0.0000000E+00
HY7	30.42664	0.0000000E+00
HY8	22.32597	0.0000000E+00

HY9	65.85852	0.0000000E+00
HY10	48.32461	0.0000000E+00
HY11	10.73494	0.0000000E+00
HY12	7.876911	0.0000000E+00
HY13	65.85852	0.0000000E+00
HY14	48.32461	0.0000000E+00
HY15	10.73494	0.0000000E+00
HY16	7.876911	0.0000000E+00
HY17	65.85852	0.0000000E+00
HY18	48.32461	0.0000000E+00
KZ1	-0.3637979E-11	0.0000000E+00
KZ2	0.0000000E+00	0.0000000E+00
KZ3	0.0000000E+00	0.0000000E+00
KZ4	0.0000000E+00	0.0000000E+00
KZ5	0.0000000E+00	0.0000000E+00
KZ6	0.0000000E+00	0.0000000E+00
KZ7	0.0000000E+00	0.0000000E+00
KZ8	0.0000000E+00	0.0000000E+00
KZ9	0.0000000E+00	0.0000000E+00
KZ10	0.0000000E+00	0.0000000E+00
KZ11	0.0000000E+00	0.0000000E+00
KZ12	0.0000000E+00	0.0000000E+00

KZ13	0.0000000E+00	0.0000000E+00
KZ14	0.0000000E+00	0.0000000E+00
KZ15	0.0000000E+00	0.0000000E+00
KZ16	0.0000000E+00	0.0000000E+00
KZ17	0.0000000E+00	0.0000000E+00
KZ18	0.0000000E+00	0.0000000E+00
HZ1	404.0400	0.0000000E+00
HZ2	296.4700	0.0000000E+00
HZ3	186.6665	0.0000000E+00
HZ4	136.9691	0.0000000E+00
HZ5	404.0400	0.0000000E+00
HZ6	296.4700	0.0000000E+00
HZ7	186.6665	0.0000000E+00
HZ8	136.9691	0.0000000E+00
HZ9	404.0400	0.0000000E+00
HZ10	296.4700	0.0000000E+00
HZ11	65.85852	0.0000000E+00
HZ12	48.32461	0.0000000E+00
HZ13	404.0400	0.0000000E+00
HZ14	296.4700	0.0000000E+00
HZ15	65.85852	0.0000000E+00
HZ16	48.32461	0.0000000E+00

HZ17	404.0400	0.0000000E+00
HZ18	296.4700	0.0000000E+00
GS11	0.0000000E+00	8.352603
GS12	0.0000000E+00	0.0000000E+00
GS21	0.0000000E+00	4.797659
GS22	2221.129	0.0000000E+00
GS31	0.0000000E+00	1.269926
GS41	2221.129	0.0000000E+00
GS51	0.0000000E+00	6.824516
GS61	0.0000000E+00	4.797659
GS71	0.0000000E+00	1.269926
GS81	0.0000000E+00	0.0000000E+00
GS91	0.0000000E+00	8.352603
GS101	0.0000000E+00	4.797659
GS111	0.0000000E+00	0.0000000E+00
GS121	0.0000000E+00	0.0000000E+00
GS131	0.0000000E+00	0.0000000E+00
GS141	0.0000000E+00	4.797659
GS151	0.0000000E+00	0.0000000E+00
GS161	0.0000000E+00	0.0000000E+00
GS171	0.0000000E+00	8.352603
GS181	0.0000000E+00	4.797659

GT11	0.0000000E+00	25.42982
GT12	0.0000000E+00	0.0000000E+00
GT21	0.0000000E+00	16.92896
GT22	0.0000000E+00	0.0000000E+00
GT31	0.0000000E+00	8.352603
GT41	0.0000000E+00	4.797659
GT51	0.0000000E+00	23.90174
GT61	0.0000000E+00	16.92896
GT71	0.0000000E+00	8.352603
GT81	0.0000000E+00	4.797659
GT91	0.0000000E+00	25.42982
GT101	0.0000000E+00	16.92896
GT111	0.0000000E+00	1.528087
GT121	0.0000000E+00	0.7219014
GT131	0.0000000E+00	23.90174
GT141	0.0000000E+00	16.92896
GT151	0.0000000E+00	1.528087
GT161	0.0000000E+00	0.7219014
GT171	0.0000000E+00	25.42982
GT181	0.0000000E+00	16.92896
GU11	0.0000000E+00	8.352603
GU12	21897.00	0.0000000E+00

