International Energy Agency

Implementing Agreement on Process Integration

Annex I (Survey and Strategy)

Supported by

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A
Process
Integration
PRIMER

by

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SUMMARY

This Primer can be regarded as a stand-alone document intended to convey the most basic aspects of Process Integration methods. It also contains towards the end some details about the more recent and advanced elements of Process Integration methods. Since emphasis is on learning, the number of references is kept at a minimum, especially in the core chapters of this Primer.

The Primer is one of the products from the Process Integration Implementing Agreement within the International Energy Agency (IEA). The other main products from Annex I (Survey and Strategy) of this IEA Agreement are:

- "IEA Implementing Agreement on Process Integration: Annex I End-User Survey", T.J. Pears, EA Technology, Capenhurst, UK, November 1997.
- "A Worldwide Catalogue on Process Integration", T. Gundersen, Telemark Institute of Technology, Porsgrunn, Norway, December 1997.

The Primer contains some general material on Process Integration (chapters 1, 2 and 3) in addition to the more tutorial chapters (5, 6, 7 and 8), and one chapter (9) on more advanced aspects of Process Integration. In the first part, there is some information about the IEA project, and the Primer attempts to put Process Integration into a broader perspective.

1. BACKGROUND

The Implementing Agreement on Process Integration within the ***International Energy Agency*** (IEA) was formally started in September 1995, motivated by the recognition that Process Integration was not used to its full potential in industry, with significant differences across geographical regions and industrial branches.

This Primer is based on the idea that there was a need for a document similar to the Pinch Technology Primer that was prepared by Linnhoff March and published by EPRI about ten years ago (1991). Since Process Integration has been expanded considerably and goes far beyond basic Pinch Technology, there is a need for a new Primer that describes the more recent developments. For completeness reasons, however, it was decided to include also the more basic and established parts of Process Integration methods.

Emphasis in the presentation of the material will be on what can be done, rather than how it is done. The Primer is written for ***practitioners*** in the process industries, and those that are interested in more details will have to consult some of the literature that is referenced here, both the journal papers and the growing number of text books available.

Finally, this Primer is expected to be one of many ways to ***disseminate*** knowledge about Process Integration into operating companies, engineering and contracting companies, consultants and even software vendors. Information about the IEA Agreement on Process Integration can be found on the ***Web*** site http://www.tev.ntnu.no/iea/pi/.

6. BASIC CONCEPTS FOR HEAT RECOVERY IN RETROFIT DESIGN OF CONTINUOUS PROCESSES

While the majority of early days methods developed within Process Integration were related to the design of new plants, most of the projects in industry are trying to make the most out of existing facilities. Typically, these ***projects*** are related to improved operation, removal of plant bottlenecks, improved efficiency with respect to energy and raw material utilization, and the introduction of new technology into an existing process.

Many terms are used for plant modifications, such as retrofit, revamp and debottlenecking. In this section, the term ***retrofit*** is used for projects trying to reduce energy consumption in the most economic way. Typical economic parameters or constraints are maximum allowed values for Payback Time and Investment Cost. The objective of a retrofit project is then to save as much energy as possible while satisfying these economic constraints.

The economy of most energy saving projects (cost of new equipment versus reductions in operating cost) is not good enough to include the losses in production if the plant has to be stopped for a period of time while the modifications are installed. Thus, the timing of retrofit projects into regular plant maintenance periods is extremely important. Further, the best retrofit projects are the ones that combine pure energy saving features with more general plant modifications.

6.1 Some Useful Representations

Grassroots Pinch Analysis can and has been used to a large extent in industry to establish the potential for energy savings in existing plants. When comparing the current energy consumption with grassroots targets, however, the identified ***potentials*** tend to be rather optimistic. In the process industries there is no "second hand" market, thus one of the prime objectives in retrofit projects is to try to improve the utilization of already invested and installed equipment. There will be discrepancies in the existing design that cannot be completely removed, only improved by smaller or larger process modifications. As a result, the optimal heat exchanger network after retrofit is likely to be quite different from the optimal grassroots design.

