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# HEAT INTEGRATION OF ETHANOL AND YEAST MANUFACTURE

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The increasing concern for the environmental impacts of human activities has stimulated the development of new methods for analysis of industrial processes and the implementation of energy conservation measures. This paper presents a research on a case study of plant for ethanol and yeast production. The production plant as physical model is divided into subsystems. There are few limits taken for the method used, such as all streams have constant specific heats and the whole process is in steady state. Every subsystem is redesigned in order to improve its energy efficiency. After these local improvements, pinch analysis on the entire system is made (all subsystems are taken as black boxes forming the entire system) to optimize energy uses with construction of heat exchanger network. The expectations for operational costs minimization are improved, so pinch analysis results serve as energy efficiency indicator, giving us direction to invest for new equipment as development project for energy savings. The economical calculations performed for the designed system (HEN) with process integration show more profitability then the old one.

**Key words:** process integration; heat integration; pinch technology; energy optimization; heat exchanger network (HEN)

## ТОПЛИНСКА ИНТЕГРАЦИЈА НА ПОСТРОЈКА ЗА ПРОИЗВОДСТВО НА КВАСЕЦ И АЛКОХОЛ

Зголемувањето на грижата за влијанието на човечките активности врз околината го стимулира развојот на нови методи за анализа на индустриските процеси и имплементација на мерките за заштедата на енергијата. Овој труд претставува истражување на случај на постројка за производство на алкохол и квасец. Производствената постројка како физички модел е поделена на потсистеми. Притоа се земени неколку ограничувања во користените методи, како што е константна специфична топлина на сите струи и стабилна состојба на системот. Секој потсистем е редизајниран со цел да се подобри искористувањето на енергијата. Откако овие локални подобрувања се направени, се прави пинч-анализа на целокупниот систем (сите потсистеми како „црни кутии“ кои го формираат системот), со која се оптимизира потребната енергија за системот со дизајн на мрежа на топлински разменувачи. Очекувањата за минимизирање на производните трошоци се докажаа, а резултатот на пинч--анализата се покажа како добар индикатор за инвестирање во подобрување на ефикасноста на искористувањето на енергијата. Економските пресметки направени за новиот дизајниран систем на топлински разменувачи со процесна интеграција ја потврдија профитабилноста на можната инвестиција.

**Клучни зборови**: процесна интеграција; топлинска интеграција; пинч-технологија; оптимизација на енергијата; дизајн на мрежа од топлински разменувачи

## INTRODUCTION

In response to the staggering environmental and energy problems associated with manufacturing facilities, the process industry has recently dedicated much attention and resources to mitigating the detrimental impact on the environment, conserving resources, and reducing the intensity of energy usage. Past decades have seen significant industrial and academic efforts devoted to the development of holistic process design methodologies that target energy conservation and waste reduction from a system perspective.

Process integration is a holistic approach to process design and operation that emphasizes the unity of the process. It can be broadly categorized into mass integration [1] and energy integration [2, 3]. The energy integration deals with the global allocation, generation, and exchange of energy throughout the process [2, 4].

Mass integration is a part of process integration which has aim to minimize outgoing material compounds through material streams via change of its concentrations. This kind of integration uses mass transfer phenomena for compound concentration changes, with mass exchangers using processes such as absorption, adsorption, extraction, ion exchange, leaching and striping. El-Halwagi defines mass integration as "systematic methodology that provides a fundamental understanding of the global flow of mass within the process, and employs this holistic understanding in identifying performance targets and optimizing the generation and routing of species through process" [1]. Mass integration is divided into water pinch technology and a part which relates to other compounds. Water pinch technology is used to optimize the quantity of water used in production systems and its reuse to minimize outgoing water.

Much of the effort in this area has been directed toward increasing heat recovery in chemical processes. Industrial heat exchanger networks (HENs) are designed because of their particular importance in recovering processes. HENs can be designed with combination of heat exchangers using different methods. All methods used in HENs design are not suitable for minimization of costs and increase of profit. In every production plant streams with high or low energy content can be found. Some of them are useable for heating or cooling processes that depend on the supply temperature and target temperature which is needed for the process, and can save energy to not go in drainage with outgoing streams. The main task of using pinch technology is to optimize the number of heat exchangers, heat exchange area, to minimize capital costs, production costs, utility costs, using present energy streams with high or low energy content. With that kind of optimization, HENs can increase profits in the production plant in the future. The method of Pinch Technology developed by Linnhoff with his professor John Flower and later with his coworker Hindmarsh is widely used in HENs synthesis, which is derived through thermodynamic analysis [2, 5]. The advantage of HENs is that they allow the recycling of energy by taking it out of hot products and passing it into cold raw materials which require heating, and *vice versa*. One of the basic postulates is making a combination of energy streams to reach maximum energy using of energy waste streams, as well as minimization of cooling duty. Pinch technology, analysis, and design are based on the First Law of thermodynamics, with some constrains derived from the Second Law of thermodynamics. Pinch point is the most common term of Pinch technology, which utilizes minimal heat exchange force or minimal temperature differences between composite curves for every analyzed case. Pinch analysis is a way to define energy and capital costs depending on the heat exchange force for heat exchangers network (HEN) and finding of the pinch point [Appendix 1]. Mubarak and Al-Kawari describe a simple method for energy saving and utility minimization by using heat exchangers waste streams [6]. The extension of the method for heat process integration and analysis with construction of composite curve as temperature dependent on enthalpy has been analyzed [7]. Staine and Favrat took into consideration heat loss through heat exchangers and pipes, as well as pressure drop and exergy [8]. In addition, some mathematical programming methods, e.g., the nonlinear programming (NLP) optimization method proposed by Quesada and Grossmann [9], and the mixed integer nonlinear programming (MINLP) optimization algorithm developed by Zamora and Grossmann [10], are also applied to the design and synthesis of HENs. Salama [11, 12] proposed a new numerical technique for determining heat energy targets in pinch analysis using a geometry-based approach. During the last several years, the authors have been active in applying the tools previously mentioned to improve process performance via productivity enhancement, energy conservation, and pollution prevention issues at various industrial sites. The tools are well suited for a various small, medium, and large size continuous chemical processes [13, 14]. Dalsgard et al. describes steps that aim at reducing the magnitude of the theoretical work and engineering effort associated with given process integration in intermediate size industries. They developed procedures and strategies for simplifying the problem and reducing the complexity of the process system [13]. Bach processes are more difficult to analyze and to implement the identified solutions as they involve dynamic performance and require an additional layer of scheduling solutions. The problem of energy integration in batch processes, for a given production schedule, is decomposed into two sequentially solved problems of scheduling and heat integration [15]. Similar method is given by Pourali et al., where the whole time is sliced to short periods where energy streams are practically continuous for a given period [16]. They analyzed three models which can be used for batch processes. These are the Time Average Model (TAM), Time Slice Model (TSM), and a model based on energy accumulation. TAM is a model where batch streams are represented as continuous streams for all plant working time, but values of the characteristics of these streams are average values for the certain time period.