GU21	0.0000000E+00	4.797659
GU22	0.0000000E+00	0.0000000E+00
GU31	0.0000000E+00	1.269926
GU41	0.0000000E+00	0.0000000E+00
GU51	0.0000000E+00	6.824516
GU61	0.0000000E+00	4.797659
GU71	0.0000000E+00	1.269926
GU81	0.0000000E+00	0.0000000E+00
GU91	0.0000000E+00	8.352603
GU101	0.0000000E+00	4.797659
GU111	0.0000000E+00	0.0000000E+00
GU121	4489.871	0.0000000E+00
GU131	0.0000000E+00	6.824516
GU141	0.0000000E+00	4.797659
GU151	0.0000000E+00	0.0000000E+00
GU161	0.0000000E+00	0.0000000E+00
GU171	0.0000000E+00	8.352603
GU181	0.0000000E+00	4.797659
GV11	0.0000000E+00	25.42982
GV12	0.0000000E+00	0.0000000E+00
GV21	0.0000000E+00	16.92896
GV22	0.0000000E+00	0.0000000E+00

GV31	0.0000000E+00	8.352603
GV41	0.0000000E+00	4.797659
GV51	0.0000000E+00	23.90174
GV61	0.0000000E+00	16.92896
GV71	0.0000000E+00	8.352603
GV81	0.0000000E+00	4.797659
GV91	0.0000000E+00	25.42982
GV101	0.0000000E+00	16.92896
GV111	0.0000000E+00	1.528087
GV121	0.0000000E+00	0.7219014
GV131	0.0000000E+00	23.90174
GV141	0.0000000E+00	16.92896
GV151	0.0000000E+00	1.528087
GV161	0.0000000E+00	0.7219014
GV171	0.0000000E+00	25.42982
GV181	0.0000000E+00	16.92896
GW11	0.0000000E+00	1.528087
GW12	0.0000000E+00	0.0000000E+00
GW21	0.0000000E+00	0.7219014
GW22	4489.871	0.0000000E+00
GW31	0.0000000E+00	0.0000000E+00
GW41	0.0000000E+00	0.0000000E+00

GW51	0.0000000E+00	0.0000000E+00
GW61	0.0000000E+00	0.7219014
GW71	0.0000000E+00	0.0000000E+00
GW81	0.0000000E+00	0.0000000E+00
GW91	0.0000000E+00	1.528087
GW101	0.0000000E+00	0.7219014
GW111	0.0000000E+00	0.0000000E+00
GW121	0.0000000E+00	0.0000000E+00
GW131	0.0000000E+00	0.2044058E-06
GW141	0.0000000E+00	0.7219014
GW151	0.0000000E+00	0.0000000E+00
GW161	0.0000000E+00	0.0000000E+00
GW171	0.0000000E+00	1.528087
GW181	0.0000000E+00	0.7219014
GX11	0.0000000E+00	25.42982
GX12	0.0000000E+00	0.0000000E+00
GX21	0.0000000E+00	16.92896
GX22	0.0000000E+00	0.0000000E+00
GX31	0.0000000E+00	8.352603
GX41	0.0000000E+00	4.797659
GX51	0.0000000E+00	23.90174
GX61	0.0000000E+00	16.92896

GX71	0.0000000E+00	8.352603
GX81	0.0000000E+00	4.797659
GX91	0.0000000E+00	25.42982
GX101	0.0000000E+00	16.92896
GX111	0.0000000E+00	1.528087
GX121	0.0000000E+00	0.7219014
GX131	0.0000000E+00	23.90174
GX141	0.0000000E+00	16.92896
GX151	0.0000000E+00	1.528087
GX161	0.0000000E+00	0.7219014
GX171	0.0000000E+00	25.42982
GX181	0.0000000E+00	16.92896
GY11	0.0000000E+00	1.528087
GY12	0.0000000E+00	0.0000000E+00
GY21	0.0000000E+00	0.7219014
GY22	0.0000000E+00	0.0000000E+00
GY31	0.0000000E+00	0.0000000E+00
GY41	0.0000000E+00	0.8317070E-07
GY51	0.0000000E+00	0.0000000E+00
GY61	0.0000000E+00	0.7219014
GY71	21897.00	0.0000000E+00
GY81	0.0000000E+00	0.8317070E-07