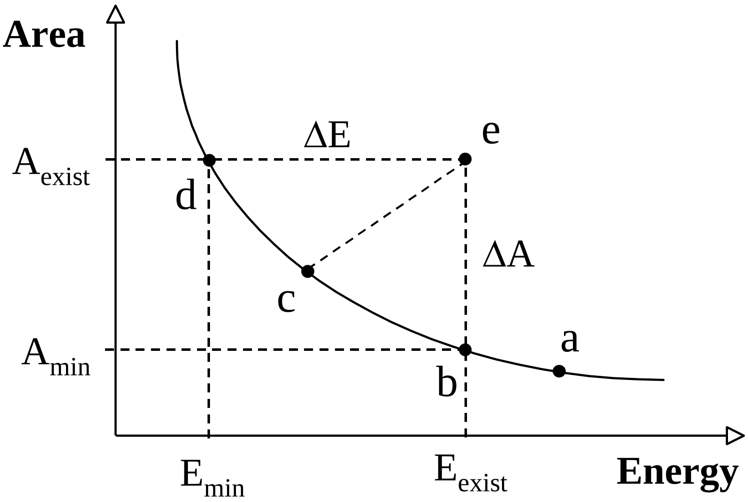

Fig. 6.1 Area-Energy Plot for Heat Exchanger Networks

In an existing plant, the heat recovery system can suffer from two types of errors, as illustrated in figure 6.1. Each point on the curved line indicates the minimum amount of heat transfer area that is required to have a certain energy consumption (or level of heat recovery). Similarly, the curve also indicates minimum energy consumption for a given total heat transfer area. The points (a) to (e) represent different design solutions that will be discussed in the following.

The curved line in figure 6.1, also referred to as the ***Area-Energy Plot***, is constructed by calculating minimum ***target values*** for energy and area as indicated in section 5.2 for different values of the minimum allowable approach temperature, ΔT_{min}. With small values of ΔT_{min}, the minimum area target is large, while the energy target is low, and opposite for large values of ΔT_{min}.

Assume that design (c) is the optimal grassroots heat exchanger network, with an optimal trade-off between operating cost and investment cost for the current energy and area prices. Network (a) has been correctly designed in the sense that it uses minimum area to achieve a certain level of heat recovery. Most likely, this design has been established by the Pinch Design Method. The ***trade-off*** in this design is wrong, however, as it uses more energy than would have been optimal with the “current” prices. In a retrofit project, it will be very hard and costly to improve this network. Moving along the curve from (a) to (c) would mean that a number of heat exchangers would have to be taken out of the network. What would be done in practice is to keep most of the existing exchangers and invest in some new ones. The corresponding retrofit project would move along a curve above the minimum target line, and this curve would be steeper than the target line.

Next, consider design (e), which is located far above the target line. If this had been a suggested new design, both investment cost (area) and operating cost (energy) could have been reduced as indicated by ΔA and ΔE. If this is an ***existing*** network, however, it is not economically tractable to try to reach design (c), since that would involve throwing away a large number of invested heat exchangers. Again, the retrofit project would follow a curve to the left, but in this case it would be flat in the beginning, since the existing network has major errors that can be corrected by moderate investments, such as re-piping and the addition of strategically placed new heat exchangers. After correcting the most obvious errors in the existing design, the cost of recovering additional heat will gradually become more costly. This means that the retrofit curve would become steeper, and payback time therefore increases with the amount of energy saved.

While network (a) is a "good" design (unfortunately with a wrong trade-off), network (e) is a "poor" design, since it uses much more energy than what could have been achieved with the amount of invested heat transfer area. The errors in design (e) are important in retrofit projects and will be discussed in detail in this section.

It should also be mentioned that the minimum area figures used to establish the target curve in figure 6.1 actually require a large number of heat exchangers, splitters and mixers (referred to as the Spaghetti Design in section 5.2.4). Thus, one would never design on the target line, but some small distance above. