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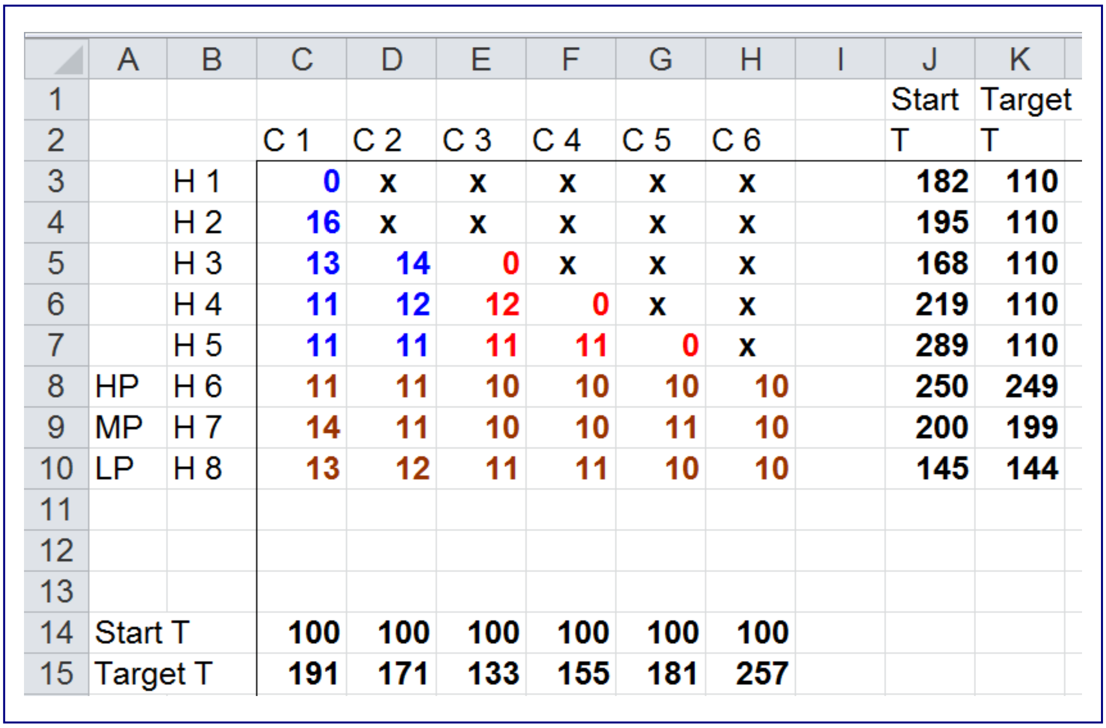

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5		H 3	13	14	0	x	x	x		168	110
6		H 4	11	12	12	0	x	x		219	110
7		H 5	11	11	11	11	0	x		289	110
8	HP	H 6	11	11	10	10	10	10		250	249
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Critical evaluation of an automated tool for heat exchanger network retrofits based on pinch analysis and the Matrix method

Master's Thesis within the Sustainable Energy Systems program

YANN LE STER & BERNHARD NOWICKI

Department of Energy and Environment
Division of Heat and Power Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013

MASTER'S THESIS

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Cover:
Example of matrix representation of a heat exchanger network in the program Matrix.xla

Chalmers Reproservice
Göteborg, Sweden 2013

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ABSTRACT

The current climate change concern comes with new energy efficiency regulations. In order to reach these new targets but also to get a more profitable process, plants have to reconsider the design of their heat exchanger networks to reduce heat losses. One way to proceed consists of retrofitting the network using the Matrix method in order to get the cheapest solution achieving a defined level of heat savings. The software Matrix.xla has been developed to run such a method. The main task of this thesis is to analyze the accuracy of the results given by the method and the software. The theoretical methodology behind the Matrix method is explained. The working procedure of program Matrix.xla is enlightened and tested on specific examples to point out several issues. Among these concerns, merging of the final solution, introduction of split streams and handling utility streams are further investigated. A complete solution is produced for the merging. However, given the complexity of the splitting issue, only one specific solution is developed together with some highlights of how to proceed for a general one. Concerning the utilities, a complete solution is elaborated. Nevertheless, this solution can be pushed further by modifying some concepts inside the Matrix method. Several ideas explaining how to proceed in this direction are described. This work brings a better understanding of how a retrofit is identified by the automated Matrix method tool and brings solutions to improve its and the Matrix method's routine. This is done in order to increase the applicability and reliability of the Matrix method and the automated tool to identify better retrofit solutions.

Key words:

Pinch analysis, Matrix method, Retrofit, Heat exchanger network, Stream splits.

Kritisk utvärdering av ett automatiserat verktyg för pinch analys med matrismetoden
Examensarbete inom masterprogrammet *Sustainable Energy Systems*
YANN LE STER & BERNHARD NOWICKI
Institutionen för Energi och Miljö
Avdelningen för Värmeteknik och maskinlära
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SAMMANFATTNING

Den nuvarande problematiken med världens klimatändring har medfört nya regleringar för en effektivisering av energiförbrukningen. För att kunna uppfylla dessa nya krav men även få en lönsammare process, så har industrier övervägt sina konstruktioner av värmeväxlarnätverk på nytt för att minska sina värmeförluster. Ett tillvägagångssätt är att göra en retrofit av sitt nätverk genom att använda matrismetoden för att få den billigaste lösningen för en fastställd nivå på sina värmebesparingar. Programvaran Matrix.xla har utvecklats för att tillämpa denna metod och huvudsyftet med denna avhandling är att analysera noggrannheten på resultaten från denna programvara jämte metoden. Den teoretiska metodiken för matrismetoden och programvaran förklaras. Arbetsgången för programvaran Matrix.xla frambringas och provkörs på specifika exempel för att identifiera och peka ut olika bekymmer med programvaran. Bland dessa problem görs en vidareutredning utav en sammanfogning av den slutgiltiga lösningen, en introduktion av strömdelningar samt metodens hantering utav externa uppvärmnings och nedkylningsströmmar. En komplett lösning för sammanfogningen färdigställs. På grund av tidsbristen och komplexiteten utav strömdelnings problemet dock, framställs bara en specifik lösning för detta tillsammans med indikationer för en fortsatt utveckling av en generell lösning. Angående uppvärmnings och nedkylningsströmmarna så utarbetas en komplett fungerande lösning. Icke desto mindre kan denna lösning utvecklas genom en modifiering av koncepten i matrismetoden. Flera idéer som förklarar hur fortsättandet i den här riktningen bör ske beskrivs. Det här arbetet ger en bättre förståelse för hur en retrofit identifieras utav den automatiserade matrismetoden, samt ger lösningar för hur denna rutin ska förbättras för att utöka tillämpligheten och tillförlitligheten av metoden och därtill även identifiera bättre retrofit lösningar.

Nyckelord:

Pinchanalys, Matrismetoden, Retrofit, Värmeväxlarnätverk.

Contents

Preface

In this study, tests have been performed with the software Matrix.xla and Pro-Pi which both are Excel add-ins written in Visual Basic. The tests have been carried out from January 2013 to June 2013. The work is a part of continuous improvement of modelling tools at the Department of Energy and Environment, Division of Heat and Power Technology, Chalmers University of Technology, Sweden.

This part of the project has been carried out with Doctor Elin Svensson as a supervisor and Professor Thore Berntsson as examiner. All tests have been carried out at the division of Heat and Power Technology at Chalmers University of Technology. The cooperation with the Pinexo^{TM} project has been very appreciated especially in the first steps of the project to identify the issues at stakes. We would also like to thank Per-Åke Franck at CIT Industriell Energi AB for his co-operation and involvement.

Finally, it should be noted that the tests could never have been conducted successfully without the sense of high quality and professionalism of the laboratory staff and in particular Elin Svensson.

Göteborg, June 2013

Yann Le Ster and Bernhard Nowicki.

Notations

Roman upper case letters

A	Area of a heat exchanger, m^2
$Aadd$	Fixed investment cost for adding area to an existing HEX, m^2
$Afast$	Total area fixed heat exchanger investment cost of a match, m^2
$Afast1$	Fixed investment cost for new HEX or adding area to an existing HEX, m^2
$Afast2$	Additional fixed investment cost for a specific match, m^2
$A_{HX,above}$	Area of HEX in solution given by the MM above pinch, m^2
$Anew$	Fixed investment cost for new heat exchanger, m^2
Ai	Additional area, m^2
$A_{init,HX}$	Initial area of a HEX before retrofit), m^2
$A_{i,saved}$	Area of HEX i that has been saved in computer's memory, m^2
$\mathrm{A_{min}}$	Minimum area required by the network, m^2
Ce	Electricity cost for motor (pipe), $/kWh
$Celi$	Electricity cost for motor (inside), $/kWh
$Celo$	Electricity cost for motor (outside), $/kWh
C	Power constant for motor cost (pipe)
Ca	Constant in heat exchanger area cost
$cArea$	Additional area cost, $
$\mathrm{C_i}$	Cold stream i
CiM	Power constant in motor cost (inside HEX)
CL	Constant in pipe cost
CM	Constant in motor cost (pipe)
CMi	Constant in motor cost (inside heat exchanger)
CMo	Constant in motor cost (outside heat exchanger)
Cp	Specific heat, J/kg.K
$C_{p,c}$	Specific heat cold stream, J/kg.K
$C_{p,h}$	Specific heat hot stream, J/kg.K
$C_{Tot\,Area}$	Total area cost, $
CW	Cold Water
D_h	Hydraulic diameter, m
Di	Pipe intern diameter, m
D_{i1}	Internal diameter of HEX 1 tube, m
D_o	External diameter of a concentric tube HEX, m
DT	Temperature difference,K
$\Delta \mathrm{T}$	Temperature difference,K
ΔT_c	Temperature difference between inlet and outlet of HEX for cold stream, K

ΔT_h	Temperature difference between inlet and outlet of HEX for hot stream, K
ΔT_{lm}	Log mean temperature difference
ΔT_{min}	Minimum temperature difference, K
ΔT_{global}	Global temperature difference, K
ΔT_{global}^{min}	Global minimum temperature difference, K
ΔH	Variation of enthalpy, kJ/kg
F	Mass flow, kg/s
F_c	Mass flow cold stream, kg/s
FC_p	Heat flow capacity, kW/K
$FC_{p,in}$	Heat flow capacity of a stream going from outside to the pinch, kW/K
$FC_{p,out}$	Heat flow capacity of a stream going from the pinch to outside, kW/K
F_h	Mass flow hot stream, kg/s
GCC	Grand Composite Curve
HEN	Heat Exchanger Network
HEX	Heat Exchanger
H_i	Hot stream i
HP	High Pressure
HEX	Heat Exchanger
IES	Industrial Energy Systems
L	Piping distance between streams, m
LP	Low Pressure
MER	Maximum Energy Recovery
MM	Matrix Method
MP	Medium Pressure
N_{cold}	Number of cold streams
N_{hot}	Number of hot streams
N_{u_D}	Nusselt number outside HEX tube
N_{u_i}	Nusselt number inside HEX tube
P	Pressure, Pa
Pi	Pressure (inside HEX), Pa
$Pifree$	Free available pressure drop (inside), Pa
Po	Pressure (outside HEX), Pa
Pofree	Free available pressure drop (outside), Pa
Pr	Prandtl number
Q	Heat load, W
Q_{bef}	Real exchanged heat load of HEX (based on ΔT_{lm} and UA), W
$Q_{C,min}$	Minimum cold utility demand, W
$Q_{H,min}$	Minimum hot utility demand, W
Q_{HX}	Load of heat exchanger, W
Q_{max}	Maximum possible heat load of a HEX, W
Q_{rest}	Remaining heat load on a stream, W
Q_{save}	Potential energy savings, W
Q_{tot}	Total heat load of a stream, W
$Q_{utilities}$	Utility demand, W

Qwx	Heat load of a HEX, W
rA	Annuity factor for HEX area, year^{-1}
Re_D	Reynold number
T	Temperature, K
$T_{cold\ in}$	Temperature of the cold stream entering heat exchanger, K
$T_{cold,in,above}$	Temperature of cold stream entering heat exchanger above pinch, K
$T_{cold\ out}$	Temperature of cold stream leaving heat exchanger, K
$T_{cold,out,below}$	Temperature of cold stream leaving heat exchanger below pinch, K
T hot in	Temperature of hot stream entering heat exchanger, K
$T_{hot,in,below}$	Temperature of hot stream entering heat exchanger below pinch, K
T hot out	Temperature of hot stream leaving heat exchanger, K
$T_{hot,out,above}$	Temperature of hot stream leaving heat exchanger pinch, K
T_{pinch}	Pinch temperature, K
Tstart	Starting temperature of a stream, K
Ttarget	Targeted final temperature of a stream, K
U	Overall heat transfer coefficient, W/m^2.K
U_{min}	Minimum amount of units
VBA	Visual Basic for Applications

Roman lower case letters

b	Power constant in heat exchanger area cost or in pipe cost
ca	Constant in heat exchanger area cost
$cPiping$	Total piping cost, $
$cpow$	Total electricity cost, $
cps	Cost of motor (outside), $
cpt	Cost of motor (inside), $
h_i	Convection heat transfer coefficient inside tube, W/m^2.K
h_o	Convection heat transfer coefficient outside tube, W/m^2.K
$\dot{m}_c$	Mass flow, kg/s
μ	Viscosity, kg/s.m
k	Thermal conductivity, W/m.K
x	Splitting ratio, J/s.K

1 Introduction

This introduction gives a brief overview of the thesis content, focusing on presenting the subject background, purpose of the thesis, its goals and its limitations.

1.1 Background

Process industry heat exchanger networks are not always arranged in very energy efficient set ups, therefore retrofit studies are recommended to be performed in order to evaluate their possibly increased energy recoveries and cost savings. Pinch analysis (Kemp 2007, Smith 2005), is an effective tool to evaluate the energy efficiency of a network, and previous work based on pinch technology has led to different approaches of performing retrofit studies. One of these approaches is the Matrix method developed at Chalmers (Carlsson 1996), which this thesis is focused on. The Matrix method results in an estimated overview for the trade-off between investment costs and energy savings for retrofits. A program (Matrix.xla) has been developed as an Excel add-in to facilitate the calculations of the method. This program is based on another program named Pro-Pi (Franck 2010) for data input. There is also a capability from within Matrix.xla to use an automated optimization routine (Matrix method optimizer) to reduce the calculation times of performing all iterations required. Yet the question of the reliability of the results is raised since some issues seem to remain, such as; incapacity of the method and the program to adapt to some specific situations, methodological and calculation errors, and the Matrix method optimizer and its capacity to always reach the best solution. Many gaps have been identified, but due to prioritized interest in other fields of science, little has been done to improve the Matrix method and the program since 2001.

To sum up, there is the Matrix method which is the methodology to identify a close-to-optimal retrofit of a heat exchanger network (HEN). The program Pro-Pi is used to input stream data and data for the existing heat exchangers in the network. This data is then used as an input by the Matrix calculation tool Matrix.xla that is a program helping the user to perform the Matrix method calculations. Finally, an automatic optimization routine referred to as the “Matrix method optimizer” is included as an option inside the program Matrix.xla to enable the replacement of manual selections by optimization.

In 2012, the Pinexo^{TM} project was initiated to distribute retrofit software commercially, and they are currently producing software based on the previously mentioned Matrix method optimizer program. Due to this and scientific reasons, there lies a large interest in evaluating the methods and assumptions behind the Matrix Method and the previously written Matrix method optimizer program based upon it.

1.2 Aim and objectives

The objective of this master thesis is to critically investigate, evaluate and improve the Matrix method, the Matrix calculation tool, and the automated routine for Matrix method optimization. The goal is to produce a thesis open for public use, describing and evaluating the strong points and drawbacks of the Matrix method and its implementation in an automated tool, followed by suggestions and possible improvements for the future. The main focus of the thesis is to do research on the drawbacks and gaps of the method in order to develop and improve the reliability and the working area of the Matrix method.

1.3 Limitations

One limitation to this work is that there has been no collection of stream data from an actual process industry as this is much too time consuming (approximately 2 working months for one person experienced in the field). All tests of the program have been performed on previous scenarios created. Furthermore, since this is a master thesis within the subject of Sustainable Energy Systems, it is not within the scope of the subject to write code for the actual program itself. Proposed algorithms for method improvements have been illustrated, and if found useful, they could later be translated and implemented in code.

1.4 Thesis outline

The thesis starts with a theoretical section including a basic description of heat exchangers followed by a brief overview of the basic concepts of pinch technology and an explanation of the Matrix method (see Chapter 3, Chapter 4 and Chapter 5). Then, the tools Pro-Pi, Matrix.xla and the automatic optimization routine are described in Chapter 6. This first descriptive part of the thesis is then followed by Chapter 7 which explains and illustrates the different issues identified in the Matrix method and the tools. Chapters 8 to 10 show deeper analyses of the main issues (merging, splitting and utilities) and bring solutions to these issues. Finally, results are summed up and discussed in the conclusion (see Chapter 11). Given that every separate issue has been handled in a different way the thesis does not include a distinct general discussion part. The discussion section is integrated in every specific chapter for every issue.

2 Methodology

The following chapter explains the methodology of how this thesis is carried out. The procedures and the list of materials are presented.

2.1 List of materials

This thesis is mainly focused on evaluating a methodology and constructed programs that carry this methodology out. Therefore a computer and software was enough for carrying out this thesis. The software used in order to carry out this thesis work was the following:

- Excel
- Pro-Pi (Franck 2010)
- Matrix.xla (Franck and Berntsson 1999)
- The Automatic optimization tool, MatrixOpt (Andersson 2001)

2.2 Procedure

The whole thesis was initiated by an analysis of the methodology behind the Matrix method followed by a study of how to use the Pro-Pi and the Matrix.xla software through several assignments and exercises in order to understand how they work but also in order to identify their working area and their limitations.

After that, the Matrix method optimizer was analyzed and tested to see how it works and applies the Matrix method. A list of all the data required for the programs by the user was made. Subsequently the outcome that the user gets from the method was detailed together with detailed descriptions of the program process paths followed.

These initial steps were followed by listing out the gaps and limitations of the programs. The impacts of the limitations on the results were estimated and an investigation of a selected set of the limitations found was initiated.

Each one of these in-depth studies of the selected set was done to understand and describe them and examples were created to show the impact and consequences of them on certain retrofit situations. This was followed by proposed solutions of how to fix the gaps in order to make the method more efficient, more accurate and so as to get a final solution with the best trade-off between investment costs and revenue from energy savings.

3 Heat exchangers and heat exchanger networks

The following section presents a brief description about heat exchangers including some general theory, different types and their modes of operation.

3.1 Description of heat exchangers

A heat exchanger (HEX) transports heat between streams going through the exchanger. In a process industry this is a key component for heat recovery and lower energy costs as it reduces the cooling demand of one stream at the same time as it reduces the heating demand of another. Most HEX's are designed to have counter current flows or cross flows as this is a very efficient way to transfer heat, and all HEX's in this thesis and the Matrix calculation tool are assumed to mainly have these modes of operation.

Any stream can only transfer heat to another stream if they have a temperature difference according to the laws of thermodynamics, and the smaller the temperature difference between these two streams is, the less the driving force for the heat transfer between them will be. The heat load of a HEX (Q) is given by:

$$Q = U * A * \Delta T_{lm} \qquad (1.1)$$

where Q is the heat transfer rate [W], U is the overall heat transfer coefficient [W/m^2·K], A is the heat transfer surface area [m^2], $\Delta T_{lm}$is the log mean temperature difference [K] where $\Delta T_{lm} = \frac{(\Delta T_2 - \Delta T_1)}{\ln(\Delta T_2 / \Delta T_1)}$, and where $\Delta T_2\ and\ \Delta T_1$ are the temperature differences between one stream's inlet and the other stream's outlet.

For a detailed explanation about the heat transfer driving forces and heat transfer properties, see Incropera et al. (2007).

Since the heat load (Q) depends on the temperature difference between the two streams, HEX's that operate between small temperature differences need to be efficient by heat exchanging through a large heat exchanging surface area, which is quite costly. The larger the heat exchanging surface area in a HEX is, the more heat can be transferred.

One of the simplest types of HEX's is the counter flow concentric tube type heat exchanger, see Figure 3.1. This HEX has one fluid flowing inside a tube in one direction and another external fluid flowing outside of the tube in the opposite direction along the annular gap between the inner tube and an external tube. The fluids exchange heat throughout this process as one fluid is hotter than the other. This HEX is used for simplicity when calculating an optimal solution for stream splitting in this thesis in Chapter 9.

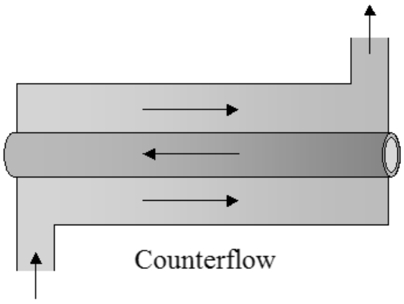
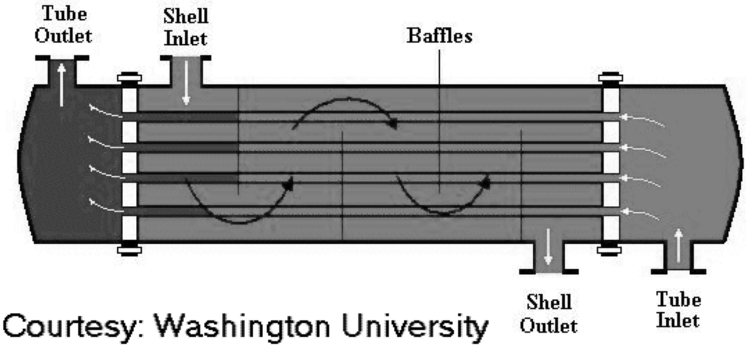


Figure 3.1 A counter flow concentric tube type heat exchanger with one fluid flowing through the inner tube in one direction and the other fluid flowing through the annular gap in the opposite direction.

An example of a more commonly used HEX that transfers heat between liquids is a shell and tube type of heat exchanger, see Figure 3.2. This HEX adds the effect of cross flow and turbulent flow which is often more efficient than simple flow along the length of a tube.



Courtesy: Washington University

Figure 3.2 The liquid coming in at the tube inlet passes through the tubes and comes out at the tube outlet. The second liquid entering at the shell inlet passes through in between the tubes and works its way through the course set up by the baffles until it finally exists at the shell outlet. The liquids exchange heat throughout this process in a cross-counter flow without being mixed.

All calculations of heat exchange between liquids performed by the Matrix calculation tool are based on shell and tube type heat exchangers. When it comes to gas streams, heat exchange across ideal tube banks (cross flow heat exchanger) are assumed which looks like the following (see Figure 3.3):

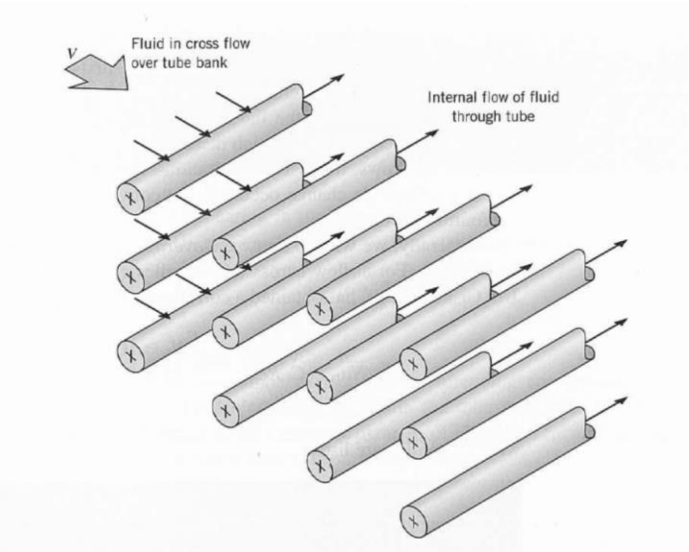


Figure 3.3 Gas is assumed to flow in between the banks of tubes externally while a fluid (gas or liquid) flows inside the tubes. This way, the external gas flow will always be ideal and a cross flow will be maintained (Incropera et al., 2007).

3.2 Heat Exchanger Networks

In a process industry, there are several heating and cooling demands at different temperatures as different processes require hot or cold streams. These process streams can be heated or cooled by installing heating or cooling utilities that require external energy inputs. However for a large process network, this is usually very energy consuming and costly, a heat exchanger network (HEN) can therefore be set up in order to recover the energy required for these different processes. This is done by setting up several HEX's between the process streams and it can be a very efficient way of using thermal energy for the system as a whole. The following chapter will explain some basic theory and rules of how HEN's should be set up.

4 Pinch Technology

The Matrix method, which is the main methodology used by Matrix.xla and Pinexo^{TM}'s software is based on Pinch technology, and this section of the thesis will briefly explain its most relevant concepts, methods and outcomes.

4.1 Description and history

Pinch technology provides the main analytical methodology, also called Pinch analysis, which is utilized by the Matrix method. The identification of the heat recovery pinch in 1982 and 1978 by Linnhoff (1982) and Umeda (1978) independently, lead to the spark that ignited Pinch technology that was developed throughout the remaining decades of the 20th century. Pinch technology provides a methodology that analyses energy flows of complex industrial processes in order to save energy. By stepwise following this methodology, the HEN solution with the fewest number of units that are required to reach the minimum energy consumption can be identified, that is; a Maximum Energy Recovery (MER) network.

For more details, the interested reader is referred to one of the standard textbooks about pinch analysis by Kemp (2007) or Smith (2005).

4.2 Basic Concepts

4.2.1 Representation of a Heat exchanger network

A HEN can easily be represented as in the following Figure 4.1.

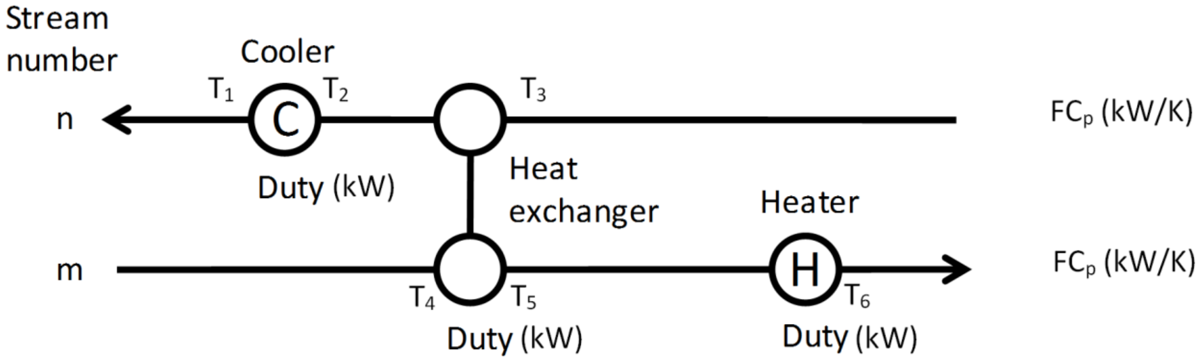


Figure 4.1 Example of representation of a HEN including a cold stream, a hot stream, a cooler, a heater and a heat exchanger.