This paper presents a case study of reducing energy use and cost in process industry by pinch analysis. The steps for simplifying the problem and reducing the complexity of the investigated process, presented by Dalsgard et al. [13], have been used.

## PROBLEM DEFINITION

In this paper a plant for ethanol and yeast production has been examined (Fig. 1). All streams in the process have been determined by their specification according to the heat integration requirements. The production plant has been separated into subsystems. The flow sheet shown on Fig. 2 represents part of the production plant which has possibilities for heat integration. Actually, streams in this part of the plant have high content of energy. For better view of the plant, it is divided into sectors (subsystems). Every subsystem has been integrated separately and after entire subsystem integration, integration between subsystems has been performed taking into consideration the outlet and inlet streams of each subsystem (black boxes) (Fig. 1). The production plant is divided into A, B, C, D, E and F subsystem. Subsystem "A" represents preparation of raw materials for using in the subsequent processes. There is need of hot water ($S_{hw}$). "B" represents a subsystem where fresh yeast is going to dry. There is need for hot air for drying ($S_{26}$) and also there is outlet waste stream of hot air ($S_{22}$) which can be used for air heating of production hall. The subsystem with waste high energy content streams ($S_{14}$, $S_{15}$) is subsystem "C". That subsystem represents the distillery plant. The subsystem which needs cooling utility is subsystem "D". That is the process of separation of yeast by filtration. There is need for cold washing water ($S_{21} \rightarrow S_{20}$). Subsystems "E" and "F" have no streams for heat integration. They represent the fermentation units, centrifugation, and yeast cream storage tanks. The flowsheet on Fig. 2 represents subsystems "A", "B", "C" and "D" with their main parts of production plant. An element like R-1 (Fig. 2) is hot water tank, which collects all clean hot water streams in the processes, and it is also a facility for energy accumulation. R-1 stores hot water, also heating it with steam injection and represents a kind of heat exchanger. H-1 (Fig. 2) is a heat exchanger which is used for conditioning of hall air temperature with hot water heating system which uses hot utility. Streams such as $S_{14}$ and $S_{15}$ have high energy content, which is going to drainage without using it to save energy in the plant. Subsystem D uses high quantities of cooling utility, but with reorganization of that system lost money for utility costs can be saved. In other subsystems shown on Fig. 2 there are streams interesting for heat integration with lost energy streams. To make the selection of energy and mass streams it has been recommended to consider only streams with higher and lower temperatures then the average ambient temperature. A selection of streams was made to do heat integration calculations with their physical and chemical characteristics. The streams in every subsystem were integrated with the main focus on the hot water needs for the process (heating $S_5$ to the target temperature), firstly continuous streams, and after that upgrades with recommendations for integration of batch streams (if there any interesting batch stream). In this work we used a model based on accumulation of energy for batch streams of hot water needed in the production process.

The quantity of energy which is consisted in outlet waste energy streams, can be compared as money value and is 1074.00 MJ/h (low pressure steam has price of 14.66 EUR/GJ – at the moment of calculation), so it is about 136000.00 EUR/year. Cost of cooling in the process, where $S_{19}$ is waste cold stream, is more than ~1100.00 EUR/year. So the total cost is approximately 137100.00 EUR/year.

## RESULTS AND DISCUSSION

It is possible to minimize the cooling utility in subsystem "D" so the cooling costs would be decreased. That is executed with an installation of a new heat exchanger for circular use of cooling (without using cooling utility in the largest period of filtration process). This subsystem is subject of other study and it will be presented in another scientific paper.