GY91	0.0000000E+00	1.528087
GY101	0.0000000E+00	0.7219014
GY111	0.0000000E+00	1.817104
GY121	0.0000000E+00	0.0000000E+00
GY131	0.0000000E+00	0.0000000E+00
GY141	0.0000000E+00	0.7219014
GY151	0.0000000E+00	1.817104
GY161	0.0000000E+00	0.0000000E+00
GY171	0.0000000E+00	1.528087
GY181	0.0000000E+00	0.7219014
GZ11	0.0000000E+00	25.42982
GZ12	-0.3637979E-11	0.0000000E+00
GZ21	0.0000000E+00	16.92896
GZ22	0.0000000E+00	0.0000000E+00
GZ31	0.0000000E+00	8.352603
GZ41	0.0000000E+00	4.797659
GZ51	0.0000000E+00	23.90174
GZ61	0.0000000E+00	16.92896
GZ71	0.0000000E+00	8.352603
GZ81	0.0000000E+00	4.797659
GZ91	0.0000000E+00	25.42982
GZ101	0.0000000E+00	16.92896

GZ111	0.0000000E+00	1.528087
GZ121	0.0000000E+00	0.7219014
GZ131	0.0000000E+00	23.90174
GZ141	0.0000000E+00	16.92896
GZ151	0.0000000E+00	1.528087
GZ161	0.0000000E+00	0.7219014
GZ171	0.0000000E+00	25.42982
GZ181	0.0000000E+00	16.92896
G1	28608.00	0.0000000E+00
HG1	31.70600	0.0000000E+00
HOVERALL	31.70600	0.0000000E+00

Row	Slack or Surplus	Dual Price
1	178178.1	-1.000000
2	0.0000000E+00	0.0000000E+00
3	0.0000000E+00	-0.6923009
4	0.0000000E+00	-1.500000
5	0.0000000E+00	-2.192301
6	0.0000000E+00	1.528087
7	0.0000000E+00	-0.6923009
8	0.0000000E+00	-1.500000
9	0.0000000E+00	-2.192301

10	0.0000000E+00	0.0000000E+00
11	0.0000000E+00	-0.6923009
12	0.0000000E+00	-5.000000
13	0.0000000E+00	-5.692301
14	0.0000000E+00	1.528087
15	0.0000000E+00	-0.6923009
16	0.0000000E+00	-5.000000
17	0.0000000E+00	-5.692301
18	0.0000000E+00	0.0000000E+00
19	0.0000000E+00	-0.6923009
20	0.0000000E+00	1.500000
21	0.0000000E+00	2.192301
22	0.0000000E+00	3.000000
23	0.0000000E+00	3.692301
24	0.0000000E+00	-0.2808714E-01
25	0.0000000E+00	2.192301
26	0.0000000E+00	3.000000
27	0.0000000E+00	3.692301
28	0.0000000E+00	1.500000
29	0.0000000E+00	2.192301
30	0.0000000E+00	6.500000
31	0.0000000E+00	7.192301

32	0.0000000E+00	-0.2808714E-01
33	0.0000000E+00	2.192301
34	0.0000000E+00	6.500000
35	0.0000000E+00	7.192301
36	0.0000000E+00	1.500000
37	0.0000000E+00	2.192301
38	0.0000000E+00	0.0000000E+00
39	0.0000000E+00	-87.69802
40	0.0000000E+00	0.0000000E+00
41	0.0000000E+00	-189.8226
42	0.0000000E+00	0.0000000E+00
43	0.0000000E+00	0.0000000E+00
44	0.0000000E+00	0.0000000E+00
45	0.0000000E+00	0.0000000E+00
46	0.0000000E+00	0.0000000E+00
47	0.0000000E+00	0.0000000E+00
48	0.0000000E+00	0.0000000E+00
49	0.0000000E+00	0.0000000E+00
50	0.0000000E+00	0.0000000E+00
51	0.0000000E+00	0.0000000E+00
52	0.0000000E+00	0.0000000E+00
53	0.0000000E+00	0.0000000E+00

54	0.0000000E+00	0.0000000E+00
55	0.0000000E+00	0.0000000E+00
56	0.0000000E+00	0.0000000E+00
57	0.0000000E+00	0.6923009
58	0.0000000E+00	1.500000
59	0.0000000E+00	2.192301
60	0.0000000E+00	-1.528087
61	0.0000000E+00	0.6923009
62	0.0000000E+00	1.500000
63	0.0000000E+00	2.192301
64	0.0000000E+00	0.0000000E+00
65	0.0000000E+00	0.6923009
66	0.0000000E+00	5.000000
67	0.0000000E+00	5.692301
68	0.0000000E+00	-1.528087
69	0.0000000E+00	0.6923009
70	0.0000000E+00	5.000000
71	0.0000000E+00	5.692301
72	0.0000000E+00	0.0000000E+00
73	0.0000000E+00	0.6923009
74	0.0000000E+00	0.0000000E+00
75	0.0000000E+00	0.0000000E+00

76	0.0000000E+00	0.0000000E+00
77	0.0000000E+00	0.0000000E+00
78	0.0000000E+00	0.0000000E+00
79	0.0000000E+00	0.0000000E+00
80	0.0000000E+00	0.0000000E+00
81	0.0000000E+00	0.0000000E+00
82	0.0000000E+00	0.0000000E+00
83	0.0000000E+00	0.0000000E+00
84	0.0000000E+00	0.0000000E+00
85	0.0000000E+00	0.0000000E+00
86	0.0000000E+00	0.0000000E+00
87	0.0000000E+00	0.0000000E+00
88	0.0000000E+00	0.0000000E+00
89	0.0000000E+00	0.0000000E+00
90	0.0000000E+00	0.0000000E+00
91	0.0000000E+00	0.0000000E+00
92	0.0000000E+00	1.500000
93	0.0000000E+00	2.192301
94	0.0000000E+00	3.000000
95	0.0000000E+00	3.692301
96	0.0000000E+00	-0.2808714E-01
97	0.0000000E+00	2.192301

98	0.0000000E+00	3.000000
99	0.0000000E+00	3.692301
100	0.0000000E+00	1.500000
101	0.0000000E+00	2.192301
102	0.0000000E+00	6.500000
103	0.0000000E+00	7.192301
104	0.0000000E+00	-0.2808714E-01
105	0.0000000E+00	2.192301
106	0.0000000E+00	6.500000
107	0.0000000E+00	7.192301
108	0.0000000E+00	1.500000
109	0.0000000E+00	2.192301
110	0.0000000E+00	-305.0327
111	0.0000000E+00	0.0000000E+00
112	0.0000000E+00	0.0000000E+00
113	0.0000000E+00	0.0000000E+00
114	0.0000000E+00	0.0000000E+00
115	0.0000000E+00	0.0000000E+00
116	0.0000000E+00	0.0000000E+00
117	0.0000000E+00	0.0000000E+00
118	0.0000000E+00	0.0000000E+00
119	0.0000000E+00	0.0000000E+00

120	0.0000000E+00	0.0000000E+00
121	0.0000000E+00	-383.7144
122	0.0000000E+00	0.0000000E+00
123	0.0000000E+00	0.0000000E+00
124	0.0000000E+00	0.0000000E+00
125	0.0000000E+00	0.0000000E+00
126	0.0000000E+00	0.0000000E+00
127	0.0000000E+00	0.0000000E+00
128	0.0000000E+00	0.0000000E+00
129	0.0000000E+00	0.6923009
130	0.0000000E+00	1.500000
131	0.0000000E+00	2.192301
132	0.0000000E+00	-1.528087
133	0.0000000E+00	0.6923009
134	0.0000000E+00	1.500000
135	0.0000000E+00	2.192301
136	0.0000000E+00	0.0000000E+00
137	0.0000000E+00	0.6923009
138	0.0000000E+00	5.000000
139	0.0000000E+00	5.692301
140	0.0000000E+00	-1.528087
141	0.0000000E+00	0.6923009

142	0.0000000E+00	5.000000
143	0.0000000E+00	5.692301
144	0.0000000E+00	0.0000000E+00
145	0.0000000E+00	0.6923009
146	0.0000000E+00	0.0000000E+00
147	0.0000000E+00	0.0000000E+00
148	0.0000000E+00	0.0000000E+00
149	0.0000000E+00	0.0000000E+00
150	0.0000000E+00	0.0000000E+00
151	0.0000000E+00	0.0000000E+00
152	0.0000000E+00	0.0000000E+00
153	0.0000000E+00	0.0000000E+00
154	0.0000000E+00	0.0000000E+00
155	0.0000000E+00	0.0000000E+00
156	0.0000000E+00	0.0000000E+00
157	0.0000000E+00	0.0000000E+00
158	0.0000000E+00	0.0000000E+00
159	0.0000000E+00	0.0000000E+00
160	0.0000000E+00	0.0000000E+00
161	0.0000000E+00	0.0000000E+00
162	0.0000000E+00	0.0000000E+00
163	0.0000000E+00	0.0000000E+00

164	0.0000000E+00	5.000000
165	0.0000000E+00	5.692301
166	0.0000000E+00	6.500000
167	0.0000000E+00	7.192301
168	0.0000000E+00	3.471913
169	0.0000000E+00	5.692301
170	0.0000000E+00	6.500000
171	0.0000000E+00	7.192301
172	0.0000000E+00	5.000000
173	0.0000000E+00	5.692301
174	0.0000000E+00	8.182896
175	0.0000000E+00	8.427150
176	0.0000000E+00	3.471913
177	0.0000000E+00	5.692301
178	0.0000000E+00	8.182896
179	0.0000000E+00	8.427150
180	0.0000000E+00	5.000000
181	0.0000000E+00	5.692301
182	0.0000000E+00	0.0000000E+00
183	0.0000000E+00	-177.2760
184	0.0000000E+00	0.0000000E+00
185	0.0000000E+00	0.0000000E+00

186	0.0000000E+00	0.0000000E+00
187	0.0000000E+00	0.0000000E+00
188	0.0000000E+00	0.0000000E+00
189	0.0000000E+00	0.0000000E+00
190	0.0000000E+00	0.0000000E+00
191	0.0000000E+00	0.0000000E+00
192	0.0000000E+00	0.0000000E+00
193	0.0000000E+00	0.0000000E+00
194	0.0000000E+00	0.0000000E+00
195	0.0000000E+00	0.0000000E+00
196	0.0000000E+00	0.0000000E+00
197	0.0000000E+00	0.0000000E+00
198	0.0000000E+00	0.0000000E+00
199	0.0000000E+00	0.0000000E+00
200	0.0000000E+00	0.0000000E+00
201	0.0000000E+00	0.6923009
202	0.0000000E+00	1.500000
203	0.0000000E+00	2.192301
204	0.0000000E+00	-1.528087
205	0.0000000E+00	0.6923009
206	0.0000000E+00	1.500000
207	0.0000000E+00	2.192301

208	0.0000000E+00	0.0000000E+00
209	0.0000000E+00	0.6923009
210	0.0000000E+00	5.000000
211	0.0000000E+00	5.692301
212	0.0000000E+00	-1.528087
213	0.0000000E+00	0.6923009
214	0.0000000E+00	5.000000
215	0.0000000E+00	5.692301
216	0.0000000E+00	0.0000000E+00
217	0.0000000E+00	0.6923009
218	0.0000000E+00	0.0000000E+00
219	0.0000000E+00	0.0000000E+00
220	0.0000000E+00	0.0000000E+00
221	0.0000000E+00	0.0000000E+00
222	0.0000000E+00	0.0000000E+00
223	0.0000000E+00	0.0000000E+00
224	0.0000000E+00	0.0000000E+00
225	0.0000000E+00	0.0000000E+00
226	0.0000000E+00	0.0000000E+00
227	0.0000000E+00	0.0000000E+00
228	0.0000000E+00	0.0000000E+00
229	0.0000000E+00	0.0000000E+00

230	0.0000000E+00	0.0000000E+00
231	0.0000000E+00	0.0000000E+00
232	0.0000000E+00	0.0000000E+00
233	0.0000000E+00	0.0000000E+00
234	0.0000000E+00	0.0000000E+00
235	0.0000000E+00	0.0000000E+00
236	0.0000000E+00	5.000000
237	0.0000000E+00	5.692301
238	0.0000000E+00	6.500000
239	0.0000000E+00	7.192301
240	0.0000000E+00	3.471913
241	0.0000000E+00	5.692301
242	0.0000000E+00	6.500000
243	0.0000000E+00	7.192301
244	0.0000000E+00	5.000000
245	0.0000000E+00	5.692301
246	0.0000000E+00	10.00000
247	0.0000000E+00	8.427150
248	0.0000000E+00	3.471913
249	0.0000000E+00	5.692301
250	0.0000000E+00	10.00000
251	0.0000000E+00	8.427150

252	0.0000000E+00	5.000000
253	0.0000000E+00	5.692301
254	0.0000000E+00	0.0000000E+00
255	0.0000000E+00	0.0000000E+00
256	0.0000000E+00	0.0000000E+00
257	0.0000000E+00	0.0000000E+00
258	0.0000000E+00	0.0000000E+00
259	0.0000000E+00	0.0000000E+00
260	0.0000000E+00	-1871.366
261	0.0000000E+00	0.0000000E+00
262	0.0000000E+00	0.0000000E+00
263	0.0000000E+00	0.0000000E+00
264	0.0000000E+00	0.0000000E+00
265	0.0000000E+00	0.0000000E+00
266	0.0000000E+00	0.0000000E+00
267	0.0000000E+00	0.0000000E+00
268	0.0000000E+00	0.0000000E+00
269	0.0000000E+00	0.0000000E+00
270	0.0000000E+00	0.0000000E+00
271	0.0000000E+00	0.0000000E+00
272	0.0000000E+00	0.0000000E+00
273	0.0000000E+00	0.6923009

274	0.0000000E+00	1.500000
275	0.0000000E+00	2.192301
276	0.0000000E+00	-1.528087
277	0.0000000E+00	0.6923009
278	0.0000000E+00	1.500000
279	0.0000000E+00	2.192301
280	0.0000000E+00	0.0000000E+00
281	0.0000000E+00	0.6923009
282	0.0000000E+00	5.000000
283	0.0000000E+00	5.692301
284	0.0000000E+00	-1.528087
285	0.0000000E+00	0.6923009
286	0.0000000E+00	5.000000
287	0.0000000E+00	5.692301
288	0.0000000E+00	0.0000000E+00
289	0.0000000E+00	0.6923009
290	0.0000000E+00	0.0000000E+00
291	0.0000000E+00	0.0000000E+00
292	0.0000000E+00	0.0000000E+00
293	0.0000000E+00	0.0000000E+00
294	0.0000000E+00	0.0000000E+00
295	0.0000000E+00	0.0000000E+00

296	0.0000000E+00	0.0000000E+00
297	0.0000000E+00	0.0000000E+00
298	0.0000000E+00	0.0000000E+00
299	0.0000000E+00	0.0000000E+00
300	0.0000000E+00	0.0000000E+00
301	0.0000000E+00	0.0000000E+00
302	0.0000000E+00	0.0000000E+00
303	0.0000000E+00	0.0000000E+00
304	0.0000000E+00	0.0000000E+00
305	0.0000000E+00	0.0000000E+00
306	0.0000000E+00	0.0000000E+00
307	0.0000000E+00	0.0000000E+00
308	0.0000000E+00	-1.500000
309	0.0000000E+00	-2.192301
310	0.0000000E+00	-3.000000
311	0.0000000E+00	-3.692301
312	0.0000000E+00	0.2808714E-01
313	0.0000000E+00	-2.192301
314	0.0000000E+00	-3.000000
315	0.0000000E+00	-3.692301
316	0.0000000E+00	-1.500000
317	0.0000000E+00	-2.192301

318	0.0000000E+00	-6.500000
319	0.0000000E+00	-7.192301
320	0.0000000E+00	6.852602
321	0.0000000E+00	-2.192301
322	0.0000000E+00	-6.500000
323	0.0000000E+00	-7.192301
324	0.0000000E+00	-1.500000
325	0.0000000E+00	-2.192301
326	0.0000000E+00	0.0000000E+00
327	0.0000000E+00	-0.6923009
328	0.0000000E+00	-1.500000
329	0.0000000E+00	-2.192301
330	0.0000000E+00	1.528087
331	0.0000000E+00	-0.6923009
332	0.0000000E+00	-1.500000
333	0.0000000E+00	-2.192301
334	0.0000000E+00	0.0000000E+00
335	0.0000000E+00	-0.6923009
336	0.0000000E+00	-5.000000
337	0.0000000E+00	-5.692301
338	0.0000000E+00	1.528087
339	0.0000000E+00	-0.6923009

340	0.0000000E+00	-5.000000
341	0.0000000E+00	-5.692301
342	0.0000000E+00	0.0000000E+00
343	0.0000000E+00	-0.6923009
344	0.0000000E+00	-1.500000
345	0.0000000E+00	-2.192301
346	0.0000000E+00	-3.000000
347	0.0000000E+00	-3.692301
348	0.0000000E+00	0.2808714E-01
349	0.0000000E+00	-2.192301
350	0.0000000E+00	-3.000000
351	0.0000000E+00	-3.692301
352	0.0000000E+00	-1.500000
353	0.0000000E+00	-2.192301
354	0.0000000E+00	-6.500000
355	0.0000000E+00	-7.192301
356	0.0000000E+00	0.2808714E-01
357	0.0000000E+00	-2.192301
358	0.0000000E+00	-6.500000
359	0.0000000E+00	-7.192301
360	0.0000000E+00	-1.500000
361	0.0000000E+00	-2.192301

362	0.0000000E+00	0.0000000E+00
363	0.0000000E+00	-0.6923009
364	0.0000000E+00	-1.500000
365	0.0000000E+00	-2.192301
366	0.0000000E+00	1.528087
367	0.0000000E+00	-0.6923009
368	0.0000000E+00	-1.500000
369	0.0000000E+00	-2.192301
370	0.0000000E+00	0.0000000E+00
371	0.0000000E+00	-0.6923009
372	0.0000000E+00	-5.000000
373	0.0000000E+00	-5.692301
374	0.0000000E+00	1.528087
375	0.0000000E+00	-0.6923009
376	0.0000000E+00	-5.000000
377	0.0000000E+00	-5.692301
378	0.0000000E+00	0.0000000E+00
379	0.0000000E+00	-0.6923009
380	0.0000000E+00	-5.000000
381	0.0000000E+00	-5.692301
382	0.0000000E+00	-6.500000
383	0.0000000E+00	-7.192301

384	0.0000000E+00	-3.471913
385	0.0000000E+00	-5.692301
386	0.0000000E+00	-6.500000
387	0.0000000E+00	-7.192301
388	0.0000000E+00	-5.000000
389	0.0000000E+00	-5.692301
390	0.0000000E+00	-8.182896
391	0.0000000E+00	-8.427150
392	0.0000000E+00	-3.471913
393	0.0000000E+00	-5.692301
394	0.0000000E+00	-8.182896
395	0.0000000E+00	-8.427150
396	0.0000000E+00	-5.000000
397	0.0000000E+00	-5.692301
398	0.0000000E+00	0.0000000E+00
399	0.0000000E+00	-0.6923009
400	0.0000000E+00	-1.500000
401	0.0000000E+00	-2.192301
402	0.0000000E+00	1.528087
403	0.0000000E+00	-0.6923009
404	0.0000000E+00	-1.500000
405	0.0000000E+00	-2.192301

406	0.0000000E+00	0.0000000E+00
407	0.0000000E+00	-0.6923009
408	0.0000000E+00	-5.000000
409	0.0000000E+00	-5.692301
410	0.0000000E+00	1.528087
411	0.0000000E+00	-0.6923009
412	0.0000000E+00	-5.000000
413	0.0000000E+00	-5.692301
414	0.0000000E+00	0.0000000E+00
415	0.0000000E+00	-0.6923009
416	0.0000000E+00	-5.000000
417	0.0000000E+00	-5.692301
418	0.0000000E+00	-6.500000
419	0.0000000E+00	-7.192301
420	0.0000000E+00	-3.471913
421	0.0000000E+00	-5.692301
422	0.0000000E+00	-6.500000
423	0.0000000E+00	-7.192301
424	0.0000000E+00	-5.000000
425	0.0000000E+00	-5.692301
426	0.0000000E+00	-10.00000
427	0.0000000E+00	-8.427150

428	0.0000000E+00	-3.471913
429	0.0000000E+00	-5.692301
430	0.0000000E+00	-10.00000
431	0.0000000E+00	-8.427150
432	0.0000000E+00	-5.000000
433	0.0000000E+00	-5.692301
434	0.0000000E+00	0.0000000E+00
435	0.0000000E+00	-0.6923009
436	0.0000000E+00	-1.500000
437	0.0000000E+00	-2.192301
438	0.0000000E+00	1.528087
439	0.0000000E+00	-0.6923009
440	0.0000000E+00	-1.500000
441	0.0000000E+00	-2.192301
442	0.0000000E+00	0.0000000E+00
443	0.0000000E+00	-0.6923009
444	0.0000000E+00	-5.000000
445	0.0000000E+00	-5.692301
446	0.0000000E+00	1.528087
447	0.0000000E+00	-0.6923009
448	0.0000000E+00	-5.000000
449	0.0000000E+00	-5.692301

450	0.0000000E+00	0.0000000E+00
451	0.0000000E+00	-0.6923009
452	0.0000000E+00	9.100327
453	0.0000000E+00	-0.8546221E-01
454	0.0000000E+00	-1.500000
455	0.0000000E+00	-2.192301
456	0.0000000E+00	0.0000000E+00
457	0.0000000E+00	-0.6923009
458	0.0000000E+00	-1.500000
459	0.0000000E+00	-2.192301
460	0.0000000E+00	0.0000000E+00
461	0.0000000E+00	-0.6923009
462	0.0000000E+00	-5.000000
463	0.0000000E+00	-5.692301
464	0.0000000E+00	0.0000000E+00
465	0.0000000E+00	-0.6923009
466	0.0000000E+00	-5.000000
467	0.0000000E+00	-5.692301
468	0.0000000E+00	0.0000000E+00
469	0.0000000E+00	-0.6923009
470	0.0000000E+00	0.0000000E+00
471	0.0000000E+00	87.69802

472	0.0000000E+00	0.0000000E+00
473	0.0000000E+00	0.0000000E+00
474	0.0000000E+00	305.0327
475	0.0000000E+00	0.0000000E+00
476	0.0000000E+00	0.0000000E+00
477	0.0000000E+00	0.0000000E+00
478	0.0000000E+00	0.0000000E+00
479	0.0000000E+00	177.2760
480	0.0000000E+00	0.0000000E+00
481	0.0000000E+00	0.0000000E+00
482	0.0000000E+00	0.0000000E+00
483	0.0000000E+00	0.0000000E+00
484	0.0000000E+00	0.0000000E+00
485	0.0000000E+00	0.0000000E+00
486	0.0000000E+00	2444.903
487	0.0000000E+00	-6.390662
488	0.0000000E+00	-5.698362
489	0.0000000E+00	-6.390662
490	0.0000000E+00	-140.9251
491	0.0000000E+00	-69.41248
492	0.0000000E+00	-30829.13
493	0.0000000E+00	-26386.87

494	0.0000000E+00	-193787.9
495	0.0000000E+00	0.0000000E+00
496	0.0000000E+00	-401878.3
497	0.0000000E+00	0.0000000E+00
498	0.0000000E+00	2451.168

VITA

Dustin Ashley Harell, 6497 NE Alder St., Apt. C, Hillsboro, OR 97124

Education

Ph.D. in Chemical Engineering, May, 2004
Texas A&M University, College Station, TX
GPA: 3.7 Overall

B.S. in Chemical Engineering, May, 2000
Michigan Technological University, Houghton, MI
GPA: 3.63 Overall

Experience

Graduate Research/Teaching Assistant (09/02 – Present)
Texas A&M University, College Station, TX

- Developing new process synthesis and integration methodologies for resource conservation, using heat pipes in heat exchange networks, and cogeneration targeting

Graduate Research/Teaching Assistant (08/00 – 05/02)
Auburn University, Auburn, AL

- Taught Aspen Engineering Suite in senior design laboratory

Presentations

Harell D., and El-Halwagi M. "Design Techniques and Software Development for Cogeneration Targeting with Mass and Energy Integration," AIChE Spring National Meeting, March 31, 2003

Harell D., and El-Halwagi M. "Thermal Integration & Optimization," Prospector XI Workshop: Compact Mobile Hybrid Radar Systems, Park City, UT, March, 2001

Publications

El-Halwagi M. M., Gabriel F., and Harell D. "Rigorous Graphical Targeting for Resource Conservation via Material Recycle/Reuse Networks," Ind. Eng. Chem. Res., 2003, 42(19) pp 4319-4328.

Xiaoyun, Q., Gabriel, F., Harell D., and El-Halwagi, M. "Algebraic Techniques for Property Integration via Componentless Design," accepted for publication to Ind. Eng. Chem. Res.

Kazantzi V., Qin X., Gabriel F., Harell D., and El-Halwagi M. M., "Property-Based Integration for Sustainable Development," accepted for publication to ESCAPE-14.