This is how the HEN's are represented throughout this thesis as well as in Pro-Pi. T represents temperature in ^{0}C, H represents an external heater, C represents an external cooler, the duty is the heat power of the utility/HEX and is normally represented in kilo-Watts, FC$_p$ is the mass flow multiplied with the with the specific heat of the medium.

4.2.2 Hot and Cold streams

In a HEN, a hot stream is defined as a material stream that has a specified flow and heat capacity with a cooling requirement in order to change its temperature from a supply to a target value. A cold stream is defined as a material stream that has a specified flow and heat capacity with a heating requirement in order to change its temperature from a supply to a target value. Thus a hot stream implies a cooling demand while a cold stream implies a heating demand. If a hot or a cold stream has been heated up or cooled down according to the size of its heating or cooling demand, it can be regarded as being "ticked off" in the network. Streams can also have soft target temperatures, this implies that their target temperatures necessarily do not have to be reached, however the streams may still be used in order to heat or cool other streams in the HEN.

In most of this thesis and in Pro-Pi, illustrated hot streams are represented with red color and illustrated cold streams are represented with blue color.

4.2.3 Utilities

Utilities are the heating and cooling media used in heaters and coolers. A hot utility in a HEN is a utility such as steam that heats a cold process stream while a cold utility, for example cooling water, cools a hot process stream.

4.2.4 Pinch temperature

The heart of pinch technology is the identification of the so-called pinch temperature in a HEN. The pinch temperature, or pinch as it is commonly called can be identified graphically or mathematically. In order to identify the pinch temperature graphically, composite curves for all the streams in the network are constructed (see Section 4.2.6). The hot composite curve and the cold composite curve are then drawn on a (ΔH, T) diagram and matched together in order to give the most energy recoverable solution by matching them as closely together as possible without violating the minimum temperature difference (ΔT_{min}) established for the HEN. The point where the ΔT_{min} between the hot and the cold streams occurs is called the pinch. Looking at Figure 4.2 on the next page; it looks like the curves are being pinched together at this exact temperature difference, hence the word pinch is commonly notated for this interval.

4.2.5 Pinch rules & violations

One of the most important concepts in Pinch technology is the one concerning the three golden pinch rules and their violations.

- Heat should not be transferred in the system through the pinch
- External heating should not be done to the system below the pinch
- External cooling should not be done to the system above the pinch

If these rules are violated, it will not be possible to obtain a MER network. This is because if external heat is added below the pinch, the same amount needs to be cooled externally. If heat is subtracted externally above the pinch, the same amount has to be added externally. If heat is transferred through the pinch, it needs to be added and subtracted later to the system. In a network the sum of the pinch violations are the potential energy savings, that is, the difference between the present and the minimum utility demand. HEN's are therefore often represented as two separate ones, one above and one below the pinch in order to not violate any of these rules accidently.

4.2.6 Composite Curves

Composite curves can be defined as theoretical compositional streams for the existing hot and cold streams of a network system. They are constructed by calculating the total enthalpy contents of all the existing streams through certain temperature intervals for the hot and the cold streams separately. An example of what they look like is shown in Figure 4.2.

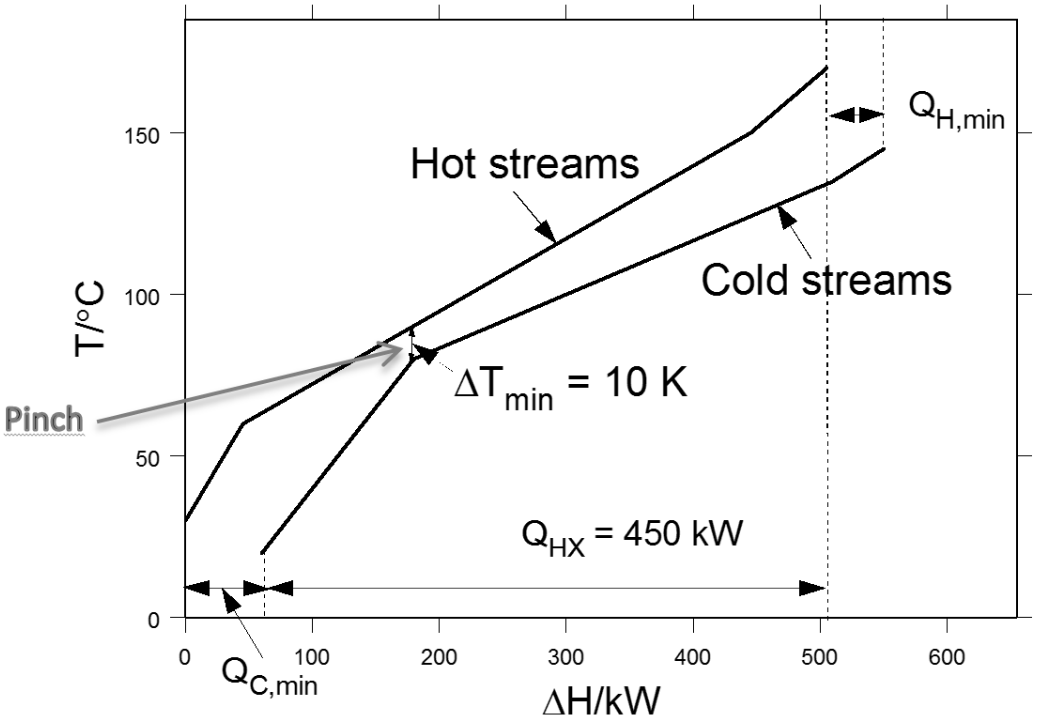


Figure 4.2 Composites curves for hot and cold streams, minimum heating demand, minimum cooling demand and location of the pinch.

Constructing heat cascade diagrams and using an algebraic algorithm as suggested and described by Kemp (2007) is the other way to identify the pinch. The pinch is easily identified mathematically with help from computational methods based on such cascade calculations implemented in software such as Pro-Pi (Franck 2010) and this is how it's done throughout this thesis work.

Once the pinch temperature has been identified, the network is divided into two parts. One part above the pinch where there is a heat deficit, a need for heating that is, and one part below the pinch and here there is a heat surplus, which means that there is a need for cooling. Q_{HX} in Figure 4.2 is the amount of heat that can be recovered (heat exchanged) between the streams in the network.

4.2.7 Grand Composite Curves

A great way to illustrate energy flows of a HEN is through a Grand Composite Curve (GCC), also called a heat surplus diagram, see Figure 4.3. It represents the net surplus and deficit of enthalpy of the network for different temperature intervals both above and below the pinch, and through a GCC the minimum heating and cooling utilities, the division of the network above and below the pinch temperature and the heat flow direction between the temperature intervals can be identified. A GCC is one of the results illustrated by Pro-Pi whenever stream data is entered. Important to notice is that all the hot and cold "net deficit streams" have been subtracted and added by $\Delta T_{min}/2$ respectively.

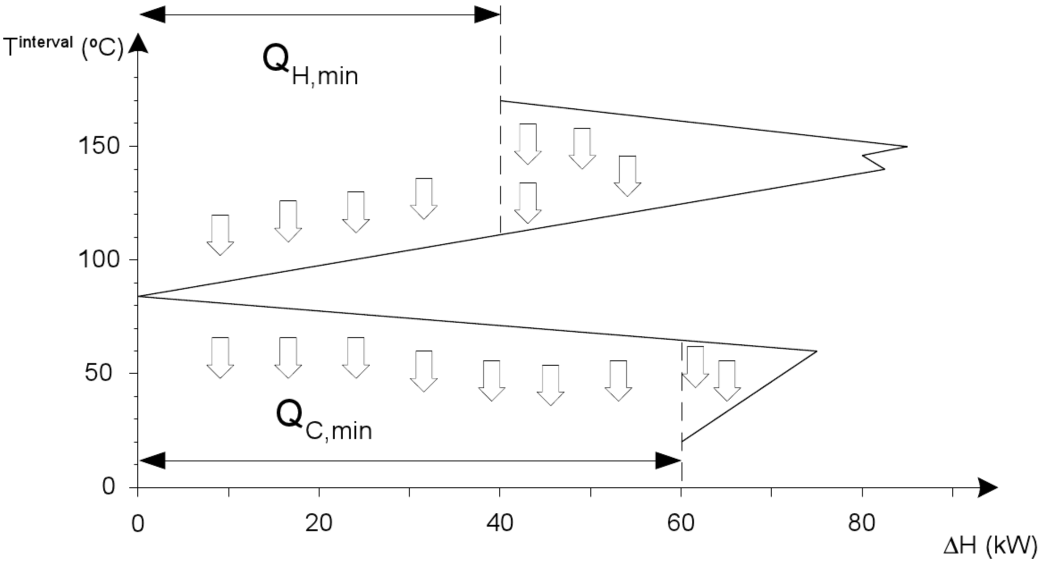


Figure 4.3 Example of a Grand Composite Curve for a HEN (Harvey 2011)

4.3 Energy and cost targeting

4.3.1 Minimum Utility Demands targeting

In a pinched HEN, there is always a minimum heating and cooling utility demand for the streams. These minimum utility demands are identified through the pinch division of the network after setting up a global ΔT_{min} for which the HEX's may operate. The minimum heat utility demand ($Q_{H,min}$) can be defined as the minimum amount of external heating that is needed in a HEN while the minimum cooling utility demand ($Q_{C,min}$) can be defined as the minimum amount of external cooling that is necessary for a HEN, they are both illustrated in Figure 4.2 and 4.3. Since energy is costly, the target is usually set for as low of an external utility demand as possible, and by subtracting the present heating and cooling network demands with $Q_{H,min}$ and $Q_{C,min}$ respectively, the potential energy savings (Q_{save}) are calculated.

4.3.2 Units targeting

Any unit described in this thesis is one that does a change to the heat energy (enthalpy) of a stream through a HEX. It can be done by heat exchanging the streams with each other in a HEX or by utilizing a utility media in a heater or cooler. In the grass root design of a network, the target is usually set for as few units as possible as this often is less costly. According to Euler's network theorem (Kemp 2007), the minimum amount of units (U_{min}) that are required to achieve a HEN with a heat recovery to a certain degree can be determined. This estimation can be used in order to analyze designs of HEN's for setting a target for the amount of units, and still achieve a desirable heat recovery.

Important to notice is that for retrofit situations, the amount of existing units probably already exceeds U_{min}. It is therefore usually not preferable to aim for the minimum number of units in a retrofitted network. What is important is instead to minimize the number of *new* units.

4.3.3 Minimum Temperature Difference and Area targeting

As explained in the previous chapter, the temperature difference and heat transferring area between two streams in a HEX influences the amount of heat that can be transferred between them. However, it is rather costly to dimension HEX's to operate with small temperature differences as this requires a large HEX area. The larger the HEX area is, the more efficient, yet more expensive the HEX will be. A smallest allowable temperature difference ΔT_{min} between any two streams in a HEN is therefore chosen due to economic and thermodynamic considerations.

The ΔT_{min} chosen for a network influences the amount of energy that can be recovered because with a smaller ΔT_{min} allowance for a network, more energy may be exchanged between each set of one hot and cold stream in a HEX. A ΔT_{min} can either be set globally for all the streams or set individually for the streams analyzed. In grass root design, the optimal and most economic global ΔT_{min} for a HEN is retrieved by considering costs for energy consumption against investment cost targets for a chosen set of different ΔT_{min}. This includes costs for the minimum amount of units, heat exchanger area, and the energy costs, see Figure 4.4. When it comes to a network retrofit situation, finding an optimum global ΔT_{min} is more difficult and therefore less reliable. In the retrofit case, the existing HEX area must be considered, for example, as suggested by Tjoe (1984), by comparing it to the minimum HEX area required for the current heat recovery level and based on that a global ΔT_{min} can be selected.

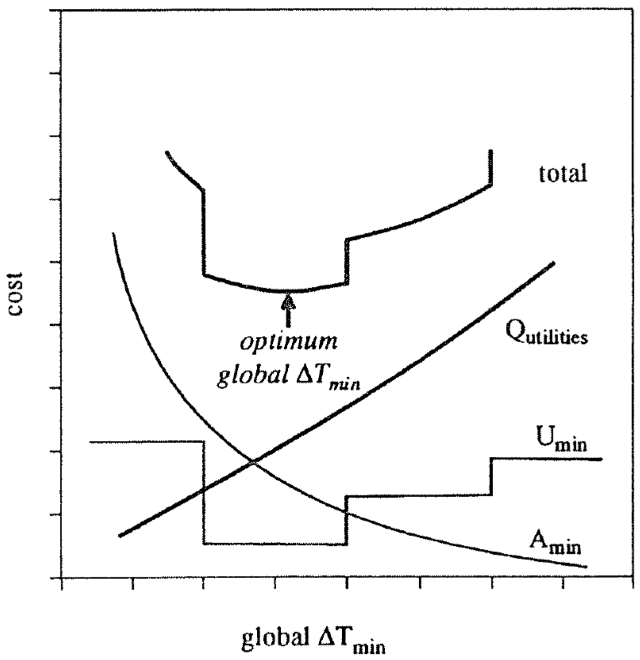


Figure 4.4 The cost of the minimum number of units, heat exchanger area, and utilities, with the total cost at different global ΔT_{min} values. The optimum global ΔT_{min} can be selected from the total cost graph (Carlsson 1996).

4.4 Retrofitting heat exchanger networks

When retrofitting HEN's, it is desirable to have as small of an investment cost as possible for the targeted energy saving. It is therefore desirable to; retain existing HEX's in their original positions as much as possible, install as few new HEX's as possible and to not re-pipe more than necessary as all of these imply large investment costs. When performing a basic retrofit, the theoretical minimum energy use for a global ΔT_{min} is compared to the actual energy consumption of the HEN. The pinch violations for the HEN are then identified and can thus be eliminated in order to reach a desirable energy target, the energy consumption will decrease by the amount of pinch violations eliminated through the retrofit.

Through the construction of a utility demand/area diagram, the energy and surface area targets of an optimal set up of the HEN can be compared to that of the existing one. Such a diagram is illustrated in Figure 4.5, the curve in this diagram (target curve) shows the energy target vs the HEX surface area target and they are both functions of ΔT_{min}. As the curve approaches a smaller HEX surface area target / larger hot utility demand, ΔT_{min} increases. The existing HEN is illustrated as point X in this graph and different retrofit options are illustrated as points A, B, C and R in Figure 4.5, these are described in Table 4.1 below.

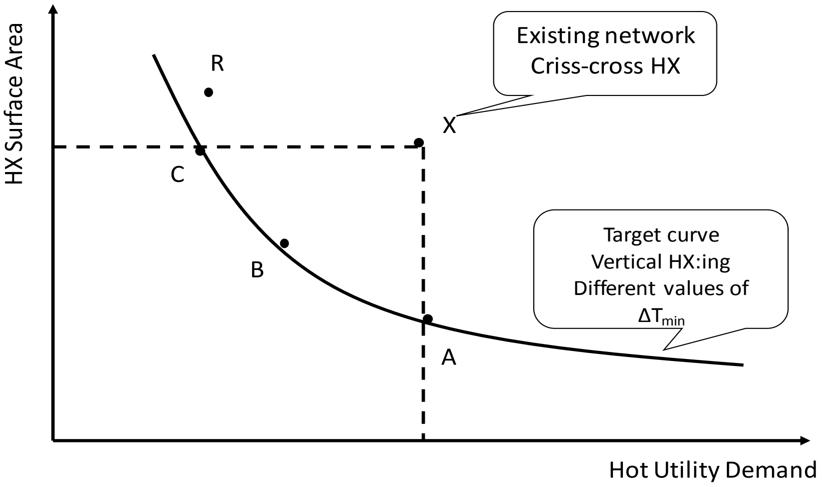


Figure 4.5 HEX surface area vs hot utility demand curve

Table 4.1 Description of different situations from Figure 4.5

Retrofit Approach	Result & Evaluation
X → A	The HEX surface area is reduced to its minimum necessary value without decreasing the hot utility demand. This option does not make use of the existing HEX surface area and is therefore a poor retrofit option.
X → B	The HEX surface area is reduced to that of an optimum grass root design at the same time as the hot utility demand is decreased. The entire installed HEX surface area is not utilized and thus this is not optimal for a retrofit.
X → C	The entire HEX surface area installed is utilized and used in its best way after the retrofit. The hot utility demand is decreased to its minimum for the area available. This is a very good retrofit option but in practice not possible as HEX's already are optimized for certain conditions.
X → R	This is a great retrofit option close to that of C, however more realistic since new HEX area usually needs to be installed. The area installed is used to its best capacity and as little new area as possible is installed. The heating demand is reduced significantly.

5 The Matrix method

5.1 Introduction

The Matrix method (Carlsson 1996) has been developed to bring economically optimal solutions to retrofit situations. Indeed, retrofitting HEN's cannot be handled by the traditional pinch design method. A retrofitting situation requires a consideration of the limitations of the current network and using the traditional pinch method would lead to dead end solutions because it would lead to a MER network that is not economically affordable. The Matrix method aims at determining the optimal amount of energy savings to pursue by taking the characteristics of the existing network into account. Several of these parameters such as the distance between the different streams are not thermodynamic data but they influence the cost of the retrofitted solution directly. The Matrix method is a procedure helping the user identifying the HEX's that are wasting energy, and it aids the user to decide how to modify the network in the cheapest way, by promoting the use of free already existing HEX's for example. It will not provide a single optimal situation but will result in several cost-effective solutions for different energy recovery levels.

5.2 What cost parameters are taken into account?

The Matrix method aims at including all the costs of the retrofitting work and to evaluate how they impact the final solution. The main parameters considered for cost calculations are the following (Carlsson 1996):

- The heat exchanger area
- The type of heat exchanger
- The construction material
- The piping costs (distance between streams, pipes diameters, construction materials)
- The Pressure drop costs (pumps and pumping power costs)
- Auxiliary equipment (valves)
- Space requirements
- Maintenance costs (cleaning, fouling)

5.3 What data is used from the current network?

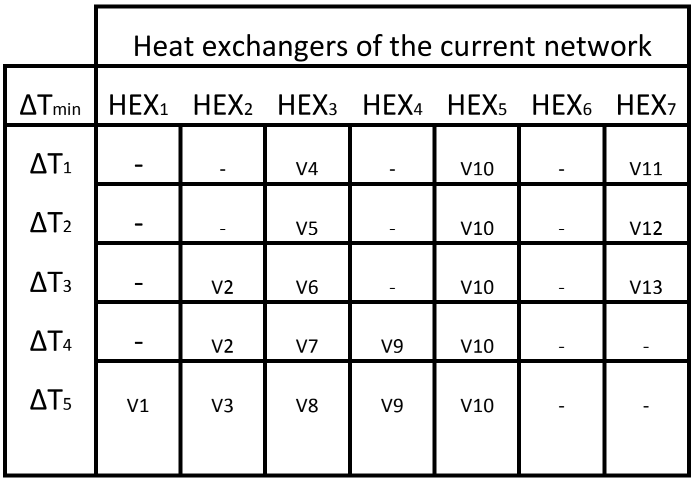
In addition to all the previous cost data, the Matrix method also requires information about the current network such as stream data (flow rate, heat capacity, supply and target temperatures, density, viscosity, thermal conductivity, fouling factor) and HEX data (UA-values, location, type, hydraulic diameter of both sides of the HEX).

5.4 What is the procedure?

5.4.1 Choice of global ΔT_{min} and pinch violations

The first step of a retrofit analysis is to choose a global ΔT_{min} for the retrofitted network. This new ΔT_{min} has to be smaller than the one used in the current network. Then, pinch analysis is used to calculate T_{pinch}, $Q_{H,min}$ and $Q_{C,min}$ plus to identify the HEX's that violate the pinch rules. Several ΔT_{min}'s should be investigated by the user. After that, the user has to choose which pinch violations that should be removed. The more violations that will be removed, the more energy savings there will be, but that also requires having a larger investment in new HEX's and HEX modifications. At this point the user has to select an optimum number of new and rearranged units. To do so, a table pointing out the size of the violations for every HEX at various global ΔT_{min} has to be built, see Table 5.1.

Table 5.1 Example of table representing the different violations for every heat exchanger of the network at different values of global ΔT_{min}.



	Heat exchangers of the current network						
ΔT_{min}	HEX_1	HEX_2	HEX_3	HEX_4	HEX_5	HEX_6	HEX_7
ΔT_1	-	-	V4	-	V10	-	V11
ΔT_2	-	-	V5	-	V10	-	V12
ΔT_3	-	V2	V6	-	V10	-	V13
ΔT_4	-	V2	V7	V9	V10	-	-
ΔT_5	V1	V3	V8	V9	V10	-	-

In this table no values are used, instead 13 hypothetical different levels of violations are symbolized as V1 to V13.

Since HEX's transferring heat from below to above the pinch point do not increase the energy consumption, they should not be modified. Instead, only HEX's transferring energy in the opposite direction (heat from above to below the pinch temperature) have to be investigated. Moreover, for each global ΔT_{min} investigated, the user might first choose to eliminate only the biggest violations and allow the small ones. Such a choice requires a splitting of the study of the network into two parts (above and below the pinch) so that the internal HEX's that are allowed to violate the pinch rules can remain in their current positions.

Then, the economic part of the Matrix method is pursued (described in detail below) to evaluate the cost of the different retrofit opportunities deleting the largest violations. This procedure has to be run several times, with different values of global ΔT_{min}'s and by rearranging different violations resulting in Figure 5.1 and Figure 5.2.

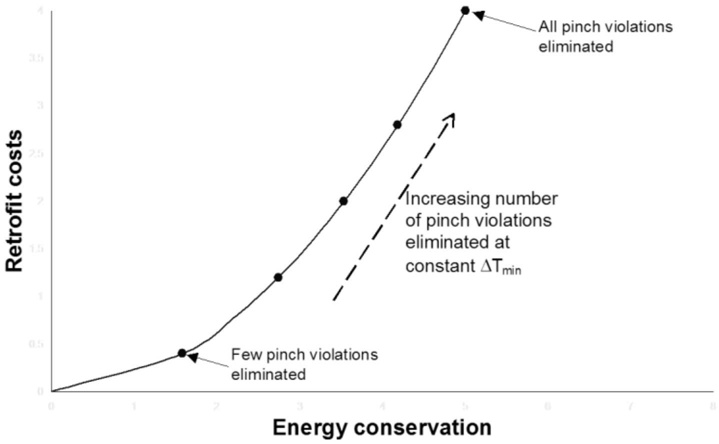


Figure 5.1 Development of retrofitting costs for different levels of energy recovery

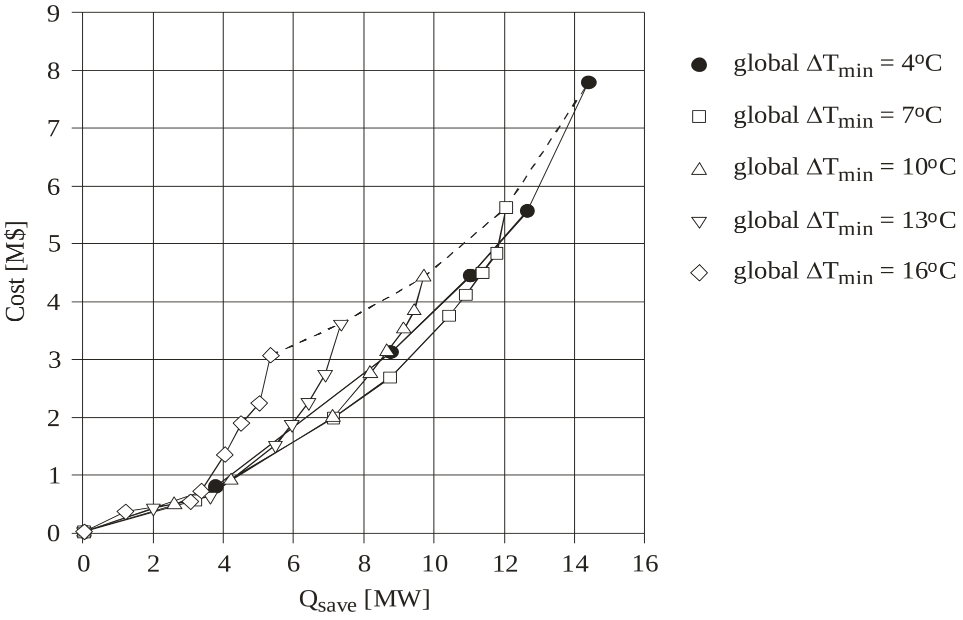


Figure 5.2 Development of retrofitting costs for different levels of energy recovery and different values of global ΔT_{min}.

At this point, the user can choose which global ΔT_{min} and which violations that have to be fixed in order to get the cost per unit of saved energy ratio that suits him/her the best.

5.4.2 The economic evaluation within the Matrix method

When the user has chosen a global ΔT_{min} and decided what violations to eliminate for the HEN, the reduction of the energy consumption is fixed. If some violations are authorized to remain in the retrofitted network, the minimum utility consumption ($Q_{H,min}$) will not be reached. In fact, the hot utility savings will only be as high as the sum of the violations deleted. At this point, the process streams are separated into two parts at the pinch temperature. In order to allow the authorized pinch violating HEX's to remain at their positions (temperature), the streams are not strictly separated at the pinch point, see Table 5.2.

For example, in this network from a course compendium (Harvey 2011), the network represented in Figure 5.3 has a pinch temperature of 114°C and a ΔT_{min} value of 22 K.

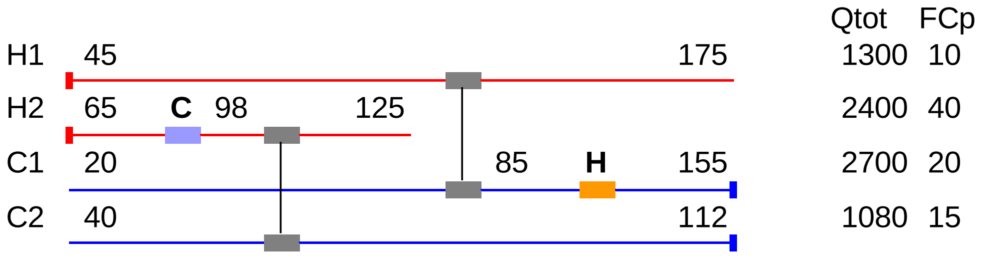


Figure 5.3 Network used as an example for economic evaluation within the Matrix method.

The user can decide to retain the match H_2-C_2 even if it constitutes a pinch violation of heat transfer through the pinch. In that case after dividing the system into two parts, the user can choose to represent the streams above the pinch as following.

Table 5.2 Representation of streams above pinch including stream C_2, violating the pinch.

Stream	**Tstart**	**Ttarget**	**Q [kW]**
H_1	175	125	500
H_2	125	98	1080
C_1	103	155	1040
C_2	40	112	1080

We can observe that H_1 and C_1 are limited by the pinch temperature while C_2 is going through it. This is how the division of the network has to be done, taking the untouched HEX's into account. The analysis of the retrofit is then done by constructing a matrix for the two separated systems. Rows correspond to hot streams and columns to cold ones. After this step, different kinds of matches are investigated between all the different streams. Several matching situations are possible. In the first situation, the heat load of a match is determined when the cold stream or the hot stream is ticked off. The second possible situation is when we use the maximum heat exchanging capacity of a currently existing HEX.

Finally, in some situations a match cannot be found between two streams by ticking one off. In such a case, the match is pursued until a specified temperature difference is reached between the streams. This ΔT has to be set as an input by the user. More precisely, the different types of matches in the Matrix method are the ones in Table 5.3:

Table 5.3 The different types of matches in the Matrix method.

Cold Tick-Off	The cold stream reaches its target temperature and is not possible to use in any following match.
Hot Tick-Off	The hot stream reaches its target temperature and is not possible to use in any following match.
No Tick-Off	None of the streams is fully used.
Not Possible	The match is not thermodynamically possible.
Heater	Hot utility is used for heating a stream.
Cooler	Cold utility is used for cooling a stream.

Above the pinch a hot tick-off can be divided into three cases:

1. The cold stream can be used in a direct following match to tick-off another hot stream.
2. The cold stream will be ticked off if it is used immediately in the next match.
3. It is not possible to use the cold stream in the next match.

If "cold" and "hot" changes place in the list above, the situation for a cold tick-off below pinch is also explained.

The first matrix starts at the pinch point. The user has to investigate every possible (or not possible) match between all the different streams. The user has to calculate the optimum design and cost match for every couple of streams and write the cost of the chosen match in the corresponding cell of the matrix. To do so, the user has to follow an optimum routine in selecting matches. The routine described by Franck and Berntsson (1999) in the paper "The Matrix method – the program Matrix.xla" is one possible procedure to choose a match between two streams above the pinch.

Select matches in the following order:

- Select hot streams that can be matched in only one way.
- Select hot streams that have no existing HEX. Select matches in order of cost but avoid ticking-off the cold stream if an existing HEX is located on the cold stream.
- Select existing matches.
- Select matches in order of cost. The match with the lowest cost should be selected first. If the most economical match hinders the possibilities of deriving a solution at the stipulated heat recovery level, this match should not be selected. This information is gained from the type of the match. If two matches of equal economic merit exist, priority is given to match type 1 over 2 and 2 over 3.

The procedure is the same below the pinch if we replace “hot” by “cold”.

Every time a match is selected, a new matrix without the ticked-off stream (if it is ticked-off) has to be calculated in order to implement the consequences of the selection of this match on the remaining streams to match. The user has to proceed like this until all the relevant streams are ticked-off and the desired energy recovery is reached (the targeted violations are eliminated). At this point, the total cost of the retrofit for the specific energy recovery can be calculated.

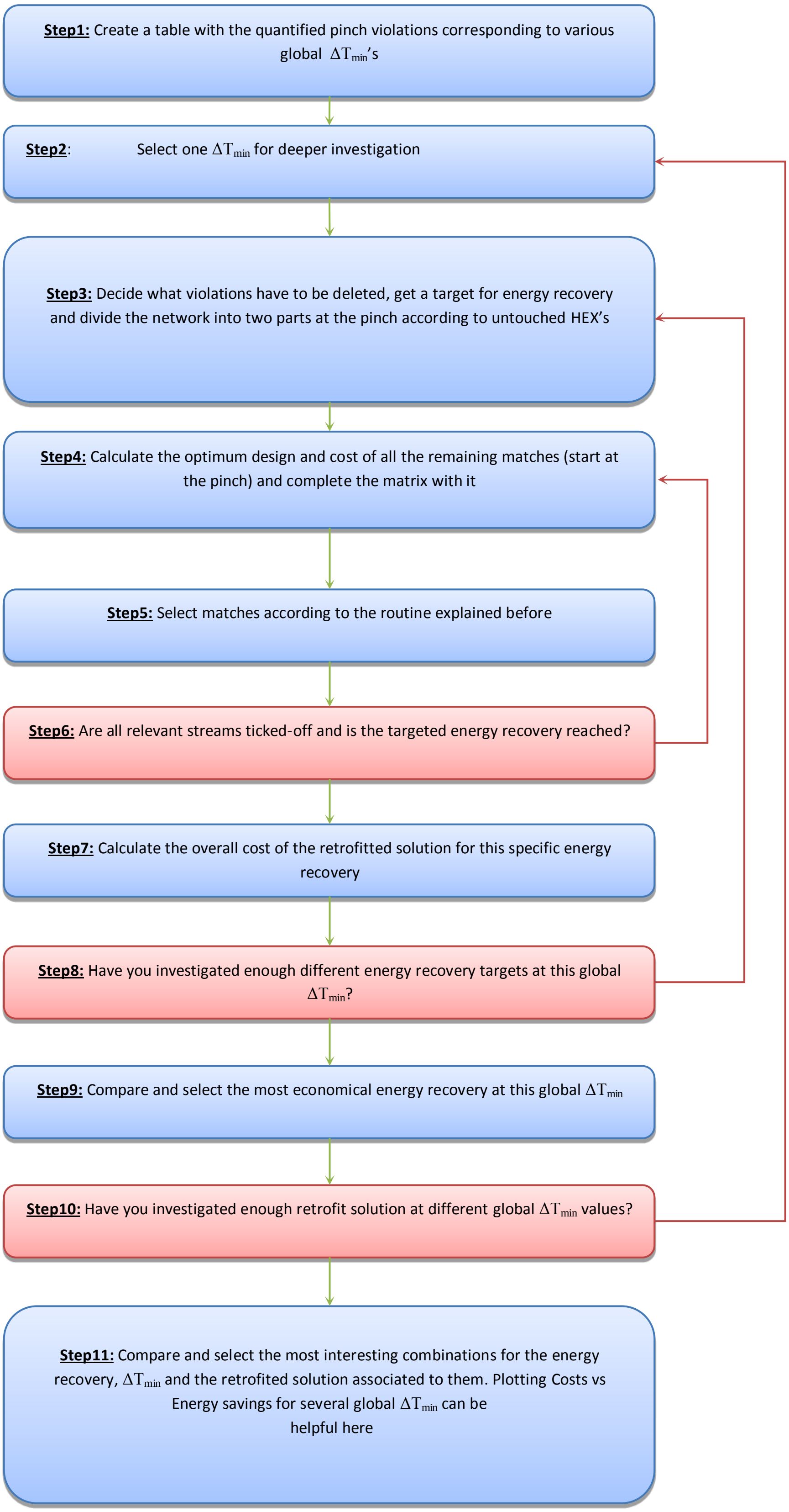
The user can then proceed to a new investigation of another way to match the streams (if some matches were not obvious) and compare the new total cost of the retrofit to make his/her final choice.

Finally, the user can do a new iteration of this method with a different targeted energy recovery (by deleting more violations for example) and appreciate if the ratio of the energy saved/cost is better than the previous solution.

5.4.3 Hot and cold utilities

Hot and cold utility HEX’s (heaters and coolers) are included in the matrix in the same way that internal HEX’s are. However, hot and cold utilities cannot be ticked-off since they aim at ticking off the internal hot and cold streams. Therefore, they are used after all the streams are used for internal heat exchange to reach the temperature goals of the un-ticked-off streams remaining. The aim is to reduce the heat load of the utility streams. The size and price of the coolers/heaters are calculated when only colds streams remain above the pinch and only hot streams below the pinch. Their costs are included in the total cost for the retrofitted solution given by the Matrix method.

5.5 Summary of the method:



Step1: Create a table with the quantified pinch violations corresponding to various global ΔT_{min}'s

Step2: Select one ΔT_{min} for deeper investigation

Step3: Decide what violations have to be deleted, get a target for energy recovery and divide the network into two parts at the pinch according to untouched HEX's

Step4: Calculate the optimum design and cost of all the remaining matches (start at the pinch) and complete the matrix with it

Step5: Select matches according to the routine explained before

Step6: Are all relevant streams ticked-off and is the targeted energy recovery reached?

Step7: Calculate the overall cost of the retrofitted solution for this specific energy recovery

Step8: Have you investigated enough different energy recovery targets at this global ΔT_{min}?

Step9: Compare and select the most economical energy recovery at this global ΔT_{min}

Step10: Have you investigated enough retrofit solution at different global ΔT_{min} values?

Step11: Compare and select the most interesting combinations for the energy recovery, ΔT_{min} and the retrofited solution associated to them. Plotting Costs vs Energy savings for several global ΔT_{min} can be helpful here

Figure 5.4 Diagram summing up the overall Matrix method

6 The different calculation tools for the Matrix method

This chapter describes the main inputs and outputs of the program Pro-Pi that produces the stream data required to run the Matrix method. The main steps followed in the software Matrix.xla are also described, including the logic behind the automatic optimization routine (Matrix method optimizer).

6.1 Pro-Pi

Pro-Pi is an Excel add-in tool developed by CIT Industriell Energi AB to help its user to do energy analysis of HEN's using pinch analysis.

The program requires several inputs from the user in order to describe the network such as:

- Stream temperatures
- Stream mass flows
- Stream specific heats
- ΔT_{min} for each stream or the global ΔT_{min}
- Heat transfer coefficients
- Utility data

From this data, Pro-Pi is able to draw a stream representation of the network (see Figure 6.1), generate GCC's (see Figure 6.2), retrieve HEX data (previously manually placed by the user), evaluate pinch violations in the network (see Figure 6.3) and enable the user to try different modifications of the network (changing HEX's, heaters and coolers). Pro-Pi is not "automated", even if it does some calculations on its own such as output temperatures, input temperatures, heat loads and violations, it is the user that has to design the network by placing the different HEX's manually.

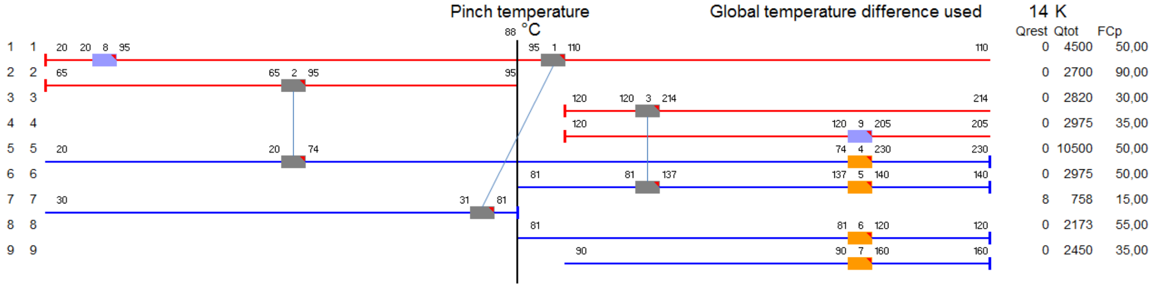


Figure 6.1 Example of representation of a heat exchanger network in Pro-Pi

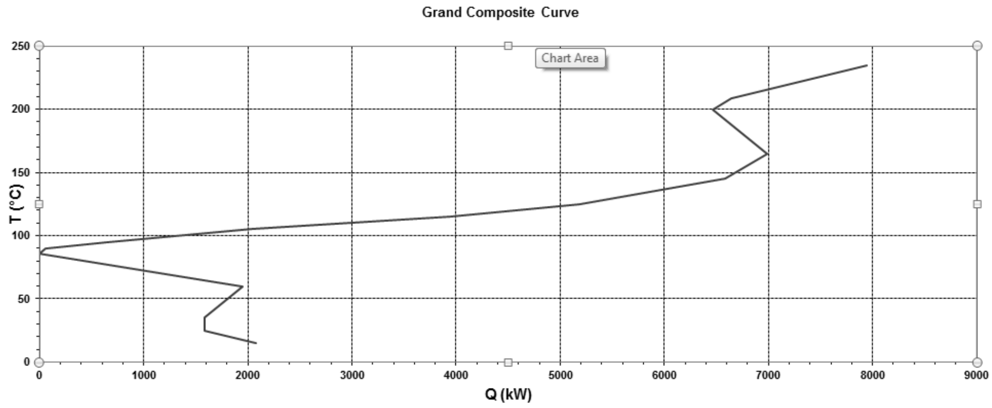
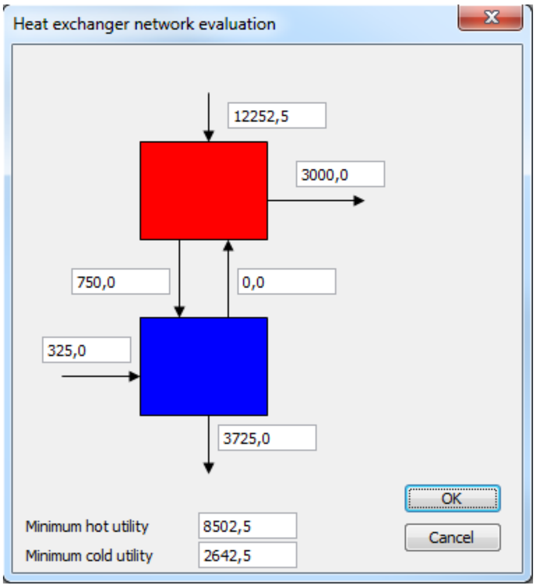


Figure 6.2 Example of Grand Composite Curve generated by Pro-Pi



12252,5
3000,0
750,0
0,0
325,0
3725,0

Minimum hot utility 8502,5
Minimum cold utility 2642,5

Figure 6.3 Example of pinch violation evaluation in Pro-Pi

6.2 Matrix.xla

The Matrix calculation tool program is an add-in to Microsoft Excel created by Franck and Berntsson (1999). This program named Matrix.xla is based on the previous work of Carlson (1996) that she developed in her PhD thesis entitled “Optimum Design of Heat Exchanger Networks in Retrofit Situations” in 1996. The software calculations are based on thermodynamic and cost data collected from the user who implements it through the add-in Pro-Pi but also directly through specific sheets inside Matrix.xla. Then, the user has to choose matches between the different streams above and below the pinch until no streams are left. The final solution is then shown in an Excel sheet and the user has to analyze both the solution above and below the pinch to get the final retrofitted network. In 2001, Anderson (2001) added an automated functionality to the program Matrix.xla when he wrote his master thesis named “Routine for Automatic Optimization of Heat Exchanger Networks with the Matrix Method”. This option allows the user to let the program choose the optimum matches between the streams instead of doing it manually. To do so, the selection between the streams obeys a precise procedure that will be described further.

6.2.1 The overall procedure of Matrix.xla

First of all the studied network has to be represented in the program Pro-Pi. Pro-Pi is integrated in the tool Matrix.xla. Following this step, the user has to create a “log sheet” in the software Matrix.xla. This sheet is used to do the link between the sheets from Pro-Pi and the program Matrix.xla (Franck och Berntsson 1999). The user has to specify the names of the sheets where the program will find the data about the streams (stream data sheet) and the network (net sheet).

Next, the user has to launch a functionality of the program, “create input data” that will create four new sheets from the stream data and the network description. The first sheet created is named “TD Data” and gathers the previous stream information. It also calculates approximate values of the utilities. The user has to complete this sheet manually by giving additional thermodynamic information about the streams. The user also has to specify the types of each HEX used. Some assumptions are made inside the program at this point. First, Shell-and-tube HEXs are assumed except for gas streams in which case ideal tube banks are assumed. Condensation is assumed to take place on the shell side, then, evaporation will be on the tube side except when the hot stream is a liquid. It has also been chosen to simplify the program and not give information about the condensation state of steam in heaters. The heat transfer correlation according to Kern (1950) is used and to calculate the optimum piping design considering pressure drops and pipe diameters, routines from Coulson and Richardson (1983) are used. The second sheet created is named “DD data”. It is a matrix with hot streams as arrays and cold streams as columns. For every possible match between two streams, the distance between the streams has to be specified by the user. A default value is set at 20 m.

The third sheet is named “HX input”. This sheet contains default values for the calculation of various combinations of heat exchanger types. The user has to implement his/her own modifications in order to adapt the calculation process to his/her own problem. For every HEX-type, if there is a lack of cost data, all the constants required can be specified by the user or set to default values in order to calculate the following costs:

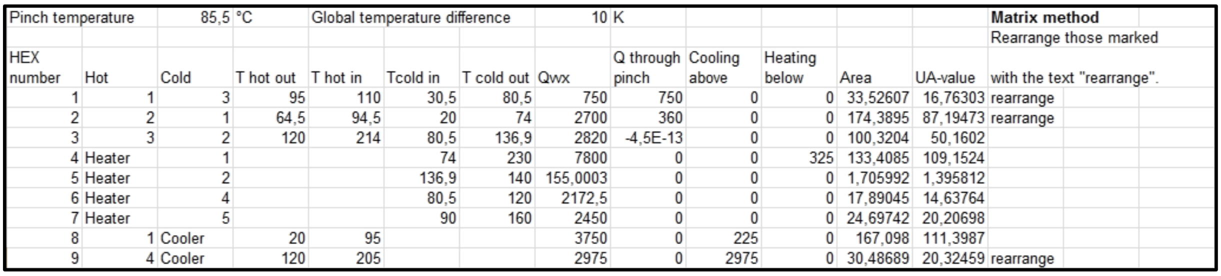
- $Motor\ costs\ inside\ the\ HEX\ (pressure\ drop\ capital\ cost) = CMi * (Pi - Pifree)^{CiM}$
- $Motor\ costs\ outside\ the\ HEX\ (pressure\ drop\ capital\ cost) = CMo * (Po - Pofree)^{CM}$
- $Electricity\ costs\ for\ motors\ (power\ cost\ of\ inside\ pressure\ drop) = Celi$
- $Electricity\ cost\ for\ motors\ (power\ cost\ of\ outside\ pressure\ drop) = Celo$
- $HEX\ area\ fixed\ costs\ = Afast$
- $HEX\ area\ variable\ costs\ = ca * area^{b}$
- $Costs\ of\ the\ pumps\ to\ overcome\ pressure\ drops\ in\ pipes = CM * P^{C}$
- $Costs\ of\ pipes = CL * L * Di^{b}$
- $Costs\ of\ electricity\ to\ run\ the\ pumps\ to\ overcome\ pressure\ drops\ in\ pipes = Cel$
- $Additional\ specific\ costs\ for\ designated\ HEX\ can\ be\ added\ to\ Afast\ if\ required$

The user can change the values of all the constants present in the formulas above (except for the physical data such as pressures and areas that are calculated) in the sheet “HX input”. By summing all these costs for every HEX, the program estimates the overall cost of the retrofitted network. The last sheet generated is the “UA data sheet”. It is a matrix with hot streams in rows and cold ones in columns. The program calculates the UA-values of the existing HEX’s in this matrix. If more than one HEX is used between the two same streams, their UA values are added.

The next step in using the program consists of selecting a few global ΔT_{min} values to carry out the analysis with. This temperature difference does not refer to the temperature difference inside the HEX’s but it’s used to specify different energy saving levels to investigate. The choice of this value should results from a previous study of minimum utility versus ΔT_{global}^{min} that is not available in the Matrix.xla program, but can be handled in Pro-Pi.

At this point, a first value of ΔT_{global}^{min} is investigated. Pro-Pi is used to draw a list of the existing HEX’s and show which ones violate the pinch rules, and by how much. At this point, the user has to choose which units to rearrange in order to reach a certain energy saving (see Table 6.1). The user also has to refer to this sheet in the log sheet for the program to be able to get access to this information.

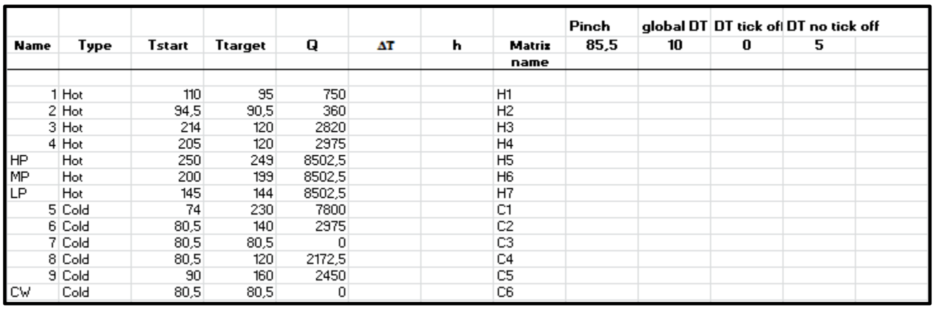
Table 6.1 Example of a sheet used for the selection of violations to be retrofitted in Matrix.xla



Pinch temperature		85,5	°C	Global temperature difference			10	K					**Matrix method**
													Rearrange those marked
HEX number	Hot	Cold	T hot out	T hot in	Tcold in	T cold out	Qwx	Q through pinch	Cooling above	Heating below	Area	UA-value	with the text "rearrange".
1	1	3	95	110	30,5	80,5	750	750	0	0	33,52607	16,76303	rearrange
2	2	1	64,5	94,5	20	74	2700	360	0	0	174,3895	87,19473	rearrange
3	3	2	120	214	80,5	136,9	2820	-4,5E-13	0	0	100,3204	50,1602	
4	Heater	1			74	230	7800	0	0	325	133,4085	109,1524	
5	Heater	2			136,9	140	155,0003	0	0	0	1,705992	1,395812	
6	Heater	4			80,5	120	2172,5	0	0	0	17,89045	14,63764	
7	Heater	5			90	160	2450	0	0	0	24,69742	20,20698	
8	1	Cooler	20	95			3750	0	225	0	167,098	111,3987	
9	4	Cooler	120	205			2975	0	2975	0	30,48689	20,32459	rearrange

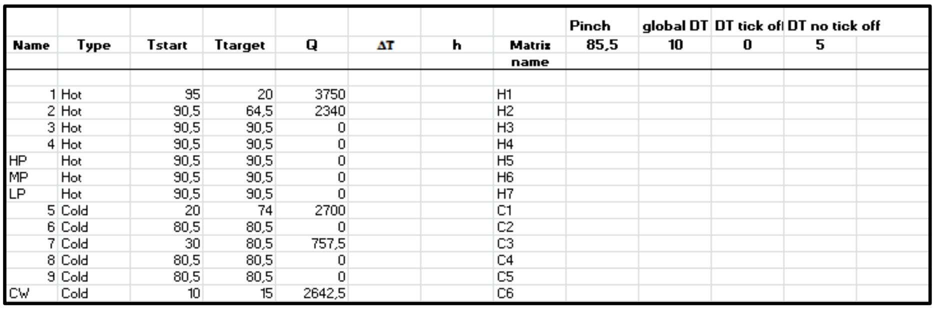
It is now required to divide the stream data into two parts at the selected ΔT_{global}^{min}. In order to avoid costly heat exchanging at very small temperature differences the user is invited to specify a minimum temperature difference in HEX’s where tick-off is thermodynamically possible and also one for those where tick-off is not thermodynamically possible. The division of the network into two parts generates two new sheets. These sheets represent the name, type, starting temperature, targeted temperature and heat load of the streams above and below the pinch. It also takes the accepted pinch violations into account by representing these HEX’s both in the regions above and below the pinch. Consequently these violating HEX’s have to be matched in both regions (see Table 6.2 and Table 6.3).

Table 6.2 Example of representation of the streams above the pinch after network splitting at the pinch in Matrix.xla. The violation on HEX #2 is rearranged.



								Pinch	global DT	DT tick of	DT no tick off
Name	**Type**	**Tstart**	**Ttarget**	**Q**	**ΔT**	**h**	**Matrix name**	**85,5**	**10**	**0**	**5**
1	Hot	110	95	750			H1				
2	Hot	94,5	90,5	360			H2				
3	Hot	214	120	2820			H3				
4	Hot	205	120	2975			H4				
HP	Hot	250	249	8502,5			H5				
MP	Hot	200	199	8502,5			H6				
LP	Hot	145	144	8502,5			H7				
5	Cold	74	230	7800			C1				
6	Cold	80,5	140	2975			C2				
7	Cold	80,5	80,5	0			C3				
8	Cold	80,5	120	2172,5			C4				
9	Cold	90	160	2450			C5				
CW	Cold	80,5	80,5	0			C6				

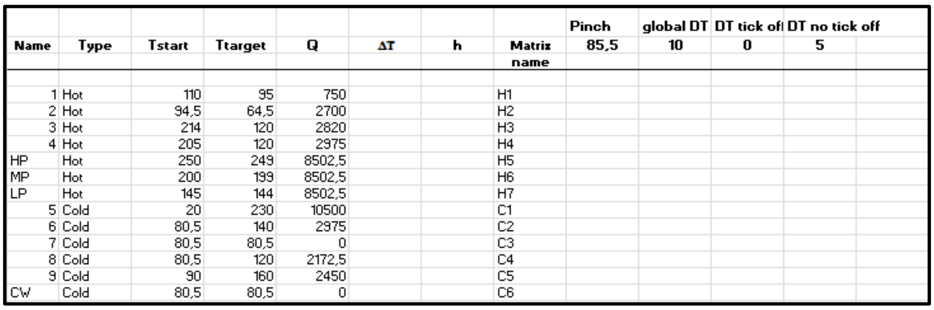
Table 6.3 Example of representation of the streams below the pinch after network splitting at the pinch in Matrix.xla. The violation on HEX #2 is rearranged.



								Pinch	global DT	DT tick of	DT no tick off
Name	**Type**	**Tstart**	**Ttarget**	**Q**	**ΔT**	**h**	**Matrix name**	**85,5**	**10**	**0**	**5**
1	Hot	95	20	3750			H1				
2	Hot	90,5	64,5	2340			H2				
3	Hot	90,5	90,5	0			H3				
4	Hot	90,5	90,5	0			H4				
HP	Hot	90,5	90,5	0			H5				
MP	Hot	90,5	90,5	0			H6				
LP	Hot	90,5	90,5	0			H7				
5	Cold	20	74	2700			C1				
6	Cold	80,5	80,5	0			C2				
7	Cold	30	80,5	757,5			C3				
8	Cold	80,5	80,5	0			C4				
9	Cold	80,5	80,5	0			C5				
CW	Cold	10	15	2642,5			C6				

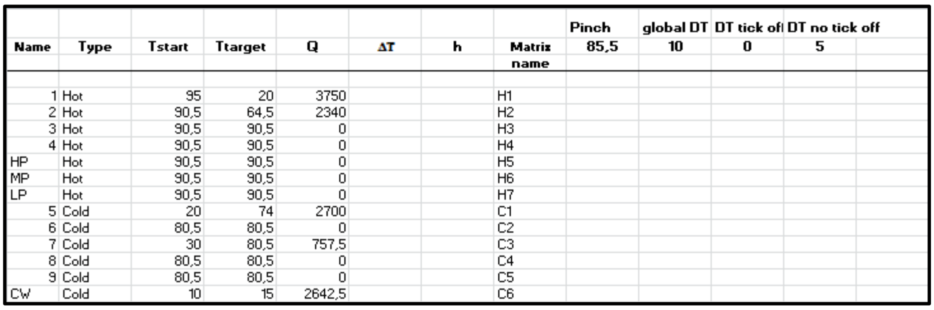
For example, HEX #2 connecting stream number 2 and 5 shows a violation of 360 kW through the pinch. Since this violation has been asked to be rearranged (see Table 6.1), stream 2 is strictly divided at the pinch in AP data and BP data (From 94.5°C to 90.5°C above and then, from 90.5°C to 64.5°C below). If we run the division of the network again without asking for this violation to be rearranged, we get the following tables (see Table 6.4 and Table 6.5):

Table 6.4 Example of representation of the streams above the pinch after network splitting at the pinch in Matrix.xla. The violation on HEX 2 is not rearranged.



								Pinch	global DT	DT tick of	DT no tick off
Name	**Type**	**Tstart**	**Ttarget**	**Q**	**ΔT**	**h**	**Matrix name**	**85,5**	**10**	**0**	**5**
1	Hot	110	95	750			H1				
2	Hot	94,5	64,5	2700			H2				
3	Hot	214	120	2820			H3				
4	Hot	205	120	2975			H4				
HP	Hot	250	249	8502,5			H5				
MP	Hot	200	199	8502,5			H6				
LP	Hot	145	144	8502,5			H7				
5	Cold	20	230	10500			C1				
6	Cold	80,5	140	2975			C2				
7	Cold	80,5	80,5	0			C3				
8	Cold	80,5	120	2172,5			C4				
9	Cold	90	160	2450			C5				
CW	Cold	80,5	80,5	0			C6				

Table 6.5 Example of representation of the streams below the pinch after network splitting at the pinch in Matrix.xla. The violation on HEX 2 is not rearranged.



								Pinch	global DT	DT tick of	DT no tick off
Name	Type	Tstart	Ttarget	Q	ΔT	h	Matrix name	85,5	10	0	5
1	Hot	95	20	3750			H1				
2	Hot	90,5	64,5	2340			H2				
3	Hot	90,5	90,5	0			H3				
4	Hot	90,5	90,5	0			H4				
HP	Hot	90,5	90,5	0			H5				
MP	Hot	90,5	90,5	0			H6				
LP	Hot	90,5	90,5	0			H7				
5	Cold	20	74	2700			C1				
6	Cold	80,5	80,5	0			C2				
7	Cold	30	80,5	757,5			C3				
8	Cold	80,5	80,5	0			C4				
9	Cold	80,5	80,5	0			C5				
CW	Cold	10	15	2642,5			C6				

In this case, stream 2 is not stopping at T_{pinch} anymore but goes straight down to 64.5^0C even in AP data. This section of the stream is then represented both in AP data and BP data. That difference clearly points out that the network division deals with authorized violations and that these HEX's will be matched both above and below the pinch which has to be considered by the user when he will have to build the overall retrofitted solution, gathering above and below pinch solutions. Moreover if the Matrix method optimizer suggests adding a new HEX for a stream that is represented in both sides of the pinch, it might lead to different solutions for the same stream above and below the pinch.

After the network has been divided, the user has to apply the Matrix method to derive solutions above and below the pinch at the specified level of energy savings. To do so, he can choose to select the matches manually, or he can choose to use the Matrix method optimizer developed by Anderson (2001). These two methods are detailed hereafter.

After both solutions above and below the pinch are reached, the user has to merge these solutions to get the final retrofitted network. The total cost of the network is simply calculated by adding the costs above and below the pinch. These costs appear in the sheets HXA and HXB that are created when the matches are completed. However, since accepted violations lead to having some stream segments to be represented in both areas studied, the user has to check manually for double or alternative solutions. The less expensive alternative should be chosen.

When the total cost of the retrofitted network is calculated, the user should investigate other solutions at different levels of energy savings, by authorizing more or less violations at the same ΔT_{global}. The whole procedure should also be repeated for several values of ΔT_{global} so that the user eventually gets a panel of possible solutions in which he will choose the best fitting one, depending on the cost versus energy saved ratio for example.

6.2.2 Manual choice of matches

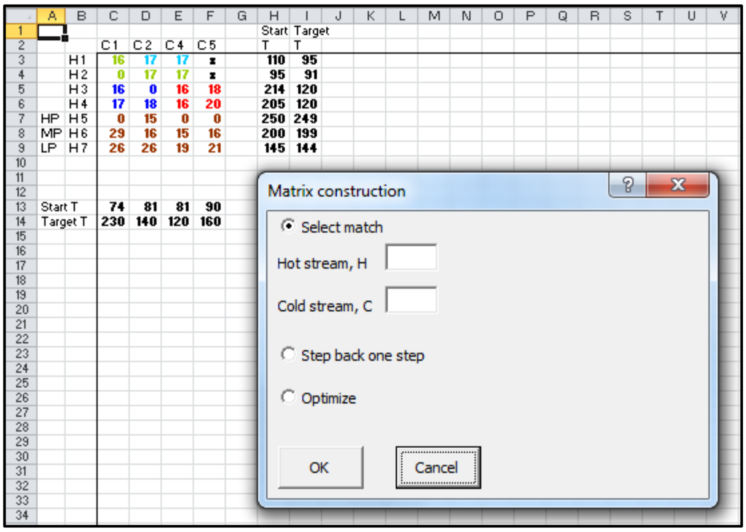
The two parts of the network are investigated separately. In order to calculate the first matrix, the user can choose to assume that existing HEX's have no cost (drive electricity is not included) or he can decide to also add the pumping costs. Then, the matrix is calculated in the sheet MBP as in Figure 6.4 (respectively MAP for the part of the network above pinch). In the matrix, rows correspond to hot streams and columns refer to cold ones. The starting and targeted temperatures of the streams are also specified and updated every time a match is selected and a new matrix is generated. Every cell of the matrix represents the annual cost of the corresponding match including both capital and operating costs. The heat load allocated to every HEX is assumed to be equal to the highest load thermodynamically possible. But that load might be limited by the minimum temperature difference inside the HEX, specified by the user to prevent costly heat exchanging, as explained previously.

The different possible matches gathered in the matrix are classified into six different categories (see Table 6.6). Here is the description of these categories below the pinch (same for above the pinch area if "cold" is replaced by "hot" and "below" by "above"):

Table 6.6 Description of the different possible types of matches in Matrix.xla

Color in the matrix	Description of the type of match.
Red	The hot stream is ticked-off below the pinch.
Dark blue	The cold stream is ticked-off. The hot stream cannot be used immediately in the next match below the pinch.
Light blue	The cold stream is ticked-off. The hot stream will be ticked-off if it's used immediately in the next match below the pinch.
Green	The cold stream is ticked-off. The hot stream can be used immediately to tick-off another cold stream below the pinch.
Orange	No tick-off.
X	The match is not thermodynamically possible.

Then, the user has to enter the names of the streams he wants to match.



		C1	C2	C4	C5	Start T	Target T
	H1	16	17	17	x	110	95
	H2	0	17	17	x	95	91
	H3	16	0	16	18	214	120
	H4	17	18	16	20	205	120
HP	H5	0	15	0	0	250	249
MP	H6	29	16	15	16	200	199
LP	H7	26	26	19	21	145	144
Start T		74	81	81	90		
Target T		230	140	120	160		

Matrix construction

● Select match

Hot stream, H

Cold stream, C

○ Step back one step

○ Optimize

Figure 6.4 Example of the sheet MBP in Matrix.xla

In order to select the optimum matches, the user can choose to follow the iterative method, see Chapter 6, and in particular Section 6.3.3. The main idea is to select the cheapest match possible but considering that a cheap match might lead to an expensive one at the next step. It is then sometimes better to choose a slightly more expensive match in order to be able to select a cheaper one at the next step. This is why an iterative method is required here, like the procedure developed by Franck and Berntsson (1999).

Utility streams are also included in the method. The location and size of the heaters are identified when there are only cold streams remaining above the pinch. It is the same for coolers which are located and get their load calculated when there are only hot streams remaining below the pinch. The cost of these utility matches is included in the final solution.

These costs are affected by the choice of the type of utility made by the user. Indeed, utility data has to be filled in the “SD data” sheet by the user that can give information about several potential kinds of utilities among which the Matrix method optimizer will have to choose to get the lowest total cost. Here, the assumption is made that utility is unlimited and it is also assumed that the type of utility has to be chosen to optimize the investment cost. However, very different solutions could be reached concerning utilities if the user would like to optimize the pay-back period instead, which would result in prioritizing LP steam as hot utility rather than HP steam for example. That choice is not given to the user in the current program.

The design is finalized when all the streams have been ticked-off. Costs and data of the different matches are stored in the sheet HXB (respectively HXA). This sheet enables the user to identify the most expensive matches. If such matches are too costly in comparison to the overall cost, then another solution without these matches should be investigated, giving priority in matching the streams that were concerned by these costly HEX’s.

6.3 Automated routine program

The automated routine program (Matrix method optimizer) written by Andersson (2001) calculates the optimal solution to a retrofit problem of a HEN, that is, the most cost effective one. The routine can shortly be described as an iterative process that follows a defined pathway towards the most cost optimal solution. Andersson (2001) represents the whole evaluation problem of a HEN as a tree in his thesis. The initial cost matrix that is constructed for the HEN according to the Matrix method is referred to as the “root node” and there is only one root node. A choice of adding/removing heat from any stream(s) is a “pathway” towards a new constructed matrix which is a new node. Each possible pathway from the root “branches out” as an intermediate node and these “branch out” as terminal nodes. The pathway from a terminal node up to the root node is defined as a complete possible solution. The further any path is followed from the root, the higher the partial cost of the network will be until a solution is reached. Sometimes it is impossible for any match between streams to be selected as this is thermodynamically unfeasible, in such a situation, the program steps back to a previous branch and tries to find another solution.

6.3.1 Matrix behavior

In the Matrix method optimizer, the rows of a matrix represent cold streams and its columns represent hot streams which is the other way around from how a matrix is presented in Matrix.xla (Franck och Berntsson 1999). As a match is selected, a new possibly smaller matrix is constructed according to the following procedure:

- A tick-off of a cold stream results in a new matrix with the corresponding row taken away and new values added to the corresponding column
- A tick-off of a hot stream results in a new matrix with the corresponding column taken away and new values added to the corresponding row
- No tick-off of any stream results in a new equally sized matrix with new values added to the corresponding column and row, however the same match cannot be selected again immediately

As the first “root node” matrix is constructed by the program, it selects a match and registers the cost. The next matrix is then constructed and a new match is selected and the cost for this match is added and registered to the partial cost of the solution. This is repeated until the end of a branch is reached and no more HEX’s can be added to the list. The end of a branch is reached either if a solution has been found or if there is no possibility to continue, a dead-end. If a dead-end is reached, the routine takes one step back and tries to find a solution through another branch by selecting a different match in the previous step of the routine. This is repeated until a solution is found and once a solution is found, that is; if all the hot streams above the pinch or all the cold streams below the pinch are empty, the utility matches are optimized. The costs for the utility matches are added to the partial solution cost and this will represent one complete solution with a total cost, the end of a branch. When all the stream combinations are checked by the program and the resultant costs are calculated, the HEN is fully evaluated according to the Matrix method.

6.3.2 Optimization strategies

The Matrix method optimizer is using 5 different strategies for its cost optimization of HEN's to work as fast as possible.

6.3.2.1 Upper bound tree search

Once a solution has been calculated, this cost will be recorded as an upper bound limit for the rest of a tree search. After this has been done, the optimizer steps back and continues searching by matching streams along other branches, however if the partial cost will reach a cost higher than that of a previous complete solution, the branch investigation will be terminated in order to save iteration time and the optimizer steps back once again until a new solution is possibly reached. When all the combinations on one level have been tested, the optimizer steps back and tests all the combinations on a previous level until all the relevant combinations have been tested. If a new cheaper solution is found, this will be recorded as the new upper bound limit and the search will continue as previously with this new upper bound limit in attention for future branch search terminations, see Figure 6.5.

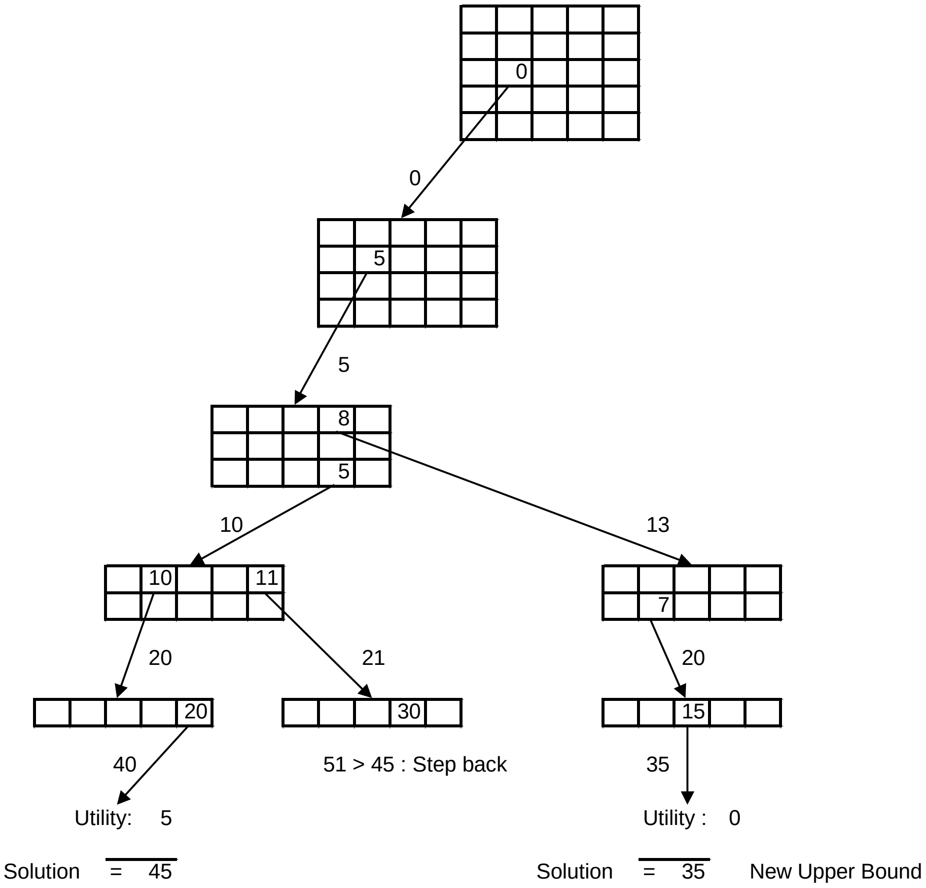


Figure 6.5 Example of the search strategy inside the Matrix method optimizer tool

6.3.2.2 Arrangement

The construction of each new matrix involves an arrangement of the costs according to their amount. This is done so that the optimizer selects the cheapest cost match of each matrix first and therefore almost certainly finds a low upper bound limit as early on in the routine as possible. The amount of iterations will be less this way and therefore iteration time will be saved in order for the optimizer to work faster. To understand how this is performed, see Anderson (2001), Chapter 3.2.2.

6.3.2.3 Combination check

Whenever a new matrix is constructed, only the corresponding match row and column will be altered. Therefore multiple matches checked in any order may not affect each other. These are called independent matches and will result in a matrix looking exactly the same no matter the order these independent matches are chosen. A combination check is thus implied to avoid the same calculations several times by the program since the resulting matrix will look the same anyway. Hence, independent matches are stored in the memory and one resulting combination of independent matches will never be calculated more than once. This saves iteration time further.

6.3.2.4 Pinch violation check

There is a function in the optimizer routine that makes sure that “the three golden pinch rules” are not violated. This is called temp_possible. If heating needs to be done below the pinch or if cooling needs to be done above the pinch, temp_possible tells the program to stop the evaluation of the matrix branch and find another branch to work on. That can happen for example when the lowest targeted temperature of the hot streams is lower than the lowest starting temperature of the cold streams above the pinch. In such a case, a cold utility would be required which is a violation above the pinch. Heating through the pinch is not considered as the problem is divided into two parts on each side of the pinch.

6.3.2.5 Loop check

If several HEX’s are used on the same matches of streams more than once, this will result in a rapid cost increase. Normally, the upper bound limit optimization will take care of this problem by not letting the optimizer continue on such a branch. Nevertheless if the first solution investigated is a branch like this and no upper bound limit has been registered yet, iteration time may be wasted on checking such combinations. Loop_check is therefore an optimization function that makes sure that the optimizer does not select a match between two streams if a HEX already is connecting them from a previous step.

6.3.3 Flow chart

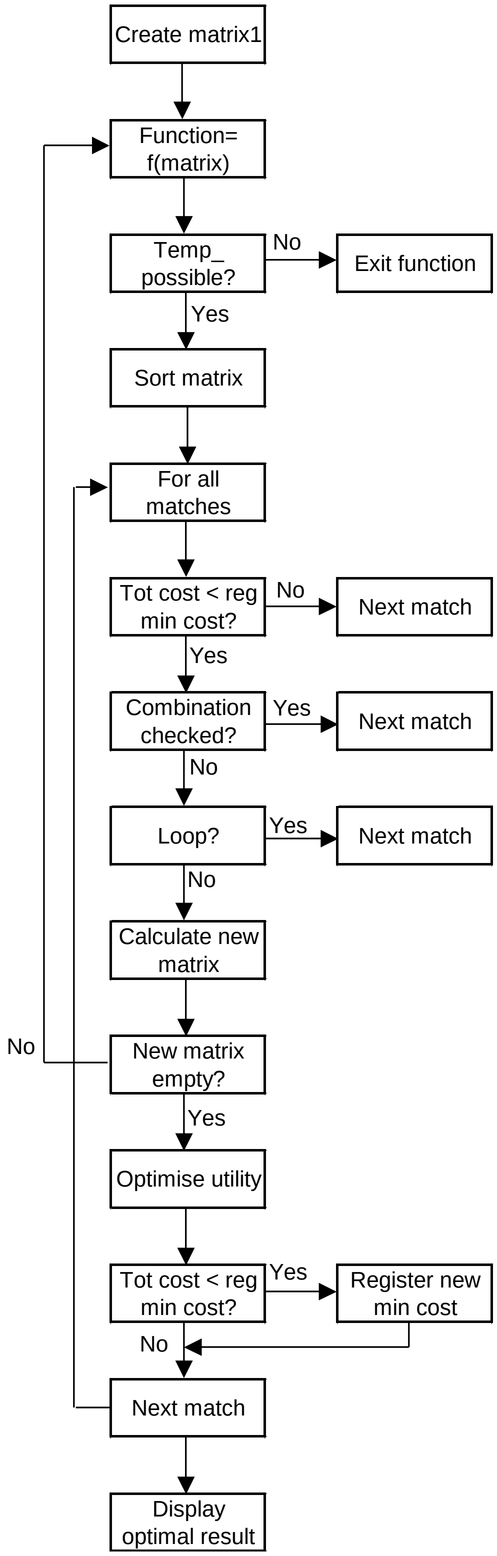


Figure 6.6 Flow chart describing the Matrix method optimizer procedure.

7 Description of issues in the Matrix method, the calculation tool and the optimizer

In the Matrix method the problem is divided into two parts by dividing the network at the pinch point. Each problem (above and below the pinch) is then solved separately. If the user chooses to reach a retrofitted network achieving the MER for a specific ΔT_{min} then, all the pinch violations across the pinch will be rearranged. Then, no criss-cross is allowed in the pinch region and the division of the problem into two might result in the following issue:

A small part of a stream involved in a violation might end up on one side of the pinch while its major part remains on the other side. In such a case, the method might use a different HEX for each part of the stream while it would be cheaper to match this stream with only one HEX crossing the pinch. That means that it would be cheaper to merge the two HEX's by allowing the small part of the stream to violate the pinch rule.

In order to handle this issue, the current Matrix calculation tool enables the user to choose which violations he wants to rearrange or not. That allows a more flexible division of the network and can reduce the number of new units and extended HEX's required considerably, resulting in a cheaper overall solution. However, this division will impact the energy recovery level every time a violation will be tolerated.

Moreover, there is no priority rule to handle the violations in the present Matrix calculation tool Matrix.xla. It is up to the user to choose which violations to accept or not. Then, a match that violates the pinch with only a small part of its total heat load can be equal in priority for rearrangement to another HEX that violates the pinch with its entire heat load if the user chooses so. That might lead to rearrange a complete HEX for solving a minor violation instead of using this money for fixing a bigger violation. The optimal choice of units to rearrange has to be identified. This is not handled by the current calculation tool and is requiring the user's knowledge and experience to prioritize the violations by considering both their size and their cost per unit of saved energy. A method developed by Carlson (1996) exists and could be implemented in the Matrix.xla program. That step of the program could easily be automated in order to prevent expensive retrofit solutions.

7.1 Merging the solutions above and below the pinch

The flexible division of the network described above also brings a second issue. Since some pinch violations are allowed, it is possible that the same HEX appears in the solutions both above and below the pinch, because the two problems are solved independently. That has no direct consequences if it is an already existing HEX since its cost is set to zero in this case, but it would have consequences on the final solution if it implies a HEX with costs since the total cost is the addition of the solutions above and below the pinch.

Consequently, the user has to compare solutions above and below the pinch to verify if any HEX appears on both sides or if two exchangers on different sides can be put together as one (how to know if it is possible)

Example 1:

In this example, we use the Matrix method to retrofit the following network:

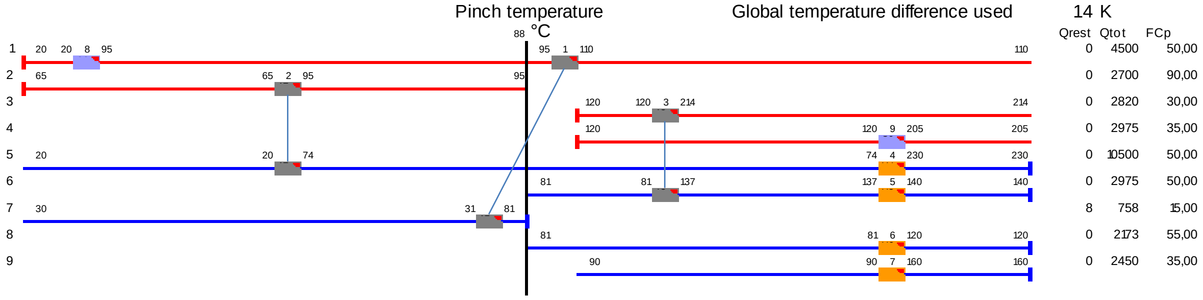
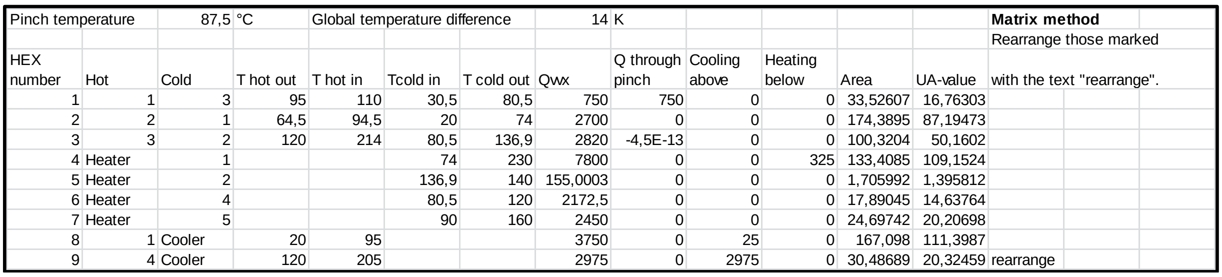


Figure 7.1 Initial network represented in Pro-Pi for example 1

We decide to rearrange only one violation, the cooler on hot stream 4:

Table 7.1 Selection of violations to be rearranged in Matrix.xla for example 1



Pinch temperature		87,5	°C	Global temperature difference			14	K					Matrix method
													Rearrange those marked
HEX number	Hot	Cold	T hot out	T hot in	Tcold in	T cold out	Qwx	Q through pinch	Cooling above	Heating below	Area	UA-value	with the text "rearrange".
1	1	3	95	110	30,5	80,5	750	750	0	0	33,52607	16,76303	
2	2	1	64,5	94,5	20	74	2700	0	0	0	174,3895	87,19473	
3	3	2	120	214	80,5	136,9	2820	-4,5E-13	0	0	100,3204	50,1602	
4	Heater	1			74	230	7800	0	0	325	133,4085	109,1524	
5	Heater	2			136,9	140	155,0003	0	0	0	1,705992	1,395812	
6	Heater	4			80,5	120	2172,5	0	0	0	17,89045	14,63764	
7	Heater	5			90	160	2450	0	0	0	24,69742	20,20698	
8	1	Cooler	20	95			3750	0	25	0	167,098	111,3987	
9	4	Cooler	120	205			2975	0	2975	0	30,48689	20,32459	rearrange

Here are the results given by the Matrix method, using the Matrix method optimizer (see Table 7.2 and Table 7.3):

Table 7.2 Results given by the Matrix method optimizer below the pinch for example 1

HEX	Hot stream	Cold stream	T hot in	T hot out	T cold out	T cold in	Q match	Annual cost
1	2	1	94.5	64.5	74	20	2700	0
2	1	3	110	94.85	80.5	30	750	0
3	1	6	94.85	20	15	10	3742.5	0

Table 7.3 Results given by the Matrix method optimizer above the pinch for example1.

HEX	Hot stream	Cold stream	T hot out	T hot in	T cold in	T cold out	Q match	Annual cost
1	1	3	95	110	30.5	80.5	750	0
2	3	2	120	214	80.5	136.9	2820	0
3	4	1	120	205	74	133.5	2975	16.93208
4	5	1	249	250	133.5	230	4825	0
5	5	2	249	250	136.9	140	155	0
6	5	4	249	250	80.5	120	2172.5	0
7	5	5	249	250	90	160	2450	0

The HEX between Hot stream 1 and Cold stream 3 is present both in the solution above and below the pinch. Since it is not a HEX that has to be rearranged and because it already exists, its cost is equal to zero and then, the fact that it is present in both solutions will not affect the final result.

<u>Example 2:</u>

In this second example, we use the exact same network as in example 1 but in addition to the cooler on hot stream 4 we also decide to rearrange the HEX between hot stream 1 and cold stream 3. Here are the results for both sides of the problem (see Table 7.4 and Table 7.5):

Table 7.4 Results given by the Matrix method optimizer below the pinch for example 2

HEX	Hot stream	Cold stream	T hot in	T hot out	Tcold out	T cold in	Q match	Annual cost
1	2	1	94.5	64.5	74	20	2700	0
2	1	3	95	79.85	80.5	30	757.5	12.4434
3	1	6	79.85	20	15	10	2992.5	0

Table 7.5 Results given by the Matrix method optimizer above the pinch for example 2

HEX	Hot stream	Cold stream	T hot out	T hot in	T cold in	T cold out	Q match	Annual cost
1	3	2	120	214	80.5	136.9	2820	0
2	4	1	120	205	74	133.5	2975	16.93208
3	1	4	95	110	80.5	94.13636	750	17.20568
4	5	1	249	250	133.5	230	4825	0
5	5	2	249	250	136.9	140	155	0
6	5	4	249	250	94.13636	120	1422.5	0
7	5	5	249	250	90	160	2450	0

In that case, the HEX between hot stream 1 and cold stream 3 is rearranged and then it only appears in the solution below the pinch, with the corresponding cost to move it from through the pinch to below the pinch. This cost corresponds to the new additional area cost and the investment cost to modify the HEX.

Example 3:

In this example we consider a new network (see Figure 7.2).

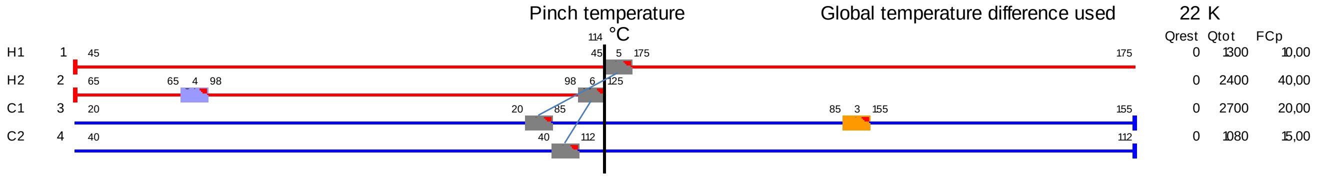


Figure 7.2 Initial network represented in Pro-Pi for example 3

Then, we proceed with the Matrix method and decide to only rearrange the violation of the HEX between hot stream 1 and cold stream 1 and the violation of the heater on cold stream 1 (see Table 7.6).

Table 7.6 Selection of violations to be rearranged in Matrix.xla for example 3

Pinch temperature		114	°C	Global temperature difference			22	K					**Matrix method**		
													Rearrange those marked		
HEX number	Hot	Cold	T hot out	T hot in	Tcold in	T cold out	Qwx	Q through pinch	Cooling above	Heating below	Area	UA-value	with the text "rearrange".		
3	Heater	1			85	155	1400	0	0	360	32,84388	26,87227	rearrange		
4	2	Cooler	65	98			1320	0	0	0	32,57844	21,71896			
5	1	1	45	175	20	85	1300	500	0	0	51,23735	25,61868	rearrange		
6	2	2	98	125	40	112	1080	-135	0	0	71,7837	35,89185			

Then, we use the program to divide the network into two parts and find a solution for each of these problems, see Table 7.7 and Table 7.8.

Table 7.7 Results given by the MM Optimizer above the pinch for example 3

Tot #	**Hot stream**	**Cold stream**	**T hot out**	**T hot in**	**T cold in**	**T cold out**	**Q match**	**Annual cost**
1	1	1	125	175	103	128	500	0
2	2	2	98	125	40	112	1080	0
3	3	1	179	180	128	155	540	0

Table 7.8 Results given by the Matrix method optimizer below the pinch for example 3

Tot #	Hot stream	Cold stream	T hot in	T hot out	Tcold out	T cold in	Q match	Annual cost
1	2	2	125	98	112	40	1080	0
2	1	1	125	91	103	86	340	11,63981
3	2	1	98	65	86	20	1320	16,44882
4	1	3	91	45	25	15	460	11,91078

We can see that both HEX's between H1-C1 and H2-C2 are present in the solutions both above and below the pinch. This is not an issue for the HEX linking hot stream 2 to cold stream 2 because this HEX is already existing and we decided not to rearrange it, then it will not induce costs. However, the HEX between hot stream 1 and cold stream 1 brings issues. Indeed, above pinch it has not any cost because this HEX already exists and does not require any changes in its area here. But, if we consider its price below pinch, this value is calculated by considering the area changes AND the unit capital cost. The Matrix calculation tool considers that this HEX is a different one below pinch than the one above pinch and consequently considers that a new HEX has to be built below pinch. Consequently, the Matrix calculation tool considers that the final solution is as represented on Figure 7.3:

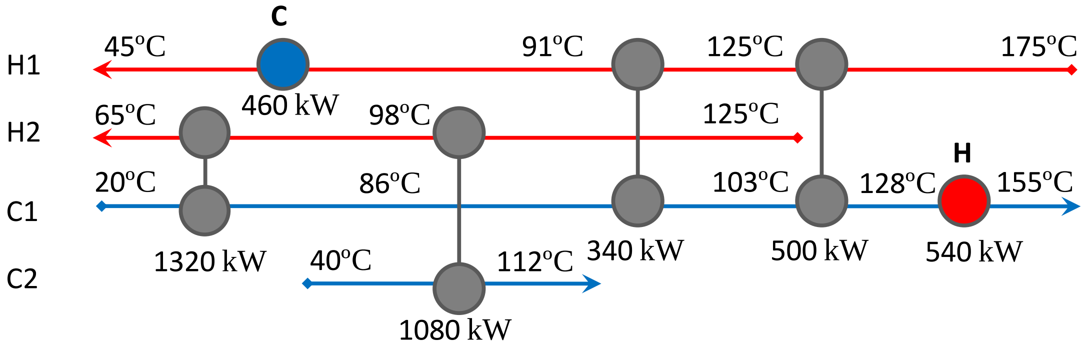


Figure 7.3 Final merged solution for example 3 as considered by the program.

In reality, the two HEX's between H1 and C1 are the same HEX. Consequently, the total price of the retrofitted solution should not consider any capital cost from this HEX that already exists. The only cost that should be included is that of its area modification. That issue is really important to fix in the Matrix calculation tool because it means that in some situations, the additional cost generated by this mistake can lead to avoiding this solution and choose a retrofitted network that is not the real optimal solution.

To summarize, there are mainly two issues in the current Matrix calculation tool, arising from the separation of the network into two parts:

- When a HEX is allowed to violate a pinch rule by not being retrofitted, it might appear in both the solutions above and below the pinch. Since it is not rearranged, such a situation will not impact the calculation of the total cost of the final solution. The main issue here is that the user should be careful and not forget to consider this HEX as only one when he will gather the two solutions to get the final retrofitted network.

- If the same two streams are matched above and below the pinch, the Matrix calculation tool might generate two different HEX's (one for both sides). That might generate additional costs because the calculation tool will consider two different capital costs while these HEX's can be combined in a unique one in the final solution. This issue requires the user to be careful when applying the tool but it might also lead to non-optimal solutions. Indeed, the additional cost generated by the division of this HEX into two different ones might lead the Matrix method optimizer to consider that this solution is not the most economical one while it should be. It is then important to try to find a way to cope with this issue, inside the calculation tool or the optimizer itself.

7.2 How to handle stream splitting

7.2.1 Definition + Example

In some cases, a stream should be split in order for a retrofit problem to be solved or to reduce the number of units as the unit cost is a large part of the HEX cost. Such a case can occur when the amount of hot and cold streams with starting/ending temperatures close to the pinch do not match each other and when the criteria for the temperature driving forces are not met.

The criteria to be met for design at the pinch according to Kemp (2007) are as follows:

- Above the pinch: $FCp_{hot} \leq FCp_{cold}$ $N_{hot} \leq N_{cold}$
- Below the pinch: $FCp_{hot} \geq FCp_{cold}$ $N_{hot} \geq N_{cold}$

F stands for mass flow of the stream (kg/s), Cp is the specific heat for the fluid in the stream (kJ/kg·K) where hot and cold denotes whether it is for the hot or the cold stream. N stands for the amount of stream branches at the pinch (including both split and full streams).

A relevant example is illustrated in Figure 7.4 below where the streams of an organic distillation are illustrated.

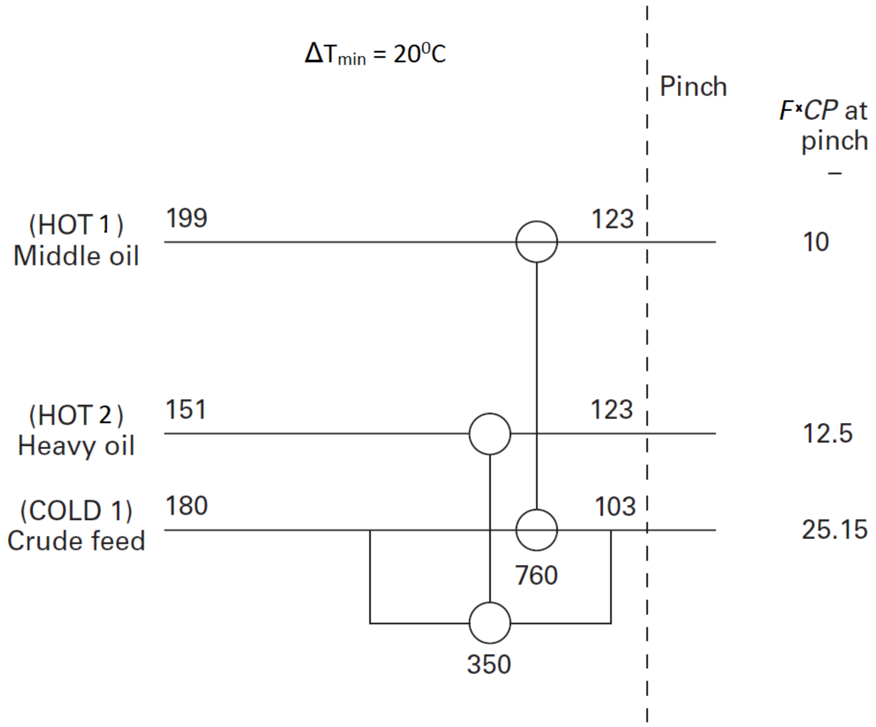


Figure 7.4 Example of network where a stream split is required.

In this situation the ΔT_{min} has been set to 20^0C and therefore it is impossible to get a solution by interchanging HEX's. A split of the cold stream is necessarily done as seen in the figure in order to avoid cooling above the pinch and thus solve the MER retrofit problem. This split is motivated due to the fact that the amount of cold streams is less than the amount of hot streams according to the criteria above combined with the fact that cold stream 1 has a higher FCp value.

There is an algorithm that helps the user knowing when and when not to split a stream due to the previous criteria given. This algorithm is expressed in Figure 7.5. It does not give answers about which stream to split and in what proportion but it can be combined with a method from Kemp (2007) and in particular Section 4.3.1 to solve these issues.

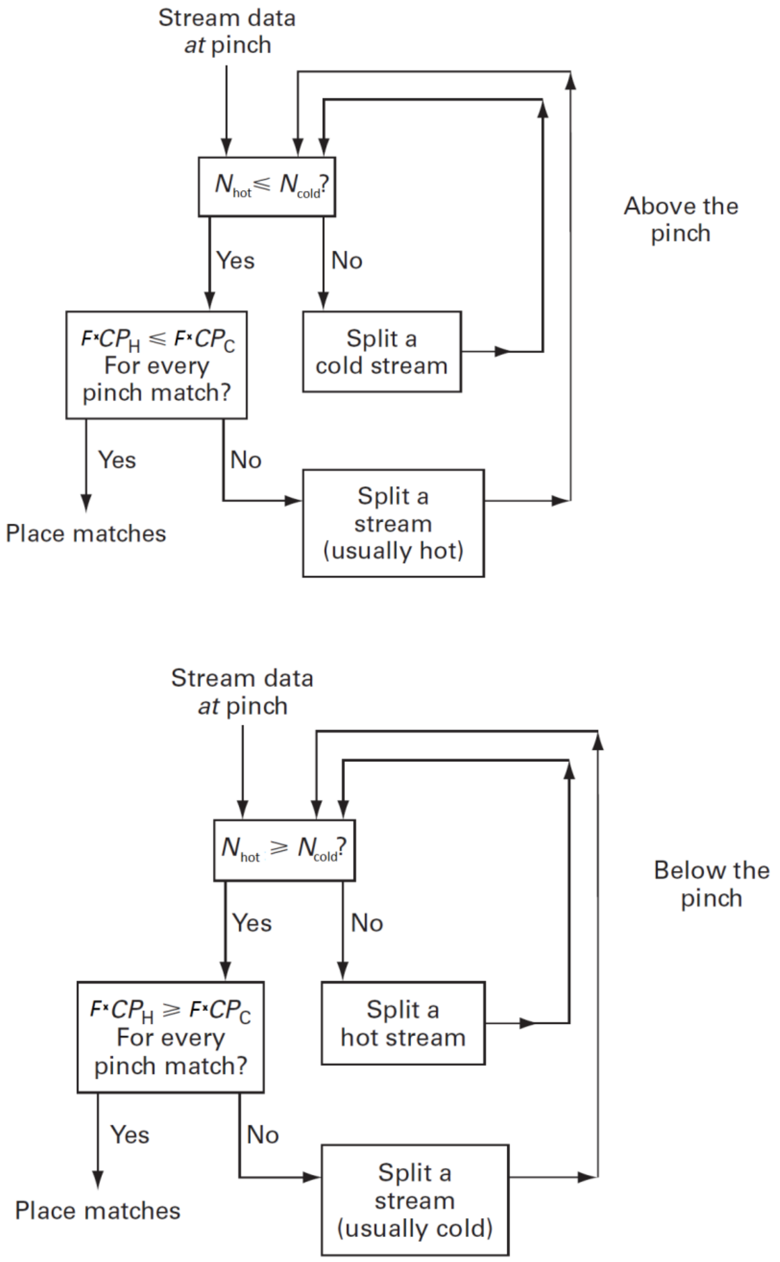


Figure 7.5 Algorithms from Kemp (2007) to help the user to identify when a split is required

7.2.2 Limitation

Currently, neither the Matrix method nor its calculation tool includes a proper methodology for stream splitting(s) in order to solve a retrofit problem. The Matrix method optimizer includes a simple evaluation of the HEX matches calculated in order to identify loops that might be avoided with a stream split. However, the actual split then has to be done manually by the user. Pro-Pi does not include an option for stream splitting either due to programming difficulties and this is not properly included in Matrix.xla (Franck och Berntsson 1999) and the Matrix method optimizer (Andersson 2001) either. If a stream is decided to be split, this needs to be done manually by starting the process over again from the beginning and altering the input stream data sheet for Pro-Pi. In the optimizer; if the only possible solution is to split a stream or a cost efficient solution is a stream split, the internal function temp_possible will terminate the branch as a stream split will not be an option and thus this solution is left out of the final evaluation of the matrix.

Yet, the optimizer tool for Matrix.xla gives the user a hint that streams should be split if a large occurrence of repeatedly alternating HEX's is part of a branch result (see the following example). This is due to the internal function named Loop_check, previously described, that detects if there are many loops between the same two streams in a terminated solution branch. Nevertheless, a stream split can be very cost efficient and "in a retrofit situation the heat exchanger area, piping, and pressure drops all influence the optimal way of splitting the stream" (Carlsson 1996). Furthermore, Carlsson (1996) mentions in her thesis that stream splits should be included in the Matrix method as the current approach of splitting a stream is based solely on judgment of the ΔT_{lm} and the temperature difference of the two sides of the relevant HEX.

Example:

If we consider the following network (see Figure 7.6) and try to retrofit it by applying the Matrix method with the optimization tool, we get no solution.

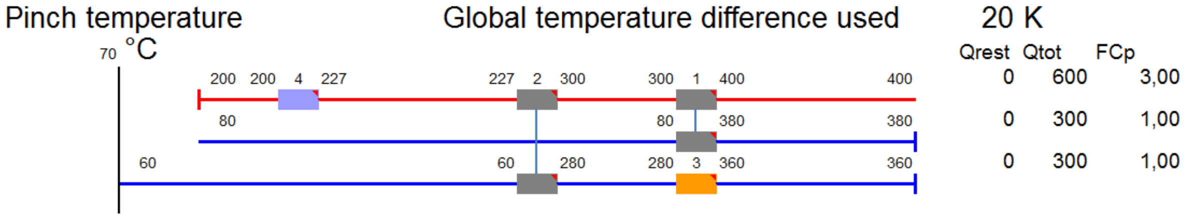


Figure 7.6 Initial network represented in Pro-Pi for example on stream splitting.

In the case below, non-tick-off matches have been selected between the streams C2 and H1 for example; creating loops between the two streams (see Figure 7.7)

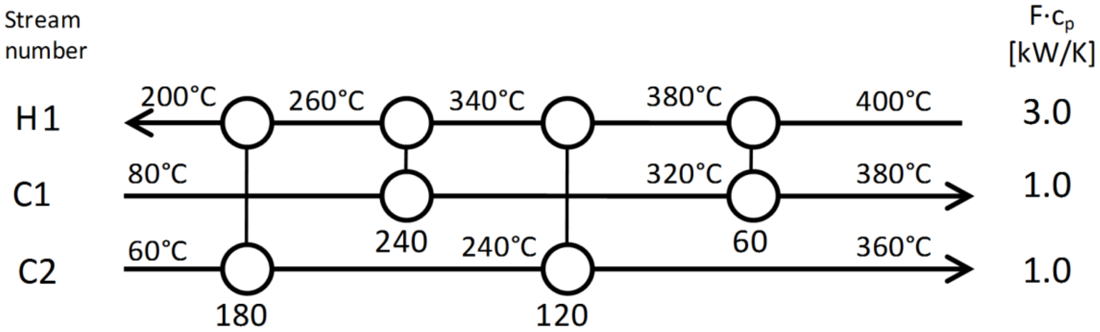
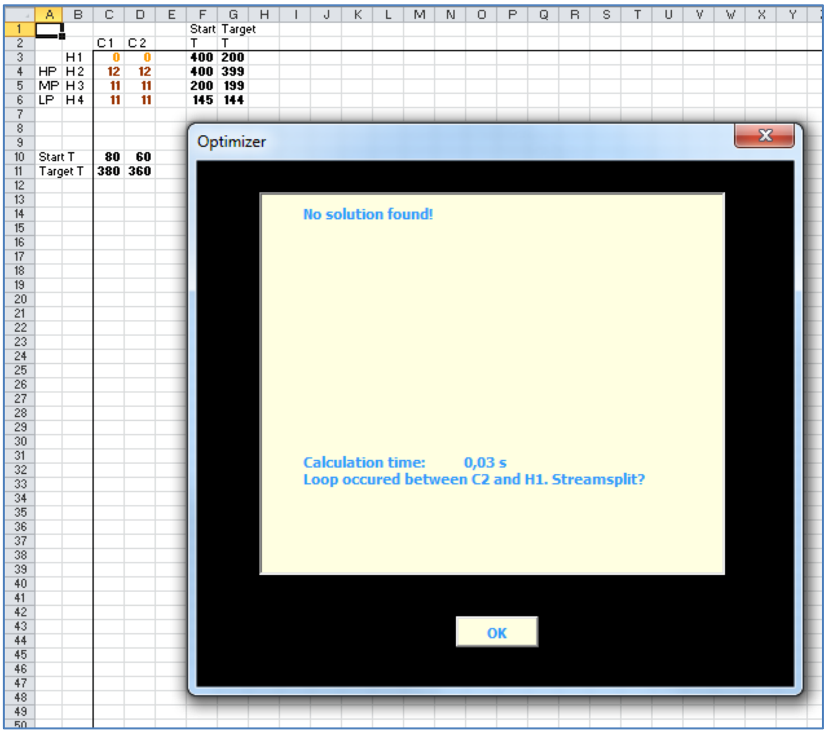


Figure 7.7 Retrofitted solution without stream split requiring loops.

The Matrix method optimizer reacts to the appearance of these loops by stopping the routine as soon as a loop is detected and makes a suggestion for the user to consider stream splitting as you can see on the following figure, extracted from the optimizer tool’s result window (see Figure 7.8).



A	B	C	D	E	F	G
					Start	Target
		C1	C2		T	T
	H1	0	0		400	200
HP	H2	12	12		400	399
MP	H3	11	11		200	199
LP	H4	11	11		145	144
Start T		80	60			
Target T		380	360			

No solution found!

Calculation time: 0,03 s
Loop occured between C2 and H1. Streamsplit?

Figure 7.8 Window resulting from using the Matrix method optimizer on the previous network, warning the user that loops are occurring and that consequently stream split(s) might be required.

It’s in this specific situation that more information about the stream split and a correct routine to do the split have to be offered to the user, so that he can get access to the optimal solution that is the one following, including a stream split (see Figure 7.9).

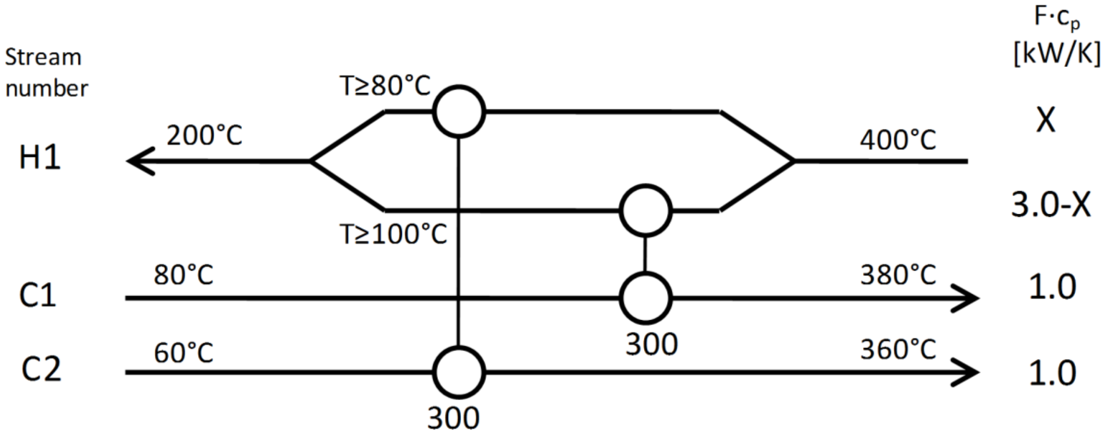


Figure 7.9 Optimal retrofitted network by splitting stream H1

This solution requires only two HEX's and not any heater nor cooler and is then the one that should be resulting from the Matrix method optimizer as the best retrofitted solution.

7.2.3 Possible improvement

"Since the streams are organized in a matrix, it is possible to apply an approximate stream splitting approach as suggested by Polley" (Carlsson 1996) to the Matrix method and the optimizing tool. This could be done by implying the stream splitting algorithm and a proper method for how to split what stream and to what extent as described in Kemp (2007), and in particular in Section 7.2.1. Since Pro-Pi shows difficulties in splitting streams due to programming issues, the Matrix method optimizer could perhaps be altered to do a stream split within the optimization calculations and then produce a new data input sheet for Pro-Pi where new streams are represented for a stream split if this is a cost efficient solution to the retrofit problem.

7.3 How to choose the optimum ΔT_{min}

To start the process of the Matrix method, the user has to decide a value of ΔT_{min}^{global}. The tool only helps the user in this choice by providing a table referencing the pinch violations of the existing HEX's for a list of various possible ΔT_{min}^{global}'s that could be inquired. The experience and knowledge of the user is required here. When the value of the ΔT_{min}^{global} is chosen, the whole method has to be processed. Then, the whole procedure has to be done again with a different value of ΔT_{min}^{global} in order to be able to draw several Cost vs Energy savings curves (see Figure 5.2). These curves will then enable the user to pick the optimum solution. Given that this is an iterative procedure, it would be interesting to improve the Matrix calculation tool Matrix.xla to make it able to run the complete method for a list of several values of ΔT_{min}^{global} in order to prevent the user from having to run the complete method several times.

7.4 Improvement of the internal calculations (Costs) and better simplifications

The main costs, like unit, piping, area and pressure drop costs are all included in the Matrix calculation tool. However some important costs such as space requirements and fouling are not included even though they are critical parameters in a retrofit design.

In addition to these omissions, some costs calculated by the current Matrix calculation tool are uncertain. The main uncertainty concerns the cost of piping. Indeed, in the current tool when a match between two streams is identified, the program can calculate which one of these streams is the least expensive to reroute and calculate the cost of new piping to bring the stream up to the second one and bring it back to its original location. This is calculated from fixed distances between the streams, though these distances could be updated after every match. This is because if we bring a stream next to another one for a first match and then use this stream again in a second match, it may be cheaper to build new piping to bring it to the second match from the first match location, instead of it original position. It is also important to notice that the heat transfer correlation according to Kern (1950) is used, and to calculate the optimum piping design considering pressure drops and pipe diameters, routines from Coulson and Richardson (1983) are used. It may be interesting to look at these theories and see if they can be improved with updated knowledge.

Moreover, other assumptions are made inside the program. First, Shell-and-tube heat exchangers are assumed except for gas streams in which case ideal tube banks are assumed. Condensation is assumed to be on the shell side, then, evaporation will be on the tube side except when the hot stream is a liquid. It has also been chosen to simplify the program and not to give information about the condensation of steam in heaters. It may be interesting to consider more accurate calculations here and to give the opportunity for the user to choose among different types of HEX's, including plate HEX's, independently of the nature of the streams, in order to better fit the situation and the network he/she has to retrofit.

Finally, the user has to specify several hard data for the different streams for the program to calculate the costs of the different matches. It may be interesting to link this data sheet to a database in order to help the user in this process and to keep the values updated. Indeed, prepared constants for investment costs for HEX's, pipes and pumps were set in 1999. While if we consider Figure 7.10 and Table 7.9 we can see that prices have increased by 78% for HEX's, by for 40% pumps and by 72% for pipes since 1999 (Chemical Engineering 2013) . These inflation rates should be used to update the data inside the program.

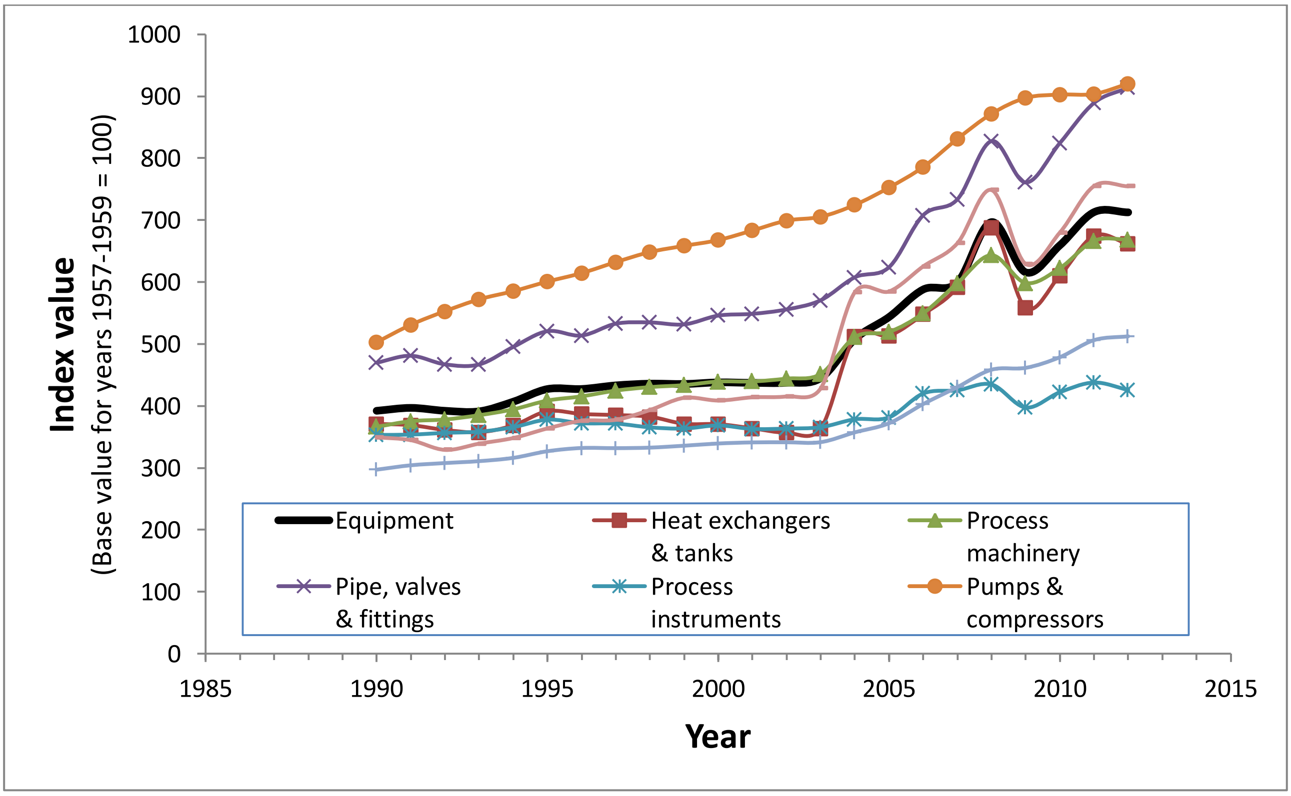


Figure 7.10 Equipment indicators chart

Table 7.9 Chemical Engineering Plant's Cost Index

Year	CEPCI	Equipment	Construction labor	Buildings	Engineering & supervision	Detailed Equipment indicators						
						Heat exchangers & tanks	Process machinery	Pipe, valves & fittings	Process instruments	Pumps & compressors	Electrical equipment	Stuctural support & misc
1990	357,6	392,2	271,4	329,5	355,9	370,9	366,3	469,8	353,3	502,9	297,1	349,4
1991	361,3	396,9	274,8	332,9	354,5	369,1	375,4	481,1	353,8	531,0	304,2	344,7
1992	358,2	392,2	273,0	334,6	354,1	361,3	378,2	467,2	356,6	553,0	307,8	329,1
1993	359,2	391,3	270,9	341,6	352,3	357,6	385,1	467,0	358,5	572,2	310,9	339,1
1994	368,1	406,9	272,9	353,8	351,1	368,6	394,6	495,3	365,7	585,3	316,2	348,2
1995	381,1	427,3	274,3	362,4	347,6	391,5	408,7	520,7	378,0	600,8	326,9	363,7
1996	381,7	427,4	277,5	365,1	344,2	387,1	415,5	513,7	372,1	614,5	332,1	376,0
1997	386,5	433,2	281,9	371,4	342,5	385,3	424,8	532,8	371,5	632,2	331,9	377,6
1998	389,5	436,0	287,4	374,2	341,2	382,7	430,5	534,8	365,5	648,5	332,8	393,5
1999	390,6	435,5	292,5	380,2	339,9	371,2	433,6	531,6	363,5	658,5	335,8	413,1
2000	394,1	438,0	299,2	385,6	340,6	370,6	439,4	545,9	368,6	667,8	339,4	408,8
2001	394,3	437,3	302,3	385,6	341,5	363,9	439,6	548,7	362,8	683,3	341,2	414,0
2002	395,6	437,5	305,8	390,4	345,3	356,9	444,2	555,8	363,5	699,2	341,4	415,5
2003	402,0	445,1	309,3	400,6	347,3	363,6	451,7	570,7	365,7	705,4	341,6	428,6
2004	444,2	508,1	307,7	427,7	345,2	511,8	511,3	607,8	378,5	724,6	357,4	583,9
2005	468,2	543,6	305,7	444,8	347,0	513,7	519,7	624,1	381,6	752,6	372,1	584,8
2006	499,6	588,0	309,3	468,6	350,9	548,0	549,7	708,0	420,1	785,7	403,1	625,3
2007	525,4	599,4	315,1	476,8	357,0	592,1	598,3	733,6	425,3	831,2	430,5	662,6
2008	575,4	696,8	321,8	506,9	352,9	687,6	643,4	827,6	434,7	871,7	458,5	748,7
2009	521,9	615,7	327,4	492,0	346,9	558,3	598,6	760,7	397,5	897,3	461,5	629,2
2010	550,8	659,4	328,9	504,3	339,1	610,4	622,5	824,4	422,2	902,6	478,7	680,0
2011	585,7	712,9	327,5	517,1	332,4	674,7	666,7	889,2	437,8	903,6	506,3	755,0
2012	584,6	712,5	322,6	525,6	328,2	661,7	668,7	913,8	425,8	920,1	512,5	754,6

7.5 Hot and cold utilities?

In the current Matrix calculation tool, the location and size of the heaters (coolers) are identified when there are only cold (hot) streams remaining above (below) the pinch. The cost of these utilities is affected by the thermodynamic data of the utility streams (given by the user). Several types of utility streams can be described so that the Matrix method optimizer can choose which one is going to be the most economical to match a specific stream with. The costs of the utility HEX's are only calculated when investments in new heaters or coolers are required, but these costs do not include the costs of the utility streams themself. This is understandable because the cost of the utility streams will not affect the process of the original Matrix method nor the final retrofitted design since the Matrix method is based on an energy recovery target (not an economic target). However, a certain level of energy recovery will not always give the same economic savings depending on what kind of utility that is reduced. It is therefore important to include the value of the utility streams within the automated procedure in order to identify the economically best retrofit design. Thus, very different solutions could be reached if the user would like to optimize the net annual profit instead of the HEN cost, which, for example, could result in prioritizing LP steam as hot utility rather than HP steam. Furthermore, by adding the cost of the utility streams we could improve the outcome for the user by giving figures on how much money that would be saved every year with this retrofitted network, and what the annualized net profit or payback period would be.

7.6 Other small issues

Table 7.10 Description of other small issues identified.

Issue detail	Category	Comments
Dealing with fouling of the streams is not included in the calculations.	Model issue	Fouling can have a cost depending on the nature of the streams and should be included in the model.
All solutions including loops are automatically rejected by the Matrix method optimizer.	Program issue	Solution including loops should be presented as results if they are the only possible result.
For unpinched problems, the Pro-Pi program puts the entire problem above or below the pinch. This means that if the HEN is put above pinch and heaters or coolers are present in the HEN, only the cooler will count as a pinch violation. However, heating will be a violation as well as it is unnecessary in this situation.	Program issue	Unpinched networks should be handled separately in the program so that both cooling and heating are considered as violations if unnecessary.
To handle the situation where a HEX already exists between two streams and a second one is added between the same streams in a different interval separated by a unit on one of the streams, the program will not consider investment costs for this second HEX.	Program issue	A control function should be added in the program so that it will be able to understand that an additional HEX is a new one even if these two streams already have been matched.
Sometimes the program calculates a value that is 40 times larger than expected when optimum piping is added to a HEX or a utility HEX match.	Calculation issue	The VBA code has to be investigated to find the origin of this error.
Pre entered in the sheet TD data, the automatic values for the FCP of the utility streams = density * mass-flow which is false.	Calculation issue	The VBA code has to be changed.

Unreliable annuity factor might appear in several situations, where it is automatically set to zero by the program, resulting in no annual cost.	Calculation issue	The VBA code has to be investigated to find the origin of this error.
Normally, whenever there is a pinch violation, if one does not enter the text “rearrange” next to that HEX in the pinch violation sheet, that stream will not be rearranged and thus that temperature interval will not be represented in the match matrix when doing a retrofit. This is correct. However, if a pinch violation does not occur, but one chooses to still not retrofit a certain heater, cooler or HEX, it will be retrofitted by the program anyway. There has to be a pinch violation occurring on a unit in order to have the option of not rearranging it.	Program issue	The code has to be modified so that the user can choose not to retrofit some units even if they do not violate the pinch rules.
Kinds of situations run manually, might lead the program Matrix.xla to give a solution while some streams still have not reached their target temperatures. That happens for example if you have a cold and a hot stream above the pinch and you decide to start by putting a heater on the cold stream. The program will tick-off the cold stream and give you the final solution without handling the hot stream.	Program issue	A function should be added to make sure that all streams reached their targeted temperature before delivering the final solution. Moreover, the program should be modified so that heaters and coolers can be placed anywhere in the network and not only at the extremities of the pinch (see Chapter 10)

8 Merging solution

In the previous chapter describing the issues of the current Matrix method and the calculation tool we have highlighted several issues about the merging of the solutions above and below the pinch in order to get the final solution.

- Issue1: If an already existing HEX is present in both solutions, it has no consequences on the results because it has no cost, nevertheless a warning should be given to the user to make him aware that this HEX is only present one time in the final solution. The best way to handle this issue would be to produce a unique final solution of the whole merged network.

- Issue 2: If a HEX that was previously across the pinch but is now moved to only one side of the pinch, we have to make sure that the Matrix calculation tool doesn't consider it as a new HEX and that its cost is only calculated from the extended area cost and the investment cost due to the modification of the HEX. There should not be any cost for investment in a new HEX here. More generally, every time the area of an existing HEX is increased (even if there is no violation) we have to make sure that the program doesn't consider it as a new HEX and doesn't add the corresponding investment costs. Only the extension of area should be added to the cost of the match.

- Issue 3: If an existing HEX is present in both solutions we have to make sure that the program won't consider it as two HEX's (the already existing one + a new one). We also have to make sure that all the area available from this HEX will be used before any additional costs of the area is calculated. Moreover, if a new HEX is present in both solutions, it shouldn´t be considered as two new HEX's, but only one.

In order to better understand how the program calculates the price of the matches and how it differs between the already existing HEX's and the new ones, we tracked this information inside the VBA code of Matrix.xla. The following diagram (see Figure 8.1) resumes the procedure followed by the program.

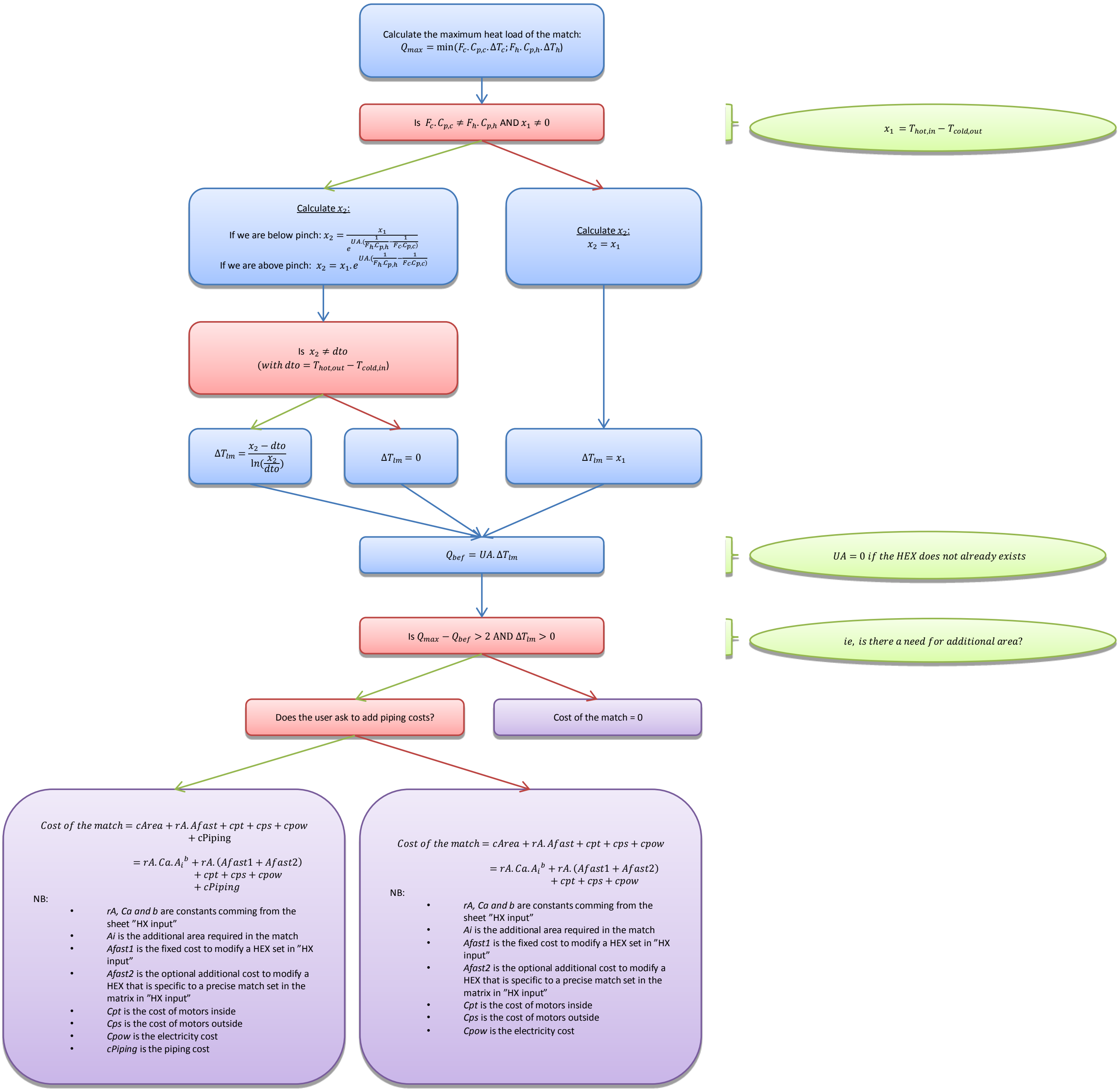


Figure 8.1 Diagram summing up the procedure followed by the program Matrix.xla to evaluate the cost of a match.

In this method used by the program we can see that there is no price difference between the cost of area that is added to an existing HEX and the cost of area for a new HEX. Since it is not the same cost (often more costly) to invest in a new HEX rather than extending an existing one, it would be a major improvement in the program to make it able to make this difference. The following explains how that easily can be implemented in Matrix.xla.

8.1 Difference of cost between extension area and new heat exchanger

The current total price for area is calculated as:

$$C_{Tot\ Area} = rA.Ca.A_i{}^{b} + rA.(A_{fast1} + A_{fast2})$$

We can consider that the area cost will stay the same for a new HEX except for that the fixed investment cost will be different. Then in the sheet “HX input” a new column A_{new} should be created next to the column A_{fast1} and the cost of area for a new HEX should be calculated as:

$$C_{Tot\ Area\ new} = rA.Ca.A_i{}^{b} + rA.(A_{new} + A_{fast2}).$$

The column A_{fast1} should be renamed to A_{add} and should only represent the investment cost for adding area on an existing HEX.

Then, the program has to know when it should pick the value A_{new} or A_{add} to calculate the area cost.

That is also easy to implement since the criteria already exists in the program but is not used properly. Indeed, in the sheet “UA data” the UA value of the existing HEX is automatically written by the program, based on the network to be retrofitted designed in Pro-Pi. The non-existing HEX’s have a UA value equal to zero in this sheet.

Consequently, just before the very last step in calculating the price of the match one more step consisting of checking the UA value should be added. If UA is equal to zero then A_{new} should be used. If UA is higher than zero then the program should proceed by using A_{add}.

Here we can highlight the fact that if a partial match is chosen between two streams, it should be stressed that two HEX’s (an existing one and a new one for example) might be present between the same streams on the same side of the pinch, creating a loop. Such a situation would compromise the UA criteria for the new HEX since this value would be different from zero. Nevertheless the program uses an internal function called “loop check” that immediately stops the routine from selecting a match between two streams that already have a HEX connecting them. Thus, the issue described above is not one anymore.

Moreover if the same issue occurs but with the existing HEX on the other side of the pinch than the new HEX (between same streams again) then, this situation is handled by the merging diagram described further in this chapter.

Here is the modified diagram taking the price difference between a new match and the increased area of an existing HEX into account (see Figure 8.2).

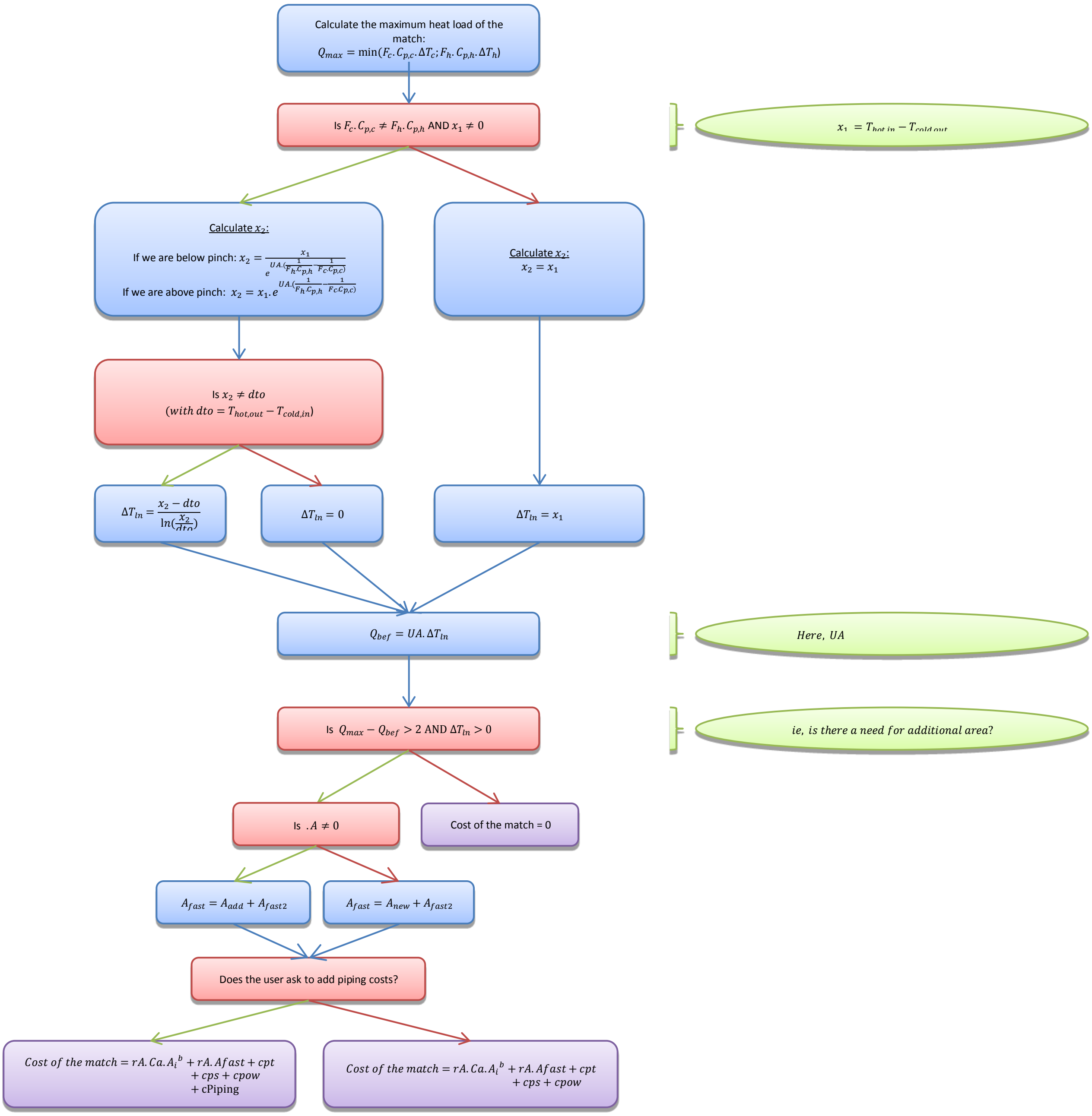


Figure 8.2 Diagram to evaluate the cost of a match taking the price difference of a new match and the increased area of an existing HEX into account.

Here we can also highlight the fact that there might be an issue in the calculation of the piping cost (pumps + pipes + electricity). Indeed, the program might not consider the additional pressure drops generated by an addition of area to an existing HEX. This increased pressure drop might require an increase in the power of the already existing pumps. Even if security gaps have been taken into consideration when they were designed the first time, they might still need to be replaced by more powerful pumps. That would have consequences on the investment price but also the running costs of the retrofitted solution. However, this is more related to the internal calculation issue and is not analyzed in this thesis.

Now, the next step is to consider this improvement of the program and to integrate it in the method aiming at generating the final merged solution.

8.2 Methodology to generate the final merged solution

In order to not completely change the Matrix method, we decided to keep the solving procedure based on the splitting of the network into two parts, above and below the pinch. Instead we developed a method based on the current one. A first solution is found either below or above the pinch and then, the second solution is built on the other side of the pinch. The difference from the current method is that this second solution will be built considering the first one. These two solutions will not be completely independent anymore.

When building the second solution, for every match investigated, the program will first have to check if this match already exists in the previous solution. If the match does not exists in the other side of the pinch then the program proceeds normally except for the fact that it has to check if this match just implies an extension of area or a new HEX. If the match already exists in the previous solution, the program has to check if the already calculated match and the newly calculated one both are close to the pinch. Indeed, if this is the case these matches can be merged together, but it is also possible to have two different HEX's working at temperatures far from the pinch, thus, two different HEX's are required. If the HEX's can be merged, the program has to check if additional area is required for this second solution, taking the fact that some area already might have been added or still is available from the previous solution into account. There is no need to check if this match requires a new HEX since this additional investment cost would have been added in the first solution. Moreover even if the user is required to consider piping costs, they should not be added here since they already have been added in the previous solution. However, if the match requires an increase in area in this second side of the pinch, additional pumping costs should be calculated and added to the ones calculated in the first solution.

Since the first solution impacts the design of the second one, this new procedure implies a requirement to be run several times with different solutions to the network on the first side of the pinch in order to not miss the optimal global retrofitted solution. This increases the complexity of the solution procedure as well as the calculation time. A compromise is to run the method at least twice, with the solution above pinch as first solution and then with the solution below the pinch calculated first.

Finally, the cheapest global solution will be presented to the user. This final solution should be presented to the user as one global solution and not as two different ones.

8.3 Diagram of the method

In this diagram (see Figure 8.3) we assume that the improvement to differentiate the cost of a new HEX from only additional area is integrated to the Matrix method.

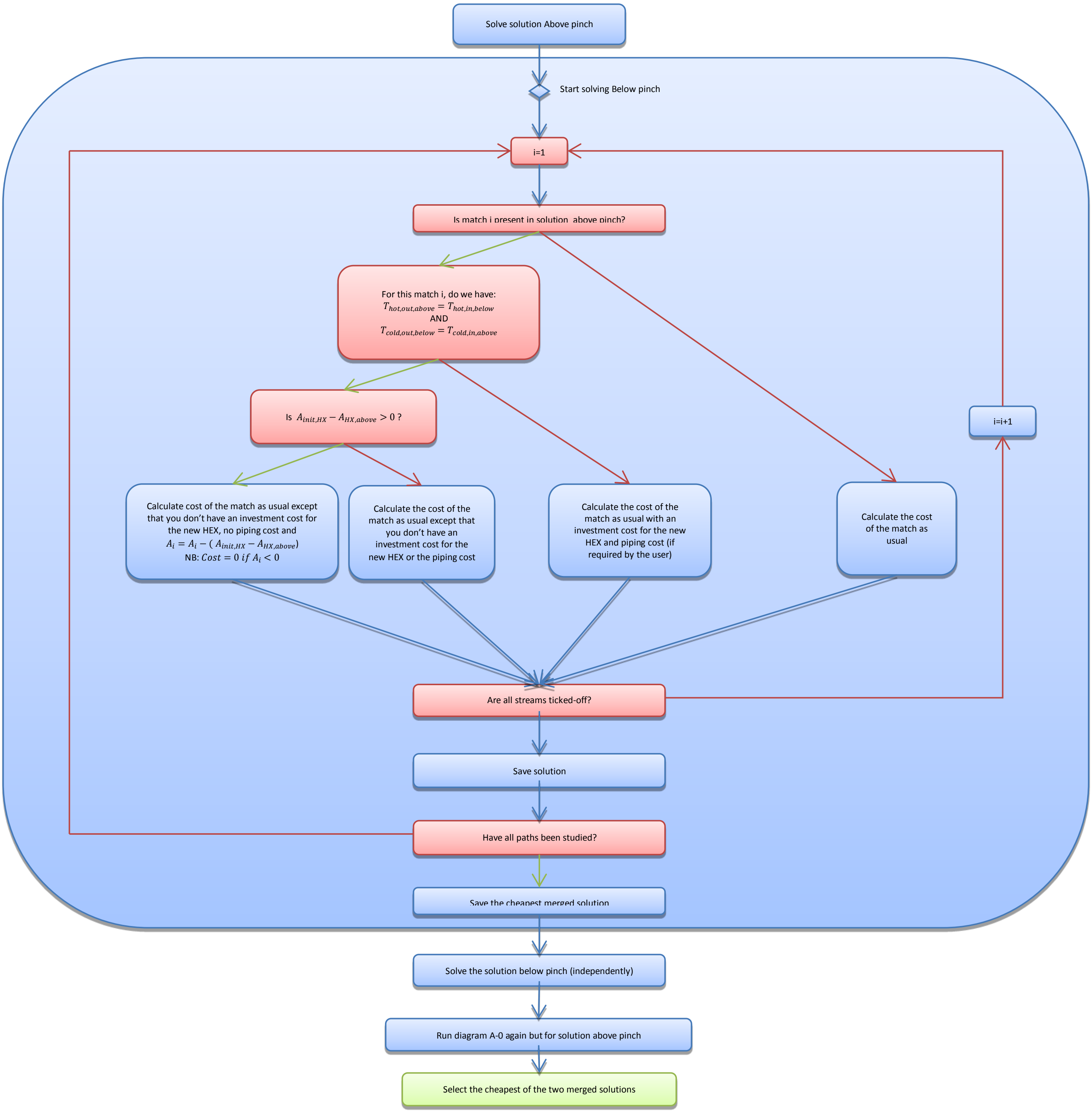


Figure 8.3 Diagram of a method to provide a merged retrofitted solution.

9 Solution for stream splitting

After running the Matrix method optimizer it is possible to end up with the result “no solution found” or “stream split?” suggesting a stream split to get a solution. So far, no tool is implemented to help the user with splitting some streams in the network to be retrofitted. Several situations might require a stream split to improve the retrofitted solution or to find a solution.

9.1 The two main situations requiring splitting

The first scenario consists of the case where the user runs the Matrix method and is unable to find any retrofitted solution for the level of heat recovery required. In such a situation, the opportunity of stream splitting should be considered to bring at least one correct solution to the retrofit.

The second situation is already identified in the current program. It consists of the situation where loops appear between two streams. This kind of loops requires a lot of units and thus, is an expensive way to solve the retrofit problem. Consequently the Matrix method optimizer cuts off the investigation of the branches involving such looping in HEN’s and suggests a possible stream split. Here again, an additional tool should help the user in identifying and proceeding with the optimal stream split in order to find an economic retrofitted solution (see example in Chapter 7, Section 7.2.2).

9.2 Using splitting instead of HEX’s requiring large areas

Stream splitting should not only be investigated when it is the only remaining way to find a solution. It should also be considered in order to optimize the retrofit solution from an economic point of view. Indeed, it is sometimes more expensive to invest in a new HEX requiring a large area than to proceed with a stream split. This kind of alternative is not included in the current Matrix method and could be an interesting improvement.

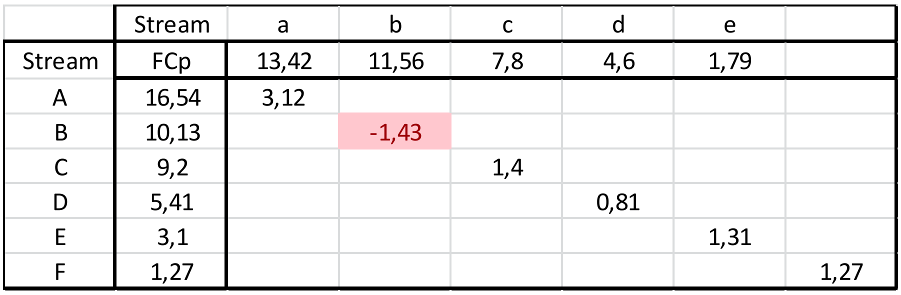
Moreover, an alternative to stream splitting should also be investigated every time a split is considered. This alternative consists of using a specific ΔT_{min} for some HEX’s instead of a global one for the complete network. Using individual ΔT_{min}’s is already available in the current method, but it should be interesting to investigate lower values in order to see if it would lead to a more economical solution than splitting the stream. Indeed, by reducing the ΔT_{min} of a specific HEX by a few degrees, it can prevent the user from the necessity of splitting a stream. However this decrease of the ΔT_{min} will induce some additional area costs. The balance between the cost of the split and the additional area cost should be evaluated in order to choose the cheapest option. The size of the HEN will alter its impacting result however. Indeed, choosing a more economic stream split in a small network instead of decreasing ΔT_{min} will have a considerable impact on a small network. However, if the network is much larger, the savings generated by investigating such a split will represent just a little part of the overall retrofit cost. Consequently, investigating stream splits in situations that can be handled in a classic way may not always be as interesting as it looks like, especially for large networks.

9.3 Identification of streams to split

First we investigate the situation where a split is required in order to be able to find a solution to the retrofit problem. That means that the Matrix method has to be run before without succeeding in finding any solution. In order to identify the streams that have to be split we developed a method inspired from Polley (1993) aiming at selecting stream splits in HEN designs (grass root method) and adapted it to a retrofit situation. The first difference between Polley´s method and ours is that in a retrofit situation it can be allowed, for economic reasons, to keep some pinch violations in the retrofitted network. Thus, the first step of the method consists of listing the existing HEX's and identifying which ones to retrofit.

Then, the minimum temperature approach between matches should occur at the pinch. In order not to violate the ΔT_{min} constraint, the matched streams' temperature profiles should not converge as we move away from the pinch. Consequently, retrofitted matched streams have to verify the criteria: $FC_{p,in} < FC_{p,out}$. If this rule cannot be observed for all retrofitted matches then a split is required. In order to help the user to verify this criterion, an FC_p matrix is built (see Table 9.1).

Table 9.1 Example of a FC_p*-Matrix inspired from Polley (1993) to help the user to identify which match does not respect the* FC_p *rule.*



	Stream	a	b	c	d	e	
Stream	FCp	13,42	11,56	7,8	4,6	1,79	
A	16,54	3,12					
B	10,13		-1,43				
C	9,2			1,4			
D	5,41				0,81		
E	3,1					1,31	
F	1,27						1,27

Streams in capital letters are the ones going out of the pinch while non-capital letters represent streams going "into" the pinch. The streams are sorted in order of heat flow capacity so that all relevant information can be read on the diagonal of the matrix directly. Indeed, if the figure on the diagonal is negative, all the following figures on the same row also will be negative.

This matrix enables the user to directly identify for which match the FCp rule is not respected. Then, if the match is among the ones that have to be retrofitted, a split has to be done on the stream with the highest FCp inside the match. In the example above, stream b has to be split. This is a thermodynamic requirement; the current network is not yet analyzed here. If many splits are required, i.e. that more than one negative value is present on the matrix diagonal; a choice has to be made. We could try to develop an automated tool that will consider every possible combination of splits. This method would require an investigation of each possible split alone but also every possible combination of several splits, running the complete Matrix method every time. Moreover, for every possible path, the Matrix method would have to be run several times for several values of split ratios in order to identify the less costly combination. This iterative method could lead to an optimal solution but could be very time consuming since the complete Matrix method would have to be run many times. Moreover in some situations, for example if there is one hot stream with a very large FCp value, it is pretty easy to know which streams to split directly. Therefore, instead of an automated method, an interactive one could be an alternative at this point. The program would identify the possible splits according to the method explained above and would present these options to the user so that he can choose what combination of splits to go with.

9.4 Different splitting scenarios

Once the user has chosen which stream(s) to split, the program has to estimate the cost of the retrofitted solution including the split(s). To do so, an optimal split ratio has to be identified for every split. Different methods are possible at this point.

9.4.1 Estimation of split ratio from current network:

In some specific situations, it appears that there already is a HEX on the stream that is going to be split and that this stream is going to be used in a match with the same opposite stream before and after the retrofit. In that specific case, the method could consider the existing network and use the already existing HEX on the stream that is going to be split to calculate an optimal value of the split ratio before running the Matrix method. The aim of this method is to make the most of the existing available area connected to that stream while splitting it. The following example illustrates one possible way to go for a stream already connected to two HEX's. The original network is presented on Figure 9.1 and the retrofitted one on Figure 9.2.

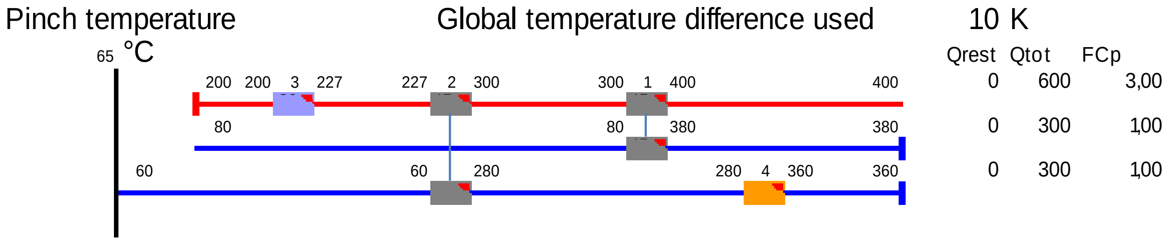
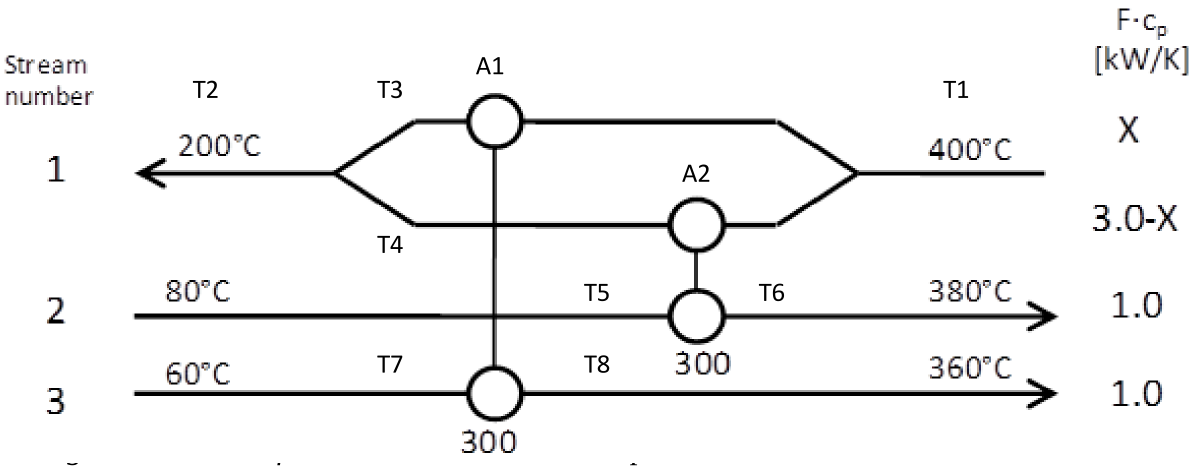


Figure 9.1 Original network before retrofit, with two HEX's on the stream to be split



The aim is to identify the split ratio that minimizes the total area cost of the two HEX's. Given that area cost is not a linear function the optimal cost might not correspond to the situation where A1+A2 reaches a minimum value. To find the optimal split ratio, we have to calculate the function giving the total area cost as a function of this ratio. In the following example, for simplification of calculations counter flow concentric tube type HEX's are assumed:

- $A_1 = \frac{x(T_1 - T_3)}{U_1 * \Delta T_{lm1}} = \frac{x(T_1 - T_3)}{U_1 * \frac{(T_1 - T_8) - (T_3 - T_7)}{\ln(\frac{T_1 - T_8}{T_3 - T_7})}}$ (7.1)

- $T_3 = T_1 - \frac{FC_{p3} * (T_8 - T_7)}{x}$ (7.2)

- $U_1 = \frac{1}{\frac{1}{h_{i1}} + \frac{1}{h_{o1}}}$ (7.3)

$$\text{With} \quad h_{i1} = N_{u_D} * \frac{k}{D_{i1}} = 0.023 * Re_D^{\frac{4}{5}} * Pr^{0.4} * \frac{k}{D_{i1}}$$

$$= 0.023 * \left[\frac{4 * \dot{m}_c}{\pi * D_{i1} * \mu}\right]^{\frac{4}{5}} * Pr^{0.4} * \frac{k}{D_{i1}}$$

$$= 0.023 * \left[\frac{4 * x}{\pi * D_{i1} * \mu * C_{p1}}\right]^{\frac{4}{5}} * Pr^{0.4} * \frac{k}{D_{i1}}$$

$$\text{And} \quad h_{o1} = N_{u_i} * \frac{k}{D_{h1}}$$

Equations (7.1), (7.2) and (7.3) enable us to get A_1 as a function of *x*. By using the same calculations it is possible to get A_2 as a function of *x* too. We can now do the link with the area cost. If we name A_{10} and A_{20} the available area in HEX1 and HEX2 the cost functions are:

$C_{Tot\,Area\,1} = If(A_1 > A_{10}, rA * [Ca.(A_1 - A_{10})^b + A_{fast}], 0)$ which is a function of *x*.

$C_{Tot\,Area\,2} = If(A_2 > A_{20}, rA * [Ca.(A_2 - A_{20})^b + A_{fast}], 0)$ which is a function of *x*.

$C_{Tot\,Area} = C_{Tot\,Area\,1} + C_{Tot\,Area\,2}$ which is a function of *x*.

We can also calculate the initial areas available in the original HEX's by using these calculations. Indeed we cannot simply use the areas given by drawing the network in Pro-Pi since this program only considers shell & tube type HEX's. After the calculation we get $A_{20} = 21.02\ m^2$ and $A_{10} = 18.48\ m^2$.

After this it is possible to compute the formula and find the x corresponding to the minimum of $C_{Tot\ Area} = f(x)$.

An Excel calculation sheet has been built to get such a value (see Table 9.2):

Table 9.2 Example of an excel sheet used to estimate the best splitting ratio to reach the cheapest split.

Data		Calculations step 1		Calculations step 2		Costs	
T1	400.00	T3	185.71	hi2	3386.49	HEX1	11207.53
T2	200.00	T4	212.50	ho2	175.94	HEX2	12680.58
T3	185.71	hi1	3768.28	DTln2	59.50	Total	23888.11
T4	212.50	ho1	175.94	U2	167.25		
T5	80.00	U1	168.09	A2	30.15		
T6	380.00	DTln1	74.85	A20	21.02		
T7	60.00	T2	198.21				
T8	360.00	A1	23.84				
FCp1	3.00	A10	18.48				
FCp2	1.00						
FCp3	1.00						
x	1.4						
Di	0.025						
µ	0.000725						
Pr	4.85						
k	0.625						
Nui	5.63						
Dh	0.02						
Do	0.045						
Cp1	4.2						
Cp2	4.2						
b	1.5						

If we use this calculation sheet on the previous network with the initial areas calculated, we get the results on Figure 9.3:

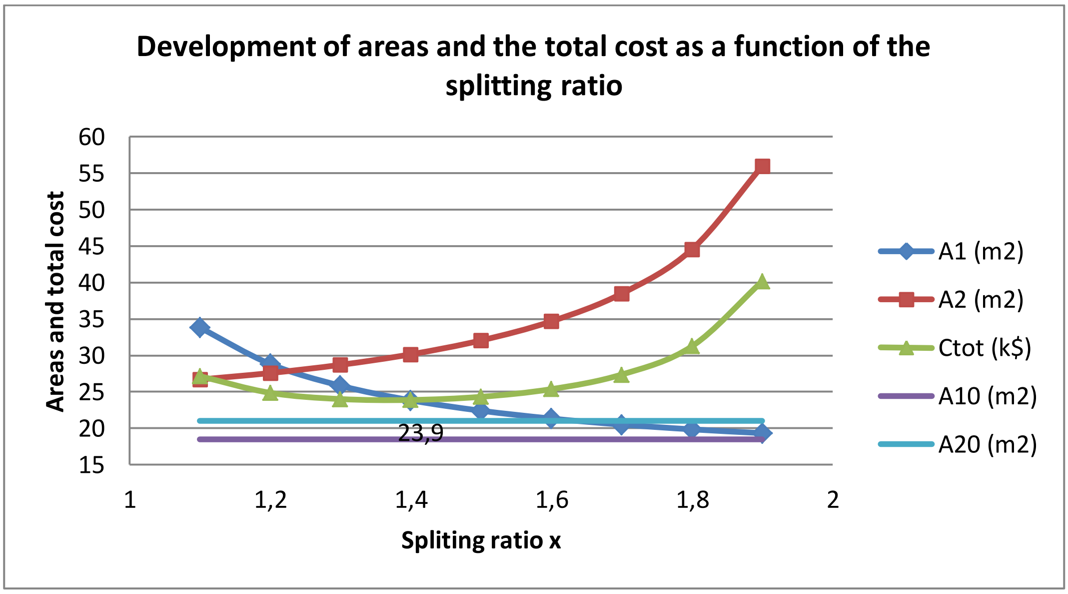


Figure 9.3 Development of areas and the total cost as a function of the splitting ratio for the retrofit of the network in Figure 9.2 using stream splitting.

In this example we can see that the total cost reaches a minimum value of 23.9 k$ for a splitting ratio of 1.4. Areas A_1 and A_2 of the HEX's stay higher than their respective initial areas after the retrofit.

However we can have some big variations in the total cost as soon as these areas become lower than their initial areas. For example if we consider a fictive network just to show these possible variations, we can consider the same initial network as before and change the initial areas (see Figure 9.4).

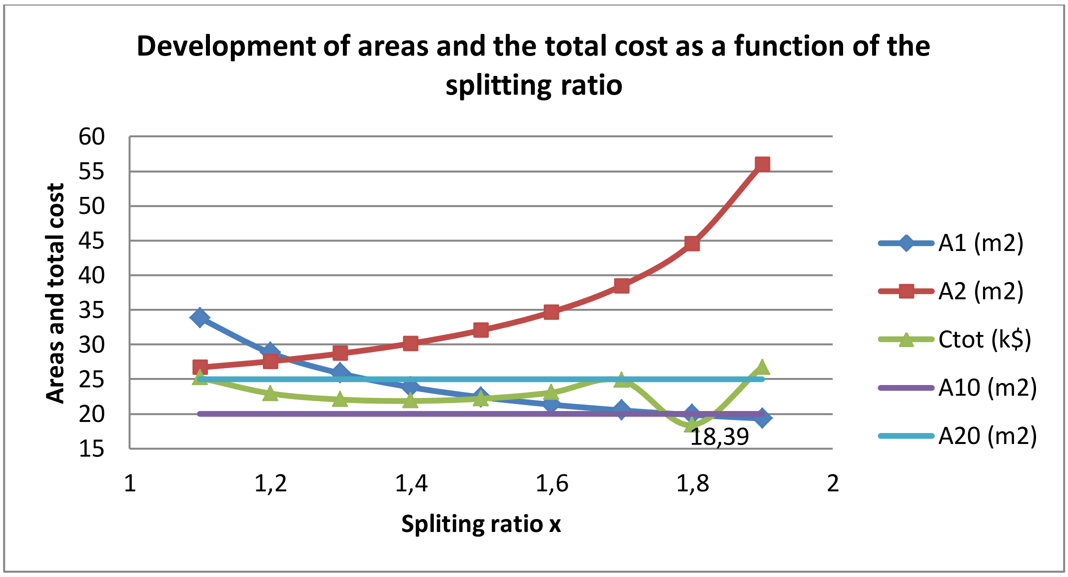


Figure 9.4 *Development of areas and the total cost as a function of the splitting ratio for increased initial areas of the existing HEX's creating a fall in the HEX1 area cost. ($A10=20m^2$ and $A20=25m^2$).*

In this situation we can see that the minimum cost is 18.39 k$ and this is reached for a splitting ratio close to 1.8. This value corresponds to the ratio where the required area A_1 for HEX1 becomes lower than the already available area A_{10}. At this ratio, the area cost of HEX1 falls to 0 which explains the fall of the total cost. Then, the cost of the area for HEX1 stays at 0 but the area cost for HEX2 continues to rise for increased values of x, which explains the increasing total cost after the sharp fall.

The same phenomenon can be observed for the other HEX if we modify the initial areas again (see Figure 9.5).

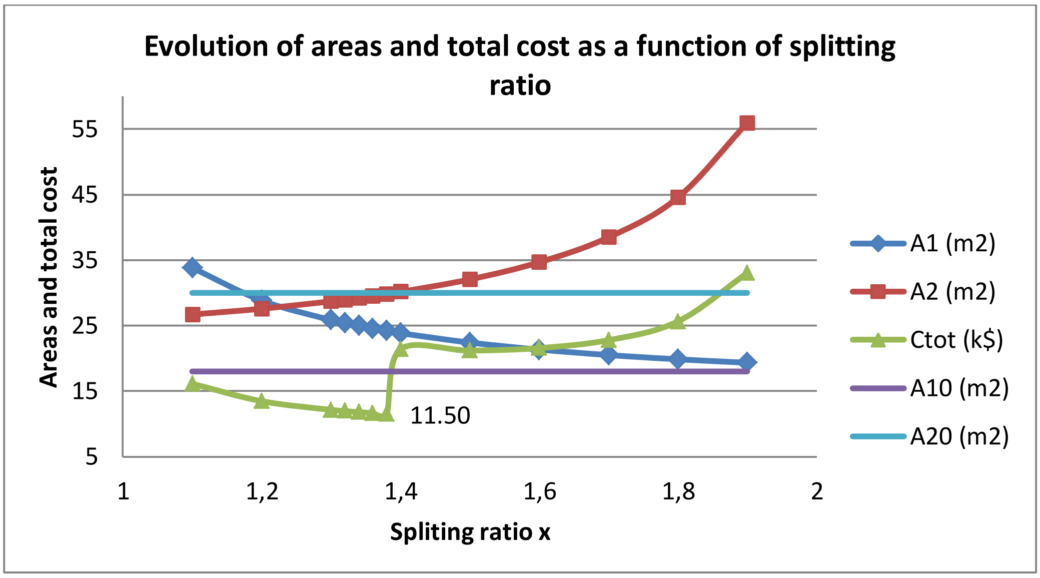


Figure 9.5 Development of areas and the total cost as a function of the splitting ratio for increased initial areas of the existing HEX's creating a fall in the HEX2 area cost. ($A10=18m^2$ and $A20=30m^2$).

In this situation we have used more points close to the sharp rise in cost to show that this happens exactly when the required area A_2 for HEX2 becomes higher than the available one A_{20}, i.e. at the intersection of the two curves. In this situation the optimum cost is 11.50 k$ and is reached for a splitting ratio of 1.4.

By using this method we make sure that the split ratio will optimize the cost of the split. Then the Matrix method can be run as usually except for that the split cost will have to be added at the end. This method makes sure to get a solution and it gives a way to try to minimize the total price induced by the split. However since the Matrix method is run afterwards, some area changes might appear on the HEX present on the split stream, or some new HEX's might appear on this same stream. That means that at this point the selected value for the split ratio might not be optimal.

Moreover this method is easy to run when the stream to be split already is connected to at least two HEX's. But it is also required to investigate how to fix the split ratio if only one or no HEX is connected to the stream to be split. Another issue of this method is that the matching of the streams to be split is locked.

9.4.2 Iterative method

Another method to handle the stream splits can be based on an iterative process. As before, if the user cannot manage to get a solution, if an advice is given for splitting (because of looping) or if the user estimates that a splitting could be beneficial, the Matrix method optimizer has to be run again. The code should be modified so that every time the Matrix method optimizer has been run a window asks the user if he wants to keep this solution (if there is one) or if wants to run the optimizer again to investigate stream splitting.

If the user chooses to investigate stream splitting, the original network that has just been retrofitted should be saved by the program in order to be able to remember the original matches and corresponding areas between the streams. Then, the user can build a new network in the Pro-Pi sheet without connecting the stream to be split to any HEX. Then the user runs the Matrix method optimizer on this network. Here again the code of the current optimizer has to be modified so that every time a match involving a split stream is investigated, the program has to check if this match was already present in the network that has been saved previously. If it is the case then the program has to check if the area required by this match is higher than the one already present in the network previously saved. If additional area is required, it's cost should be added in the cost of the match. That process has to be run for several values of x until the user gets a solution that fulfills his requirements.

In order to automatize this method, the code could be written so that the user doesn't have to re-draw a new network in Pro-Pi for every splitting ratio investigated. Instead, the FCp values could be automatically changed at every iteration in the TD data sheet. Indeed, this sheet is the one used by the Matrix method optimizer and is built from the Pro-Pi network. Modifying TD data directly enables the optimizer to run automatically for every splitting ratio without asking the user to draw a new network. One advantage of this method is that the split streams do not have to be matched with the streams it was matched with before (as it was required in first method). They can be matched with any other stream. The optimizer will then compare this match with the saved ones to see if that match existed in the original network or not in order to adapt the calculation of the cost according to the area available or not. The following diagram describes this iterative method (see Figure 9.6):

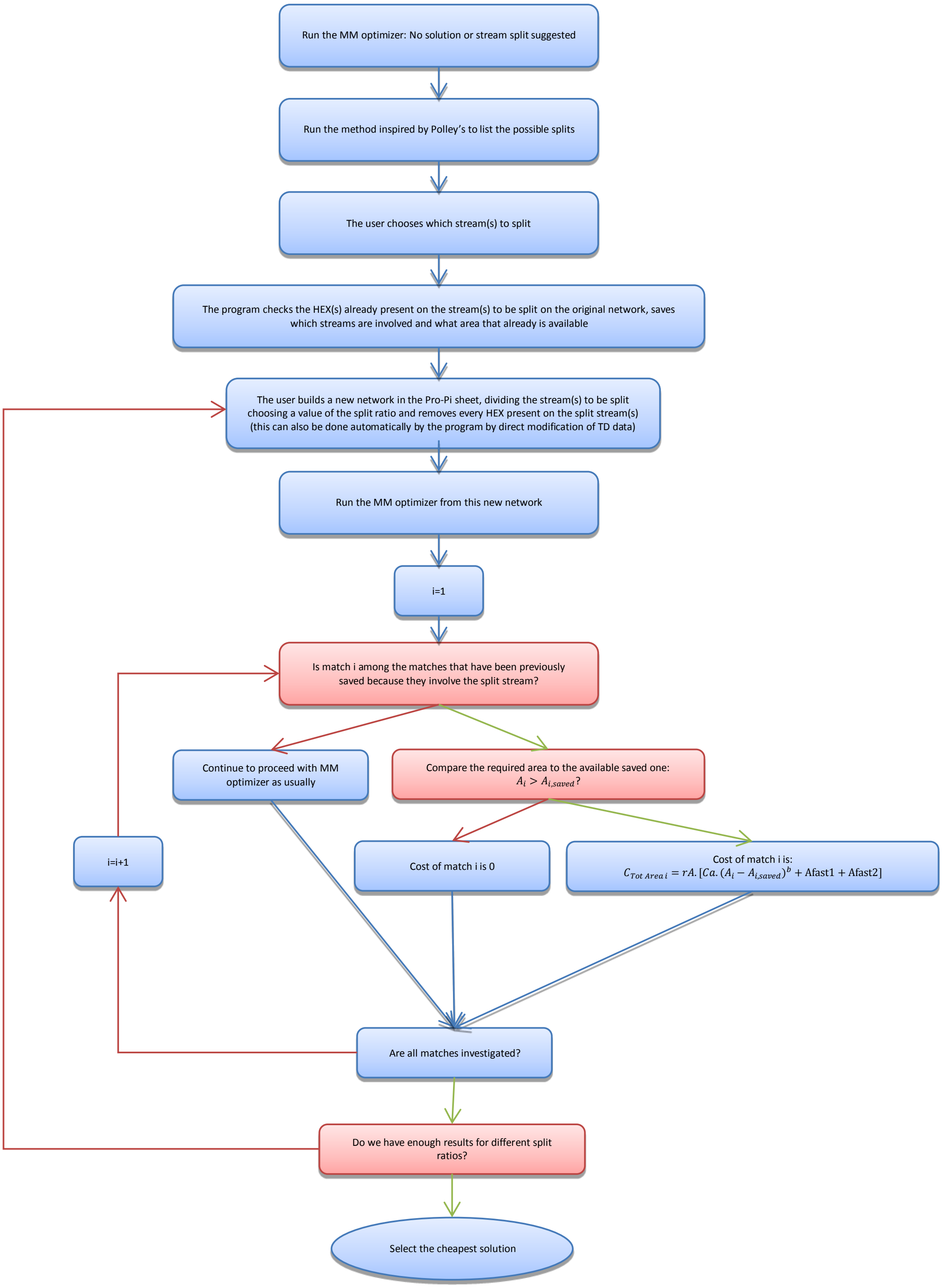


Figure 9.6 Diagram for the iterative method handling stream splitting.

10 Improvement of utility considerations in the Matrix method

10.1 The issue

The way the Matrix method and the Matrix calculation tool deal with utilities is that it assumes the energy cost for all added utility to be the same. The energy costs of the utility streams are not at all taken into account into the method. In reality, there will be different annual energy costs depending on what type of utility that is used. It is typically more expensive to use High Pressure (HP) steam than Medium Pressure (MP) or Low Pressure (LP) steam for instance. It is also more expensive to use a cooling utility at very low temperatures (e.g. requiring refrigeration) compared with cooling water. Thus, depending on where in the network utility is added, the annual utility energy costs may be very different. This is an issue as the current optimal solution achieved by the Matrix method and the calculation tool only considers investment costs and might in fact lead to high operating costs for utility use.

In addition, the Matrix method optimizer has the objective to minimize the investment cost of the retrofitted network, which is a function of the area cost. Consequently, when the optimizer comes to the step of choosing what kind of utility to use, if the temperature levels of LP and HP steam allows the Matrix method optimizer to use either one, it will choose the HP steam since it will imply less area for the heater and thus, a lower investment cost. What is not accounted for here is that it is possible that the annual savings made on the area cost may be lower than the annual saving we would make on the running cost by using LP steam instead of HP steam.

<u>Example 1</u>

If we consider the following simple existing network; there is one hot stream, and one cold stream (see Figure 10.1).

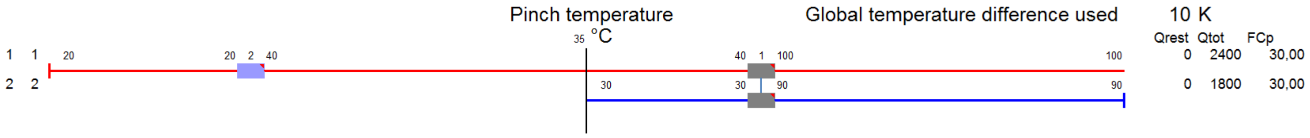


Figure 10.1 Original network for example 1.

Due to planned changes in the process that is using the cold stream, the plant management is investigating the possibilities to distribute the stream at a higher temperature. The temperature target of the cold stream therefore gets increased to 160^0C. The new network will look like the following which implies a need for retrofit with supplementary heating of the cold stream using utility (see Figure 10.2).

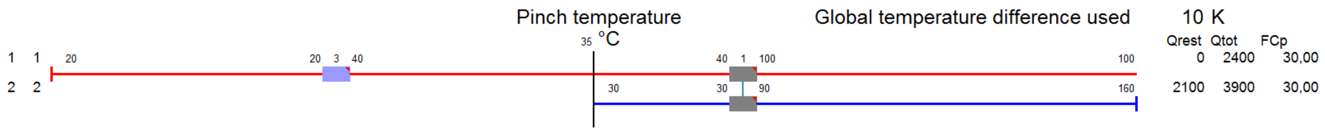


Figure 10.2 Network to be retrofitted due to increased targeted temperature of cold stream.

If we run the Matrix method, using the optimizer tool, we get the following solution (see Figure 10.3):

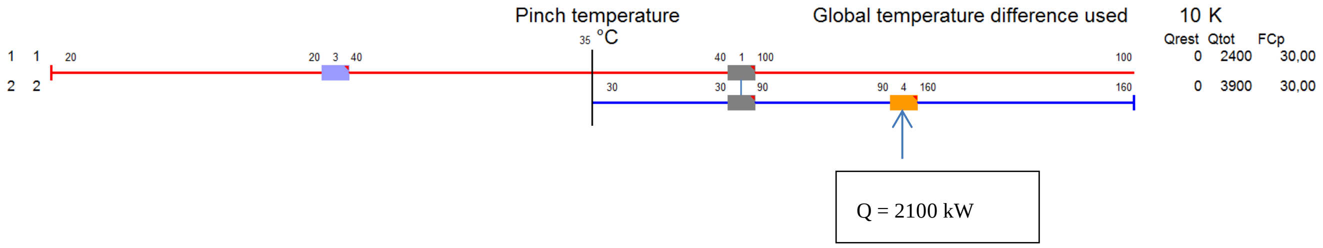


Figure 10.3 Retrofitted network using the current Matrix method optimizer tool.

The heater is using HP steam. If we proceed to the same retrofit using the manual matrix method calculation tool, when we get to the final step of choosing the utility for the heater we end up with the following matrix. We have three different hot utility levels: LP, MP and HP steams (see Table 10.1):

Table 10.1 Description of the different utility streams available.

Utility					
Name	**Type**	**T** **°C**	**T** **°C**	**DT** **K**	**h** **kW/m2K**
HP	Hot	250	249	0,5	4,5
MP	Hot	200	199	0,5	4,5
LP	Hot	145	144	0,5	4,5
CW	Cold	10	15	0,5	2

Here is the matrix evaluating the possibilities to tick-off the cold stream (see Table 10.2).

Table 10.2 Matrix generated in the Matrix calculation tool, estimating the cost of ticking-off the cold stream with the different levels of utility.

				Start	Target
		C 1		T	T
HP	H 2	**11,81**		**250**	**249**
MP	H 3	**13,19**		**200**	**199**
LP	H 4	**15,24**		**145**	**144**
Start T		**90**			
Target T		**160**			

Generally, the rows of the matrix represents the hot streams to be retrofitted with cost alternatives depending on with which streams they can be matched, and with their corresponding starting and ending temperatures (^{0}C). The column(s) of the matrix represents the cold stream(s) to be retrofitted with match costs, including starting and ending temperatures (^{0}C).The costs are all alternatives (in k$) for ticking of the cold stream 1 (C_1) with the three different levels of utility available (HP, MP and LP). This cost includes the fixed annual HEX investment cost, the pump costs, the electricity cost (for running the pumps), the area cost and the piping costs. The price differences are not very sharp because the fixed annual investment cost to buy the heater (10 k$/year) is much higher than the other costs. However if we focus on the decimals, we can see that MP is significantly more expensive than HP, and LP is more expensive than HP. The Matrix method optimizer only considers the prices in this matrix which explains why it chooses the HP steam.

However, if we consider the cost of steam, we can assume that LP steam costs 15 $/MWh, MP steam costs 20 $/MWh and HP steam costs 30 $/MWh and if we consider that the annual operation time is around 6000 hrs/year we can estimate the total annual cost for the heater and utility as:

$$C_{heater+utility} = C_{heater} + C_{utility}$$

With C_{heater} being the cost for the match according to the Matrix method and

$$C_{utility} = Q_{heater} * Annual\ operation\ time * Cost\ per\ MWh \quad (8.1)$$

We can estimate the new total cost for HP and MP steam utilities (LP steam is not interesting in this case since it cannot tick-off the cold stream completely). Moreover, since steam price is based on a current value, we have to consider the inflation of prices for HEX’s, piping and pumps (see Chapter 7.4). In order to simplify the calculations, we consider an average inflation of 78% on investment costs, corresponding to HEX’s inflation rate:

- $C_{Tot,HP} = 11.81 * 1.78 + 2.1 * 6000 * \frac{30}{1000} = 399.05\ k\$/year$ (8.2)
- $C_{Tot,MP} = 13.19 * 1.78 + 2.1 * 6000 * \frac{20}{1000} = 275.51\ k\$/year$ (8.3)

Consequently, considering the utility stream’s cost it is more economical to choose the MP utility even if the investment cost is higher than the HP utility’s one.

Example 2

Here follows another example of a network where the choice of utility and its location might affect the optimal solution. This example is constructed only to illustrate a specific issue in the methodology and aims at staying simple. The magnitude of the problems illustrated might be exaggerated since a real network would not start from such an inefficient design. This example shows that the method is unable to handle such issues that might occur in larger networks.

We assume that the following process plant streams are present in a HEN (see Figure 10.4).

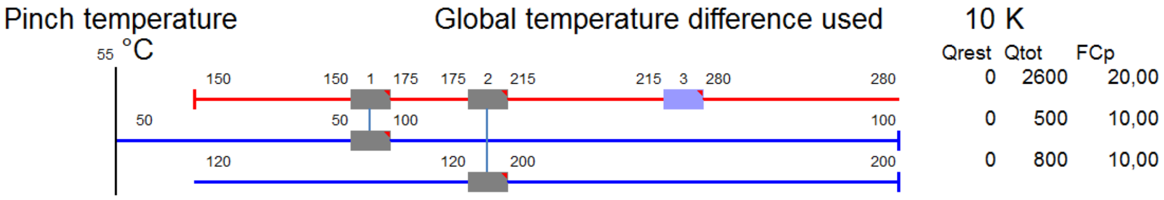


Figure 10.4 Original network for example 2.

A new process is added to the plant that requires the addition of a new cold stream and thus a HEN retrofit is desired to heat this new stream up in the most economical way (see Figure 10.5):

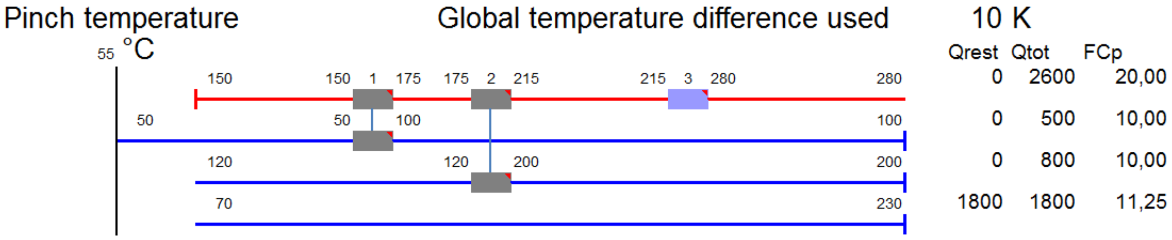


Figure 10.5 Original network with an additional new cold stream to be retrofitted.

If we run the current Matrix calculation tool, the optimizer will give us the following retrofitted network (see Figure 10.6) with the following costs (see Table 10.3):

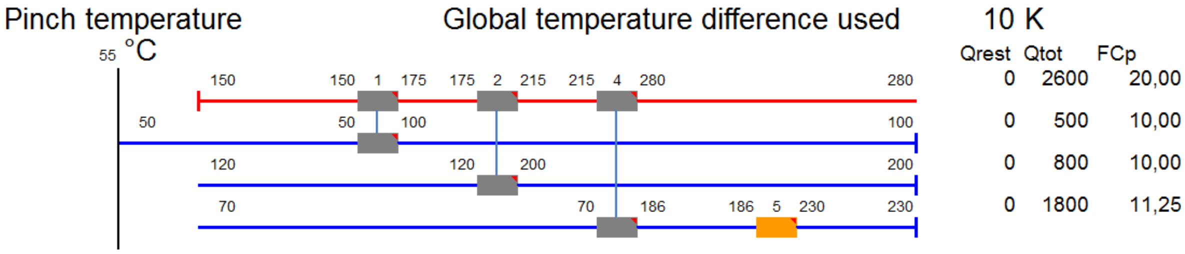


Figure10.6 Retrofitted network using the Matrix method optimizer tool

Table 10.3 Cost summary for the retrofitted solution presented in Figure 10.6

								Tot annual cost	22.780 k$/year	90.360 k$	0.190 k$/year
HEX	Hot stream	Cold stream	T hot out	T hot in	T cold in	T cold out	Q match	Annual specific cost	Annual cost	Investment	Annual operation
1	H1	C1	150.00°C	175.00°C	50.00°C	100.00°C	500 kW	0	0	0	0
2	H1	C2	175.00°C	215.00°C	120.00°C	200.00°C	800 kW	0	0	0	0
3	H1	C3	215.00°C	280.00°C	70.00°C	185.56°C	1300 kW	8.739 $/kW	11.361 k$/year	44.939 k$	0.126 k$/year
4	H2 (HP steam)	C3	249.00°C	250.00°C	185.56°C	230.00°C	500 kW	22.840 $/kW	11.420 k$/year	45.421 k$	0.065 k$/year

Table10.3 shows the result given by the Matrix method optimizer. The annual specific cost describes the annual cost for each kW installed. The annual cost is the annual investment cost based on an annuity factor of 0.25, added with the annual running costs that include the operation cost of the electricity for driving the motor and the pumps (does not include utility stream cost). The investment cost is based on the fixed costs for purchasing/retrofitting a HEX added with the additional HEX area and motor costs. Note that the piping costs are excluded in this example.

The total annual cost is 22.78 k$/year (investment without piping + running costs). If we add the price of HP steam, assuming an annual operation time of 6000 hours, and if we consider the increase in process equipment costs (see Section 7.4) we get a total annual cost of:

$$C_{Tot,HP} = 22.78 * 1.78 + 0.5 * 6000 * \frac{30}{1000} = 130.60\ k\$/year \qquad (8.4)$$

We can decide to place the heater close to the pinch instead of using it at the hot end of the cold stream. Doing this allows us to use LP steam as a utility stream instead of HP steam. Such a design is not investigated by the current optimizer but we managed to run this configuration manually by dividing cold stream 3 into two parts just for the calculations. The first part goes from 70 to 114°C for the heater and a second part from 114 to 230°C for the HEX matched with hot stream 1. The results are shown in the following figures (see Figure 10.7).

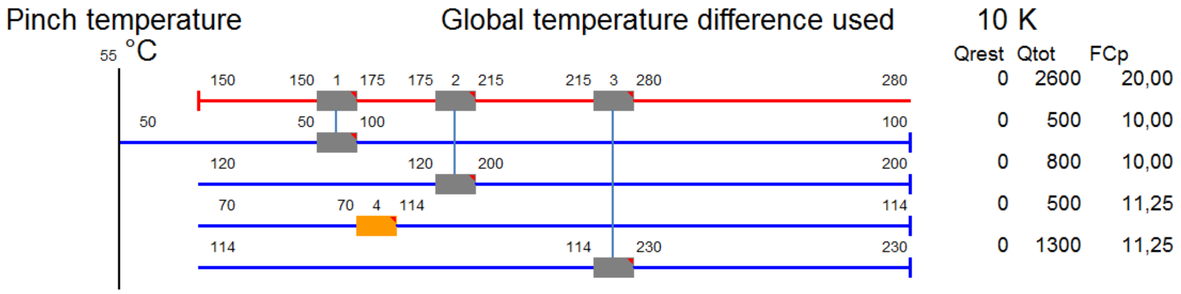


Figure 10.7 Network with cold stream 3 divided into two streams to run calculations.

The network above actually represents the network shown below (see Figure 10.8):

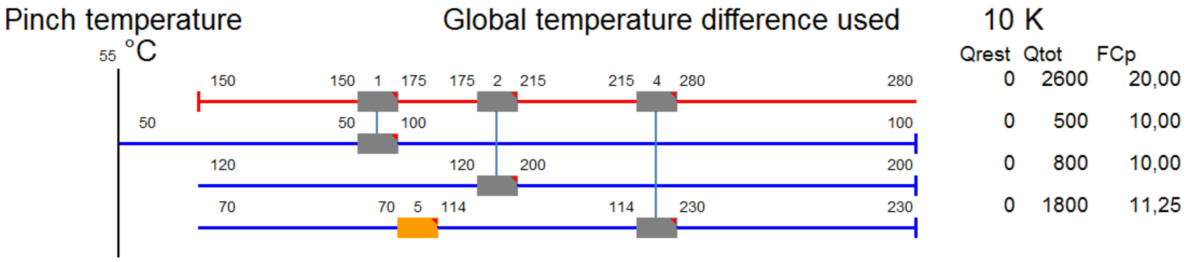


Figure 10.8 The real network investigated, without representing cold stream 3 by two separated streams.

As described previously, the bottom cold stream in the network is represented by two different streams. This is due to the current heuristics of the Matrix calculation tool which doesn't allow a HEX to exchange heat far away from the pinch before heat has been exchanged close to the pinch.

In order to implement this possibility to place heaters close to the pinch, new heuristics are required. Indeed, if we place a heater before a HEX, we need to know how large it should be. The tick-off rule that is normally used is not relevant in this case. Here it is easy to say that Q_{heater} should be $Q_{h,min}$, but in a larger network with several heaters it will be more complex.

The two tables below represent the manual solution described above by the Matrix method optimizer with LP and HP steam utilized respectively (see Table 10.4 and Table 10.5):

Table 10.4 Results of the retrofit for example 2 using LP steam.

								Tot annual cost	23.305 k$/year	92.203 k$	0.255 k$/year
HEX	Hot stream	Cold stream	T hot out	T hot in	T cold in	T cold out	Q match	Annual specific cost	Annual cost	Investment	Annual operation
1	1	1	150.00 ^{0}C	175.00 ^{0}C	50.00 ^{0}C	100.00 ^{0}C	500 kW	0	0	0	0
2	1	2	175.00 ^{0}C	215.00 ^{0}C	120.00 ^{0}C	200.00 ^{0}C	800 kW	0	0	0	0
3	1	3	215.00 ^{0}C	280.00 ^{0}C	114.44 ^{0}C	230.00 ^{0}C	1300 kW	9.398 $/kW	12.217 k$/year	48.049 k$	0.205 k$/year
4	4 (LP steam)	3	144.00 ^{0}C	145.00 ^{0}C	70.00 ^{0}C	114.44 ^{0}C	500 kW	22.176$/kW	11.088 k$/year	44.153 k$	0.050 k$/year

Table 10.5 Results of the retrofit for example 2 using HP steam.

								Tot annual cost	22.559 k$/year	89.354 k$	0.221 k$/year
HEX	Hot stream	Cold stream	T hot out	T hot in	T cold in	T cold out	Q match	Annual specific cost	Annual cost	Investment	Annual operation
1	1	1	150.00 ^{0}C	175.00 ^{0}C	50.00 ^{0}C	100.00 ^{0}C	500 kW	0	0	0	0
2	1	2	175.00 ^{0}C	215.00 ^{0}C	120.00 ^{0}C	200.00 ^{0}C	800 kW	0	0	0	0
3	1	3	215.00 ^{0}C	280.00 ^{0}C	114.44 ^{0}C	230.00 ^{0}C	1300 kW	9.398 $/kW	12.217 k$/year	48.049 k$	0.205 k$
4	4 (HP steam)	3	144.00 ^{0}C	145.00 ^{0}C	70.00 ^{0}C	114.44 ^{0}C	500 kW	20,684 $/kW	10.342 k$/year	41.305 k$	0.016 k$

The total annual cost is 23.305 k$/year (investment + running costs without piping) when LP steam is used which is slightly above the solution utilizing HP steam far away from the pinch which is optimized by the optimizer tool (see Table 10.4). However if we add a cost for the annual utility steam usage and consider the increase in equipment cost as described previously, we get the following result:

$$C_{Tot,LP} = 23.31 * 1.78\ k\$/year + 0.5\ MW * 6000h * \frac{15\$/MWh}{1000} = 86.55\ k\$/year \qquad (8.5)$$

Thus, the cost difference between this LP solution and the first solution utilizing HP steam with the steam cost included is: $130.60 - 86.55 = 44.05\ k\$/year$ which means that the solution utilizing LP steam is approximately 40% cheaper than the one calculated by the Matrix method optimizer if the utility costs are considered. Furthermore, if we would choose to utilize HP steam instead of LP steam close to the pinch in the second solution (see Table 10.5), but this time exclude the utility costs, we would still get a cheaper solution than when utilizing HP steam far away from the pinch temperature.

The solution where HP steam is utilized close to the pinch has an annual cost of 22.56 k$/year with the steam cost excluded. The solution where HP steam is utilized but used far away from the pinch on the bottom stream has an annual cost of 22.78 k$/year.

These two examples show that the current Matrix method optimizer does not always reach the most economical solution for a given energy recovery target because of two omissions. Firstly, it does not include the utility stream price, which can make the difference between two possible retrofitted networks. Secondly, it only considers utilities at the parts of the streams furthest away from the pinch due to heuristics rules. Instead it can be well advised to place heaters and coolers closer to the pinch in order to reach a better distribution of the driving forces, ΔT_{lm}, between different units and thus optimize the new area, or just to be able to use a cheaper utility stream than the one required at the part of the process stream furthest away from the pinch to tick it off.

10.2 How to improve the method

10.2.1 Adding a utility cost at the end

There are different ways to deal with this issue. One approach would be to simply add the annual energy cost in addition to the utility investment costs when adding the utility heater at the end of the Matrix method operation. This way they will be accounted for and the optimizer will thus be able to find the optimal utility use for a certain network configuration through its iterative approach. This method makes sure that the Matrix method optimizer will choose the optimal utilities at the cold and hot ends of the network, but it does not affect the previous choices of matches. This method also requires the user to give the number of running hours per year as an input.

Furthermore, since the Matrix calculation tool heuristics determine that HEX's are placed from the pinch and outwards, it may be impossible to place utility HEX's close to the pinch without using them to tick off the entire stream. However, a solution with heaters and coolers close to the pinch may be a more economic approach if this enables the use of lower cost utilities.

10.2.2 Adding a saving cost to matches in different utility regions

This section presents another idea of how to deal with the utility, but there are still a number of pieces missing before being able to implement this approach. The idea consists of choosing HEX matches depending on the utility energy costs that will be avoided. This approach is more difficult as the utilities are added lastly in the Matrix calculation tool. Therefore we will not know in advance what heating utility energy cost might be saved by simply adding or rearranging a HEX in the network. For every match investigated, the calculation tool should identify what kind of utility that will be reduced by using this match and by quantifying it. Then, the cost saved by reducing the utility demand will be reduced from the match cost as a saving cost. By using this method we make sure that the Matrix method optimizer will make the most economic choice at every step and will not go through match paths that would eventually be costly because of high final utility costs. Consequently, this method optimizes the choice of utilities but it also reduces the iteration time (because of the upper boundary limit).

One way to use this technique inside the Matrix method is to assign specific price boundaries to the network corresponding to the utility that is demanded. Then, every cold stream will be associated to a cost for the zone in between these boundaries, a cost that corresponds to the relevant hot utility that is demanded for this zone. During the matrix process, every time a match is chosen, the price of heat load saved by this match will be deduced from the match´s cost. The following equation describes the cost of a match according to this approach:

$$C_{match} = rA.Ca.A_i{}^b + rA.(Afast1 + Afast2) + cpt + cps + cpow + cPiping - C_{steam\ for\ zone} * Q_{utility\ saved} * Annual\ operation\ time$$

(8.6)

Corresponding issues by using this approach:

- There will be merging issues between the zones (for example; if a cold stream passes through 2 heating zones, should it assign to a utility price corresponding to the more expensive zone assigned to one heater installed or will it be cheaper to install two heaters with two different utility levels?)

- This method does not represent the real cost of the match, it is just here to help the method to find the optimal path

- There may be a situation where a heater already exists and uses HP utility in the MP zone for example. How will this be handled in the calculation of the saving costs?

10.2.3 Several solutions on a divided network

Another way to improve the true utility cost is to divide the HEN into as many parts as there are hot utility levels instead of just dividing it at the pinch. When utility streams are added to the HEN there will be several pinches added which the HEN gets divided by. Then, we run the Matrix method on each and every one of these parts of the network. When running the Matrix method, every zone will only be able to use its own level of hot/cold utility if heaters or coolers are required and the utility will in this case be added at the end of the Matrix methodology operations with both the investment and the corresponding annual utility cost.

Corresponding Issues:

-It will be difficult to divide the network into more than two parts inside the program

-There will be increased merging issues to get the final solution

-We might end up with several heaters of different energy levels while it would be cheaper to only use one at the highest energy level to reduce the investment cost. The economic balance between investment and running costs should be included here.

10.2.4 Including the utility streams inside the network as soft streams

In this approach, utility streams are included in the network as normal streams, except that they cannot be ticked-off. The program is allowed to use them in order to tick-off process streams, but it should not try to tick-off the utility streams. Utility streams have soft target temperatures that don't have to be reached to solve the network. Consequently, utilities will not be considered only at the cold and hot ends of the network. If they bring a cheap solution close to the pinch, a heater might be used instead of adding a new HEX for example. The cost of the utility stream also has to be included here, depending on the location of the heater on the stream. In this method the utility streams will have to be identified as soft streams from the beginning. By soft streams we mean streams that have soft ending temperatures, that is that these temperatures do not need to be reached in order to solve the network and should thus not be prioritized for usage. The Matrix method optimizer would then be run on hot streams (that have to be cooled), cold streams (that have to be heated) and soft streams (that can be used to heat or cool other streams but should not be prioritized).

Issues:

-We have to make sure that the program will not try to use more heat from utility streams than desired/required ($Q_{h,min}$)

-New heuristics might be required for placing the matches.

-How should the soft streams be handled in the computer program?

-We still have to include the cost of the utility streams (as a cost this time)

11 Conclusion

This thesis brings a better understanding of the Matrix method itself and the manual matrix calculation tool program used to run this method including the Matrix method optimizer tool after a thorough investigation and evaluation. The logics of the method and the programs are explained and analyzed. Several issues are pointed out, among which the merging issue, the stream splitting issue and the utility issue are the subjects of a deeper analysis. Improvements have been identified for every one of these issues where solutions have been developed and presented.

This research is mostly based on the previous work of Carlsson (1996), Andersson (2001) and Franck (2010) and aims at developing the missing parts in their works to improve the working area of the Matrix method.

Merging issues refer to the merging of the network above and below the pinch, a step which has not yet been included in the Matrix method optimizer routine. A complete solution to handle merging issues is presented. This solution is based on the current program and is able to bring a final retrofitted solution for the complete network.

Stream splitting is not handled by the Matrix method today. Given the complexity of stream splitting issues, no perfect solution is presented. Improvements are given to solve simple situations such as the case where the stream to split is connected to at least two HEX's in the existing network. A method is also introduced, helping the user to identify the situations where a split is required, and an iterative method brings a general solution. This last method improves the current method considerably; then again it cannot always lead to the best retrofitted network.

Finally, a major improvement is introduced by considering costs of utility streams. A simple and easy method to implement is described to consider these costs. Nevertheless, other methods are also suggested to handle the utilities in a better way by allowing them to be placed anywhere in the network and not only at the extremities of the pinch. These utility consideration methods describe the potential gain of such solutions but they also rise additional difficulties that are not all overcome in this thesis.

Still, a good overview of the issues with the Matrix method and the program is presented and the suggested implementations give a good foundation for further research work and program enhancements.

Finally, the main issues of the Matrix method have been addressed and even if the methods proposed to solve them cannot always reach the optimal solution or handle every situation, they definitely increase the application area of the method and enable it to reach better solutions than previously.

12 Suggestions for future work

The solutions presented have not been implemented in the program code since this was not in the scope of the thesis work, which directly results in the fact that no real tests of the suggested methods could be performed on real scenario networks. Furthermore, some of the methods suggested are left incomplete due to the complexity of adapting them to all different kind of networks.

The next step would be to write the code to include the solutions developed for merging and utilities. However, some research work remains to be pursued before writing the code for stream splitting if an ideal stream splitting solution is desired. If a general solution for stream splitting is enough, it may be implemented by following this thesis advice. Furthermore, there should be an investigation of how interesting it is to perform a stream split on a network if there already is another way of presenting a solution. For instance, if it is possible to get a solution by looping HEX's or by lowering the ΔT_{min}, the solution should be compared to the optimal stream split in order to evaluate the economic effect on the HEN.

Another future work can also be to fix all the small bugs and calculation errors inside the current program and to improve the accuracy of the input data such as the area cost of HEX's.

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