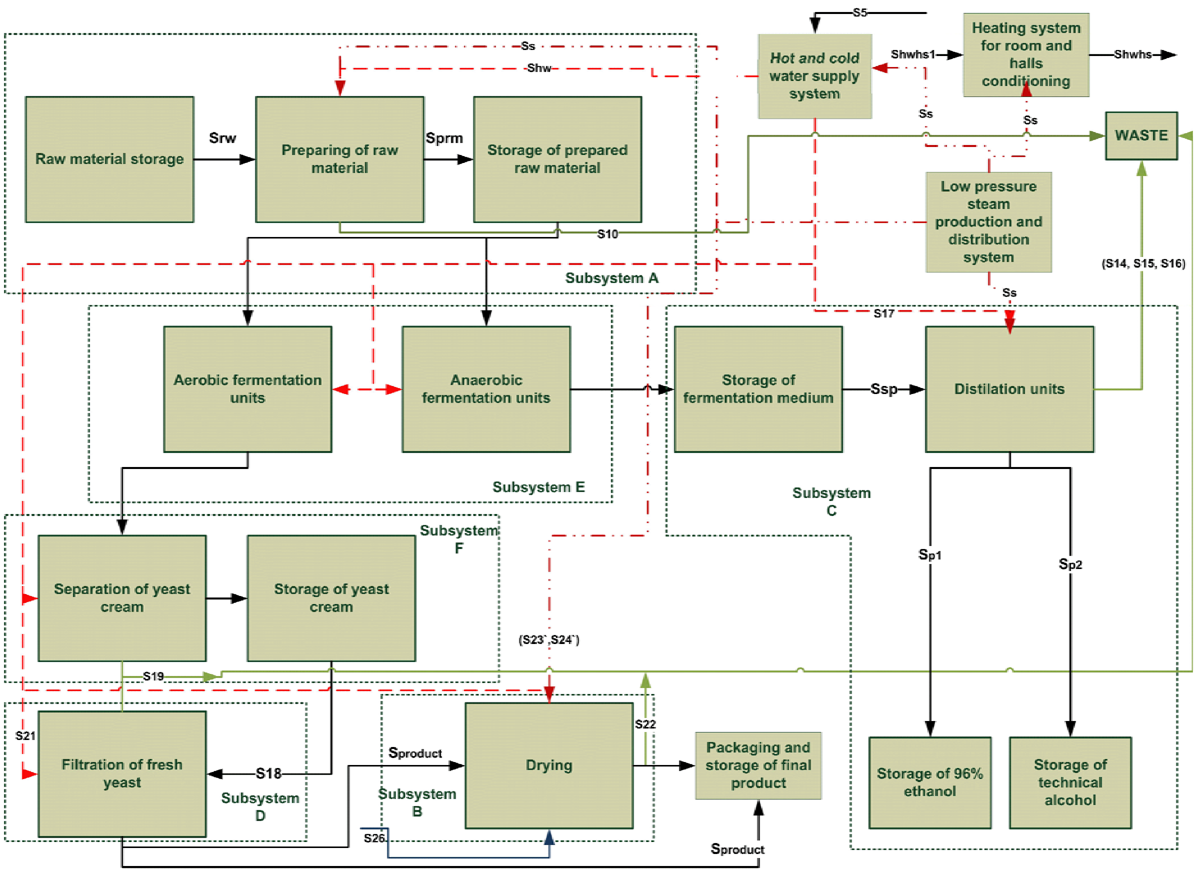



**Fig. 1.** Block diagram of production system divided to subsystems and "black boxes" (production units)
(Colours can be seen on the on line Internet issue)

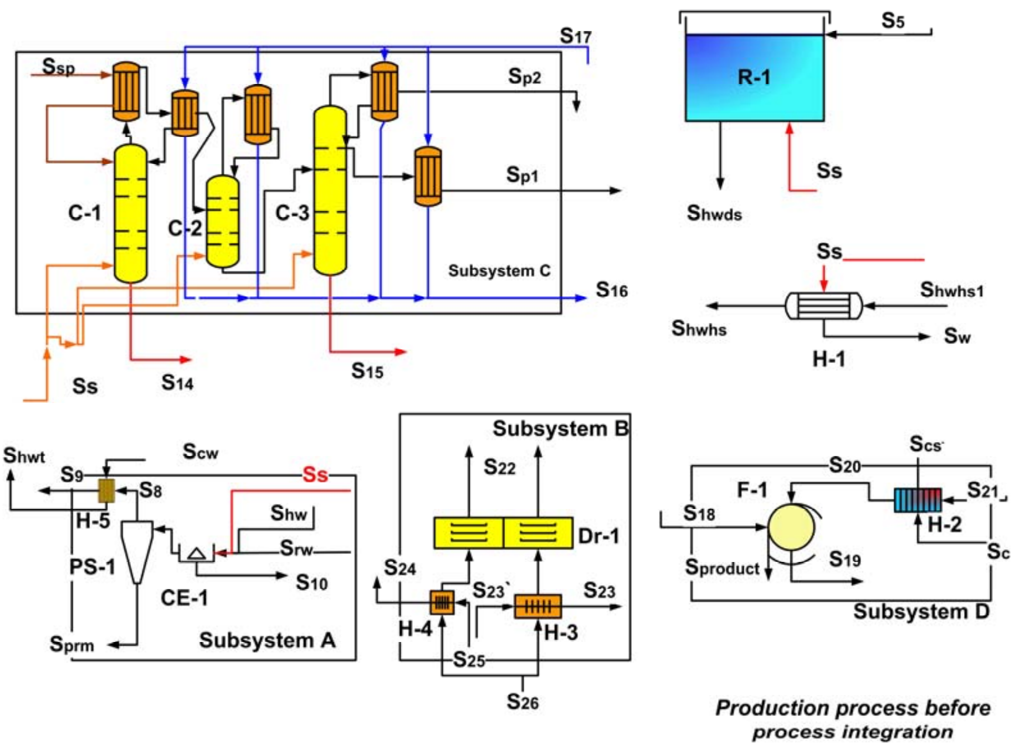



**Fig. 2.** Flowsheet with selected subsystems of process plant.
$S_{hwds}$ – hot water distribution system, $S_{hwhs}$ – hot water heating system, $S_{hwt}$ – to hot water tank, SS – steam, $S_{cw}$ – cooling water, $S_{prm}$ – prepared row material, $S_{w}$ – waste, C – column, H – heat exchanger, Dr – dryer, F – filtration, R – reservoir, PS – phase separator, CE – centrifuge

Table 1

*Characteristics of process streams**

| Stream | Flowrate ($m^3$/h) | Supply temperature (°C) | Target temperature, (°C) | Heat capacity (kJ/kg °C) | Composition |
|---|---|---|---|---|---|
| **$S_5$** | **5** | **5** | **90** | **4.187** | **Hot water** |
| **$S_6$** | **30** | **5** | **90** | **4.187** | **Hot water** |
| $S_7$ | 30 | 40 | 90 | 5.5 | NaOH solute |
| $S_8$ | variable | 105 – 120 | – | – | Evaporative components |
| $S_9$ | variable | 60 | – | – | Evaporative components |
| $S_{10}$ | 6 | 80 | – | – | Sludge, row material |
| **$S_{14}$** | **3.94** | **106** | **25** | **4.2** | **Organic components, water** |
| **$S_{15}$** | **1.3** | **105** | **25** | **4.204** | **Organic acids, water** |
| **$S_{18}$** | **3.35** | **6** | **–** | **3.56** | **Yeast cream** |
| **$S_{19}$** | **4.9** | **7–10 (6*)** | **15** | **4.187** | **Water** |
| **$S_{20}$** | **4** | **15 (7*)** | **–** | **4.187** | **Cold water** |
| **$S_{21}$** | **4** | **18** | **15 (7*)** | **4.187** | **Water** |
| **$S_{22}$** | **25000** | **35** | **–** | **1** | **Air with dust** |
| $S_{23}$ | 1.1 | – | – | – | Saturated steam, 3 bar |
| $S_{23'}$ | 1.1 | 80 | – | – | Condensate mixed with steam, 3 bar |
| $S_{24}$ | 1.5 | 30 | – | 4.187 | Cooling water (outlet) |
| $S_{25}$ | 1.5 | 18 | – | 4.187 | Cooling water inlet |
| **$S_{26}$** | **11000** | **35** | **90** | **0.99** | **Air** |
| $S_{SP}$ | 5 | 60 | – | – | Semiconducted product |
| $S_{p1}$ | 0.6 | 20 | – | – | Product 1 |
| $S_{p2}$ | 0.2 | 25 | – | – | Product 2 |
| $S_{product}$ | 2 | 12 | 6 | 3.2 | Biomass |

* Streams in bold are characteristics of selected process stream for heat process integration

In Fig. 1 the scheme of subsystems as black boxes (with schemes of each selected subsystem inside) and their inlet and outlet streams is presented. These streams have to be integrated to minimize utility costs. For this purpose HX-NET software can be used [17].

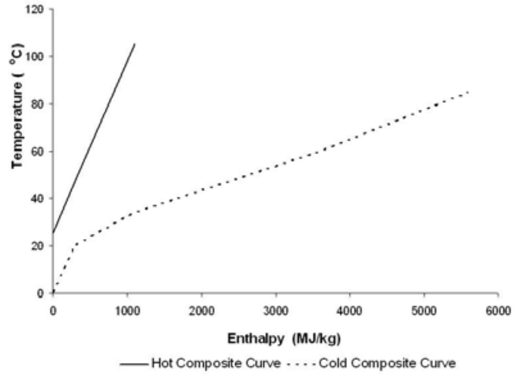
For the project it is proposed that the lifespan be 5 years, with 10% pay back. The utilities present in the system are low pressure steam with cost of 14.66 EUR/GJ, and cold water (cold utility). The data given in the Table 4 and the data for project conditions and utilities are sufficient for starting with the pinch analysis and HEN design.

The initial $\Delta T_{min}$ for starting with pinch analysis is adopted to be 10 °C. That value is random and chosen by the designer. With that value all calculations of the pinch analysis algorithm are started.

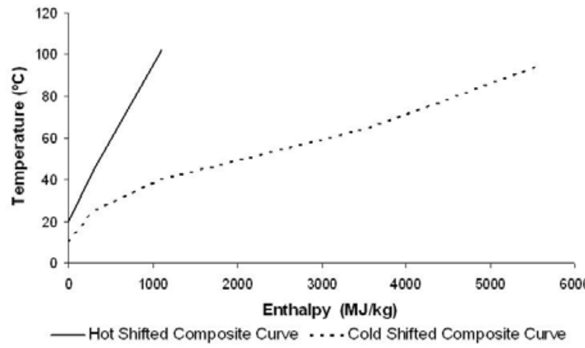
Table 2

*Streams to be integrated between subsystems*

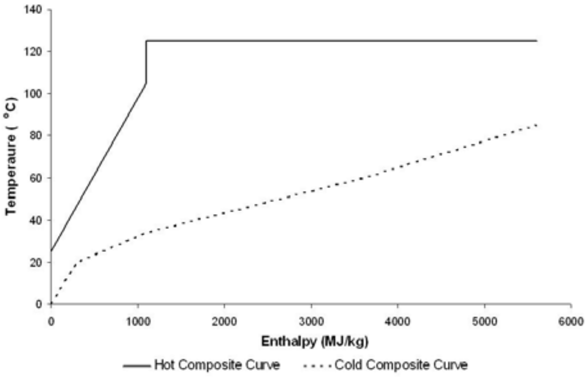
| Stream | Flow ($m^3$/h) | $T_{inlet}$ (°C) | $T_{target}$ (°C) | Heat capacity (kJ/kgK) | Conductivity (W/mK) | Density (kg/$m^3$) | Viscosity (cP) | Pressure (bar) |
|---|---|---|---|---|---|---|---|---|
| $S_5$ | 5 | 5 | 90 | 4.187 | 0.6 | 1000 | 1.2 | 6.00 |
| $S_{HWHS}$ | 8 | 20 | 60 | 4.187 | 0.6 | 1000 | 1.2 | 3.00 |
| $S_{14}$ | 3.94 | 106 | 25 | 4.2 | 0.8 | 625.15 | 1.5 | 1.25 |
| $S_{15}$ | 1.3 | 105 | 25 | 4.204 | 0.8 | 584 | 1.5 | 1.21 |
| $S_{26}$ | 11000 | 35 | 90 | 1 | $2.9\ 10^{-2}$ | $4.1\ 10^{-3}$ | $2\ 10^{-2}$ | 2.00 |



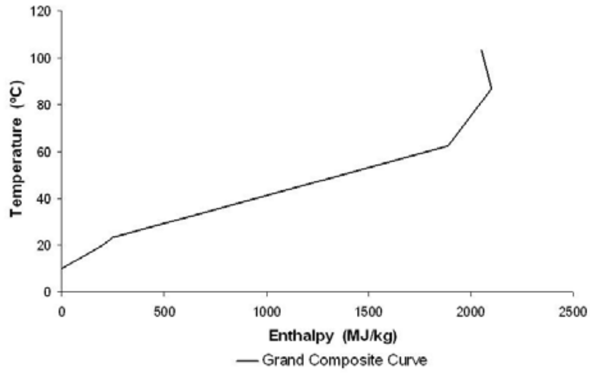

**3a.**




**3c.**

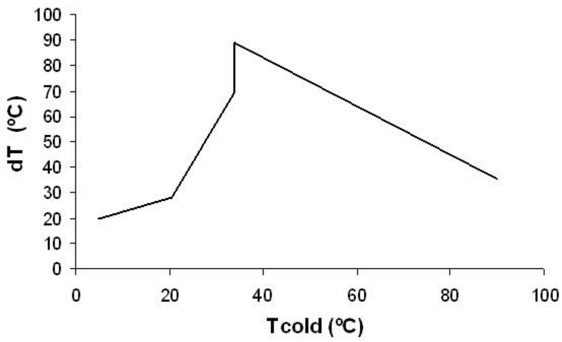



**3b.**

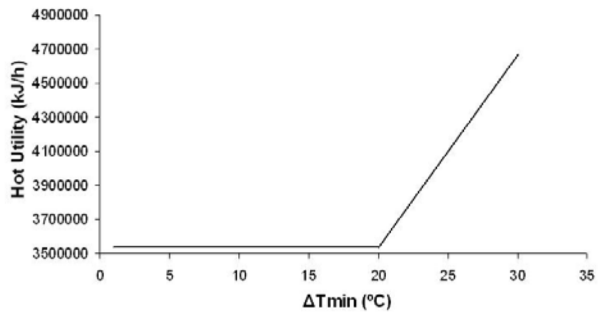



**3d.**

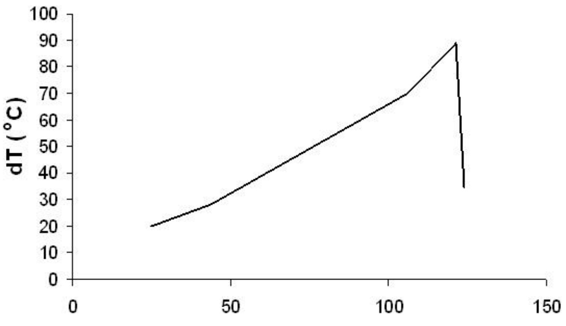
**Fig. 3.** Composite curves for the system (alternative 1 / variation 1)




**a)** Plot of cold stream

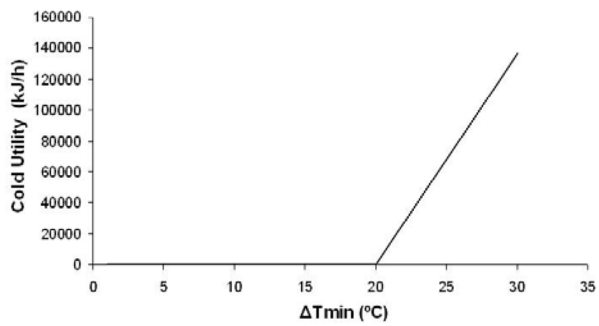



**a)** hot utility



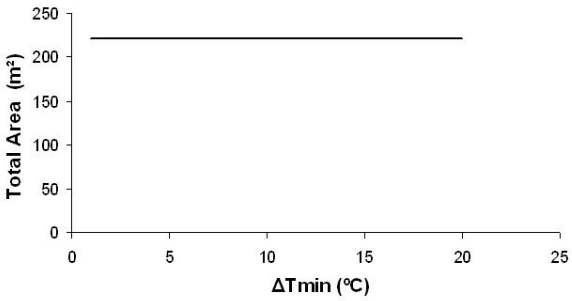

**b)** Plot of hot stream

**Fig. 4.** Driving force in HEN (alternative -1/ variation -1)

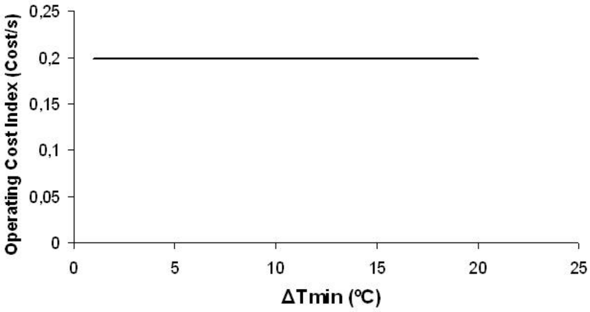



**b)** Cold utility

**Fig. 5.** Range targets of the utility (alternative –1/ variation –1)




**a)** Total heat exchange area




**b)** Operating cost index

**Fig. 6.** $\Delta T_{\min}$ influence on

The HX-NET software generates and draws the composite curves (Fig. 3). The plots of composite curves provide data for hot utility demand, but this system does not need cold utility. The pinch point is at the beginning of cold (5 °C) and hot (25 °C) curves (Fig. 3-a and 3-b). This is not a typical case for a pinch. Balanced composite curves present hot and cold composite curves with added demand of hot or cold utilities (Fig. 3-b). The sum of energy in balanced composite curves is zero. The horizontal part of the hot balanced composite curve represents hot utility demand and its value is the difference between the end value of the horizontal line (right point) and beginning value of the horizontal part (left point). The HX-NET software, by using composite curves shifted for $\pm\frac{\Delta T_{\min}}{2}$ (Fig. 3-c), also generates the grand composite curve (Fig. 3-d). The grand composite curve is constructed as difference between the hot and cold shifted composite curves. If shifted composite curves are balanced, then new grand composite curve is balanced too. Driving forces indicate the way of their changing through the HEN and their minimal values on axis are always in the pinch point (Fig. 4-a and Fig. 4-b).

After finishing first 4 steps of the pinch analysis (Appendix I), optimization of the system viewed must be done. Optimization means determination of optimal $\Delta T_{\min}$ for the case through determination of the minimum heat exchange area, optimal number of heat exchanger units, and minimum costs (operational and capital costs).

Total heat exchange area calculation is based on equation (1) as sum of heat exchange area for enthalpy intervals determined on composite curves.

$$A_{\text{network}} = \sum_{k=1}^{n\ \text{intervals}} \frac{1}{\Delta T_{IM,k}} \left( \sum_{i}^{\text{hot streams}} \frac{q_i}{h_i} + \sum_{i}^{\text{cold streams}} \frac{q_i}{h_i} \right) \tag{1}$$

The number of heat exchange units is determined by equation (2).

$$N_{u,\min} = (N_A - 1) + (N_B - 1) \tag{2}$$

The HX-NET software generates the capital costs, number of heat exchanger units, and heat exchange area for different values of $\Delta T_{\min}$. The economical estimation is based on equations (3) and (4) Operating cost represents cost for utility using, and they are calculated with equation (5), as well as total annual costs, equation (6).

$$\text{Capital Costs Index} = a + b\left(\frac{A_{exchange}}{Shell}\right)^{c} \cdot Shell \tag{3}$$

$$\text{Annualized factor} = \frac{\left(1+\frac{ROR}{100}\right)^{PL}}{PL} \tag{4}$$

$$OC = UC_{hu,\min} \cdot Q_{cu,\min} \tag{5}$$

$$TAC = \text{Annualized factor} \cdot CC + OC \tag{6}$$

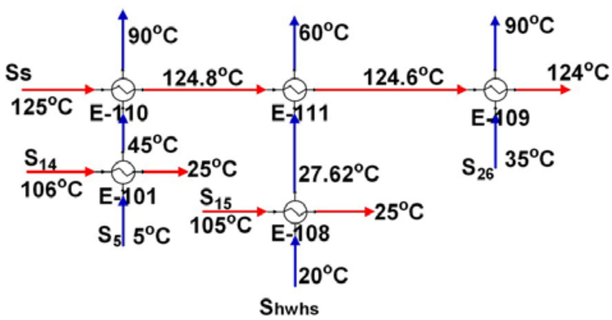
where *ROR* is Rate Of Return, *PL* is Plant Life and *Shell* is number of shell units in net.

Graphical presentations of generated energy targets for hot and cold utility are shown on Fig. 5-a and 5-b. Graph lines could be divided into two parts. The first part is constant function part and the second is increasing function part. Constant function has the same range for cold and hot utility between 1 – 20 °C. That part has minimal utility targets. Other parameters depend of utility targets, so they have functions similar to utility energy target. The heat exchange area is determined as constant value for $\Delta T_{\min}$ range of 1 to 20 °C (Fig. 6-a).

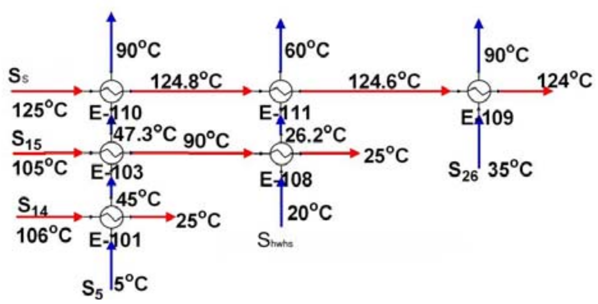
Calculations for $\Delta T_{min}$ higher then 20 $^oC$ are not determined by the software. Operating costs have similar function with the same $\Delta T_{min}$ consnt range (Fig. 6-b). This happened because the increase of $\Delta T_{min}$, increases hot and cold utility needs for the analyzed system (Fig. 5-a and 5-b). Increasing come under 20 $^oC$ and that is the reason for increasing of operational costs to very high values. Optimal value of $\Delta T_{min}$ is every $\Delta T_{min}$ in the range of 1 to 20 $^oC$, because that range has constant value which represents minimum costs, minimum heat exchange area, and minimum number of heat exchangers. $\Delta T_{min}$ is used with an initial value of 10 $^oC$. The minimum number of heat exchangers is 5.

After performing pinch analysis using HX-NET, the HEN could be designed. Using pinch technology rules for HEN design, the designer can make many alternatives for different combinations of connecting heat exchanger units. This software warns the user when some of the pinch technology rules are broken.

In this work two alternatives of possible HEN are made (Fig. 7-a and Fig. 7-b). Alternative 1 (Fig. 7-a), also presented on HX-NET designed grid diagram (Fig. 8), has two variations. These variations are made to use some of the already installed equipment.




**7a)** alternative 1 / variation 2; $S_{hwhs}$ – hot water heating system




7b) alternative 2

**Fig. 7.** Designed of HEN

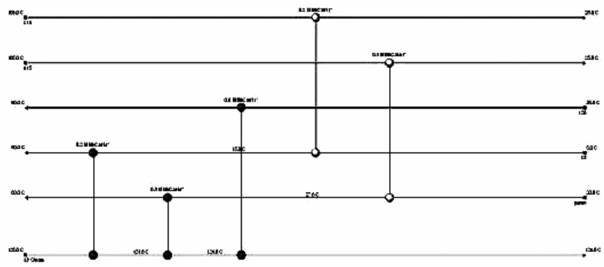


**Fig. 8.** Grid diagram for new HEN designed with HX-NET (alternative 1/ variation 1)

There are a few questions on how to use some streams, such as separated steam from condensate at different pressures ($S_{S\text{-outlet}}$, $S_{23}$, $S_{24}$,$S_W$), and what could be made with the outlet hot air stream ($S_{22}$). It is proposed to use injector to take the separated steam (phase separation) back to the main plant inlet utility stream, as well as to bring back condensate to steam boilers with pumps. Hot air stream $S_{22}$ could be used for air conditioning of the plant hall, before filtrating by air filters. A great part of the energy is used for heating cold water (hot water for process needs), also heating rooms and production halls (hot water heating system, $S_{hwhs}$), so the way of solving this case has to be focused on minimizing the costs for preparing hot water for this purposes.

The final results obtained for both alternatives are shown in Tables 3 and 4. The unit E-111 has the same performances in both alternatives. In the alternative 2 heat exchanger E-103 enables using the heat of the waste streams $S_{14}$, $S_{15}$, to $S_5$ more efficiently, because the inlet temperature of $S_5$ into E-110 is higher (47.3 $^oC$ by the First Law of Thermodynamics). In this alternative, with installation of E-103, the number of heat exchangers is increased, indicating increase in capital costs. The sum of energy which will be transferred in both alternatives is the same quantity.

Table 3

*Results for alternative 1 / variation 2*

| Unit | E-101 | E-108 | E-109 | E-110 | E-111 |
|---|---|---|---|---|---|
| Heat exchange area ($m^2$) | 71.3 | 28 | 62 | 24.9 | 19.5 |
| LMTD ($^oC$) | 36.76 | 26.42 | 57.52 | 54.34 | 79.78 |
| Ft-factor | 0.9984 | 0.9585 | 0.9984 | 0.9985 | 0.998 |
| Heat transfer (MJ/h) | 837.4 | 255 | 2.482 | 942.08 | 1085 |

Table 4

*Results for alternative 2*

| Unit | E-101 | E-103 | E-108 | E-109 | E-110 | E-111 |
|---|---|---|---|---|---|---|
| Heat exchange area ($m^2$) | 71.3 | 2.61 | 25.87 | 62 | 24 | 19.5 |
| LMTD ($^oC$) | 36.76 | 51.07 | 23.09 | 57.52 | 53.46 | 79.78 |
| Ft-factor | 0.9984 | 0.9978 | 0.9648 | 0.9984 | 0.9995 | 0.998 |
| Heat transfer (MJ/h) | 837.4 | 47.9 | 207.67 | 2.482 | 893.9 | 1132.2 |

One of the most important calculations for optimization i.e. determination which alternative is better for its realization as a project, is economical calculations. For that purpose the CAPCOST software has been used [18]. To estimate equipment cost the bar module method using data for heat exchange area, operating pressure, and construction material, has been used. CEPCI index for 2006 is 516.8 [19]. The CAPCOST software uses module costing technique, which is common technique to estimate the cost of a new chemical plant. Such cost estimation is accepted as the best strategy for making preliminary cost estimation. With this estimation, the sum of direct and indirect costs is given as multiplication of purchased cost of equipment for base conditions (using the most common material, and operating near ambient pressures), and multiplication factor (for specific conditions) representing Bar Module Cost.

The results of the equipment costs estimated by CAPCOST software are given in the Table 5.

Table 5

*Estimated equipment costs*

| | |
|---|---|
| Heat exchangers | 114 900.00 $ |
| Air filter unit | 1 000.00 $ |
| Air fan | 1 500.00 $ |
| Sum | 117 400.00 $ |

The production costs, represented by the energy, which is saved with this integration, are given in the Table 6.

Table 6

*Calculated saved energy by process heat integration*

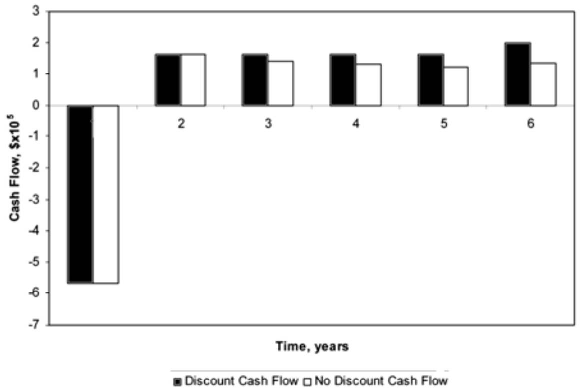
| | |
|---|---|
| Stream $S_{14}$ (12 months using) | 105 000.00 EUR |
| Stream $S_{15}$ (6 months using) | 16 200.00 EUR |
| Cooling integration | 1 000.00 EUR |
| Heating of rooms (6 months) | 47 570.00 EUR |
| Sum of cost saving / year approx. | 170 000.00 EUR<br>or approx. 210 800.00 $ |

The sum of equipment cost is 117 400.00 $ and the bar module cost is 566 300.00 $, which means that the sum of direct and indirect costs for the new plant is 566 300.00 $. For economical calculations, taxes for profit are assumed to be 42%.

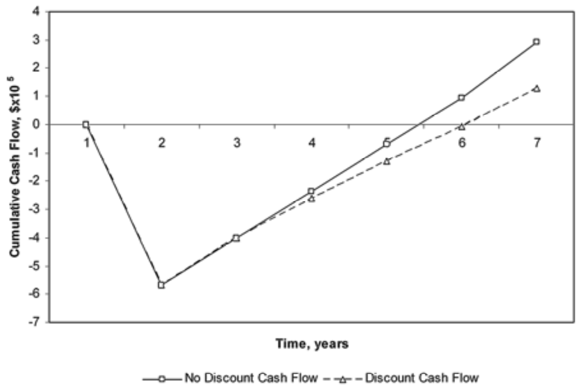
In the alternative 1 / variation 1, the heat exchanger network uses three already installed heat exchangers and two new heat exchangers: E-109, E-110 and E-111 are not installed, and instead of them an already installed R-1, hot water tank with direct injection of steam on it, and two existing heat exchangers H-2 and H-3, are used (Fig. 2). The alternative 1 / variation 2, uses two already installed heat exchangers H-2 and H-3. The alternative 2 is similar to alternative 1 / variation 1, upgraded with another new heat exchanger E-103 (Fig. 7-b).

No discount and discount cash flow for plant 5 years life time are given in Fig. 9-a. During the plant lifetime, the amount of no discount cash flow is the same for every year except for the last, where the end value of the plant is included. Depreciation of the plant is calculated with Straight Line Depreciation Method [20], which means equal depreciation amount per year. Using an interest rate for depreciation of money, the discount cash flow plot can be calculated, and it is presented in Fig. 9-a. This calculation can be used for obtaining cumulative no discount and discount cash flow (Fig. 9-b). In the year of investment cash flows are negative, because there is no income profit. In the first year of plant life, there is incoming profit which leads to positive value of cash flow. At the end of plant life, the value is positive since it contains salvage and working capital. Using the cumulative cash flow (Fig 9-b) the economical parameters can be determined. These parameters are used for decision making about which project is better. Using these plots, the values of ROROI (Rate Of Return Of Interest) is determined to be 30.31%, and the CCP = 1.515 (Cumulative Cash Position). The value of NPV (Net Present Value) at the end of plant life with 8 % interest is 115 155.00 $ and the PVR (Present Value Rate) is 1.2 (Table 7).

The economical parameters for the investigated alternatives shown on Table 7 could be compared to determine the most profitable project. These economical parameters are better if their values are higher. Alternative 1 / variation 1 has the highest rate of return of investment and net present value at the end of plant life. That means alternative 1 / variation 1 is the best case, and then alternative 1 / variation 2 is following. The economical parameters, ROROI, CCP, NVP and PVR for the alternative 2 are the lowest which means that this alternative is not acceptable for additional detailed investigation. The values of rate of return, plant life, depreciation method, CEPCI index, rate of interest, and taxes for all investigated cases are the same. This helps in decision making in a right way.




a) Cash flow




b) Cumulative cash flow

**Fig. 9.** Economic parameters for alternative 1 / variation 1

Table 7

*The calculated economical parameters for investigated alternatives of HEN*

| Investigated alternatives of HEN | ROROI (%) | CCP | NVP ($) | PVR |
|---|---|---|---|---|
| Alternative 1 / variation 1 | 30.31 | 1.515 | 115 155.00 | 1.200 |
| Alternative 1 / variation 2 | 26.99 | 1.349 | 47 312.00 | 1.070 |
| Alternative 2 | 26.33 | 1.316 | 31 403.00 | 1.044 |

## CONCLUSION

Calculations done for the designed system with process integration using pinch technology has shown that the new system is more profitable than the old one, since the energy, production, and capital costs have been minimized. Integration in Subsystem D leads to lower temperature of the final product of separation, as well as minimal needs of cold utility. Using the prepared hot air outlet for hall air conditioning excludes present heating with utility.

The three investigated cases done by HX-NET software using pinch technology are all profitable. Comparing the two alternatives, it is determined that alternative 1 / variation 1 is better than alternative 1 / variation 2, while alternative 2 is less profitable than alternative 1.

This work is proof for saving energy with small investment in production plant. The pinch technology method gives a clear overall view in respect to energy consumption efficiency in process plants, and should be implemented regularly for designing new and investigating existing plants in order to choose the optimal alternative.

## NOTATION

$A_{exchange}$ – heat exchange area, $m^2$

CC – installed capital cost, $

CCP – cumulative cost position

CEPCI – chemical equipment plant cost index

$\Delta T_{min}$ – minimum temperature difference, $^oC$

$\Delta T_{LM}$ –LMTD – logarithmic temperature difference, $^oC$

Ft-factor – LMTD correction factor

HE – heat exchanger

HEN – heat exchange network

HWHS – hot water heating system

MNLP – mixed integer nonlinear programming

$N_A$ – number of process and utility streams above pinch

$N_B$ – number of process and utility streams below pinch

NPV – net present value $, MKD, EUR etc

$N_{u,\ min}$ – unit target

OC – operating costs, $/year

PL – plant life

PVR – present value rate

$Q_{cu,min}$ – energy target of cold utility, kW

$Q_{hu,\ min}$ – energy target of hot utility, kW

ROR – rate of return

ROROI – rate of return of investment

TAC – total annual cost, $

TAM – time average model

TSL – time sliced model

$UC_{cu}$ – cold utility cost, $/kW year

$UC_{hu}$ – hot utility cost, $/kW year

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## APPENDIX I

### BASIC PRINCIPLES OF PINCH TECHNOLOGY

For implementation of heat process integration with Pinch technology, Pinch analysis must be done. Pinch analysis is consisting of 9 steps in following order:

1) Identification of Hot, Cold and Utility Streams in the Process
2) Thermal Data Extraction for Process and Utility Streams
3) Selection of Initial $\Delta T_{\min}$ Value
4) Construction of Composite Curves and Grand Composite Curve
5) Estimation of Minimum Energy Cost Targets
6) Estimation of Heat Exchanger Network Capital Cost Targets
7) Estimation of Optimum $\Delta T_{\min}$ Value
8) Estimation of Practical Targets for HEN Design
9) Design of Heat Exchanger Network (HEN)

1) First, it must be determined which streams are hot, cold and with what kind of utilities the plant includes. Hot stream is determined with high inlet temperature and lower target temperature, and cold streams are determined with low inlet temperature and higher target temperature. Designer must know present utility in the process plant to use some of them for its demand in new designed HEN.

2) The thermodynamic characteristics of each stream (include utilities), such as heat capacity of fluid in energy stream, its flow and inlet and target temperatures for each energy stream must be determined.

3) To start with system design one must determine the initial minimum force of heat exchange ($\Delta T_{\min}$). Linnhoff March [2] determined that the $\Delta T_{\min}$ depends on the industrial process, so he finds average values which are given in Table A1.

Table A1

*Average values for $\Delta T_{min}$ given by Linnhof [1, 2]*

| Industry | Experience $\Delta T_{min}$/°C |
|---|---|
| Oil refinery | 20 – 40 |
| Petrochemistry | 10 – 20 |
| Chemical industry | 10 – 20 |
| Low temperatures processes | 3 – 5 |

4) With definition of those parameters, one can start with creation of Composite Curves (CC, that means CCC – Cold Composite Curve and HCC – Hot Composite Curve), as well as Grand Composite Curve (GCC). Hot and Cold Composite Curves (as function of temperature depends by enthalpy of energy streams) are graphical representation of heat availability in process (hot composite curve) and heat demands in the process (cold composite curve). Grand Composite Curve is designed with the shifting method. That method involves shifting (along the temperature axis) of the hot composite curve down by ½ $\Delta T_{min}$ and that of cold composite curve up to ½ $\Delta T_{min}$. After shifting, the grand composite curve is designed as differences of enthalpy (horizontal differences) between shifted composite curves.

5) Next step is estimation of minimum energy cost targets. They could be determined when $\Delta T_{min}$ is defined. Total energy costs could be calculated graphically from composite curve plot or arithmetically with equation A.1.

$$\text{Total energy cost} = \sum_{U=1}^{n} Q_U \cdot C_U \qquad \text{(A.1)}$$

where $Q_U$ = duty of utility, U / kW),

$C_U$ = unit cost of utility, U / $/kW or yr,

$U$ = total number of utility used.

6) Estimated value of capital cost targets of HEN depends on the number of heat exchangers, the overall network area, and the distribution area between the exchangers. Calculations could be made using equations A.2 and A.3.

$$\text{HEN Area}_{\min} = A_1 + A_2 + A_3 + \ldots + A_i = \\ = \sum_i \left[ \frac{1}{\Delta T_{LM}} \sum_i \frac{q_j}{h_j} \right] \qquad \text{(A.2)}$$

$$C(\$)_{HEN} = \left[ N_{\min} \left\{ a + b \left( \frac{A_{\min}}{N_{\min}} \right)^c \right\} \right]_{AP} + \left[ N_{\min} \left\{ a + b \left( \frac{A_{\min}}{N_{\min}} \right)^c \right\} \right]_{BP} \qquad \text{(A.3)}$$

where $a$, $b$ and $c$ are constants in heat exchanger cost estimation. They depend on the heat exchanger type and its construction material.

7) Using these equations one can make a plot of Energy and Capital Costs depending on $\Delta T_{min}$. With optimization of those functions the optimal $\Delta T_{min}$ and optimal number of heat exchangers can be determined, as well as the optimal capital costs for HEN. This is going to lower Capital Costs, lower utility energy use and lower heat exchange area. After estimation, the HEN design is next step.

8) Construction of HEN is making combinations for heat exchange between two or more energy streams throughout the heat exchange area. There are few rules for HEN design. Energy streams could be split or mixed with each other if it is possible in real system. New HEN cannot contain energy stream loops, because it needs more heat exchangers in network. The Second Low of Thermodynamics must be respected, which means heat energy is going from place with higher temperature to place with lower temperature. There shouldn't be any crossing roads between temperature profile lines of cold and hot streams into heat exchanger. The determined $\Delta T_{min}$ must be respected in every part of the new HEN. The left part of the Composite Curves (energy streams that consist of that part) from the Pinch point must only give out energy taken with cold utility. Similarly, the right part from the Pinch point needs energy taken from the hot utility. There shouldn't be any heat exchange through the Pinch point.

9) Finally, all constructed HEN are compared. After that the best HEN is chosen with the lowest capital, process and utility costs, lower number of heat exchangers, lower heat exchange area, and HENs where all rules of Pinch technology are implemented.

Every software for heat process integration with Pinch technology works on algorithm based on these 9 steps of Pinch analysis. Those kinds of software are HX-NET, Aspen Pinch, and HINT etc. Their algorithm includes all rules that Pinch technology gives us.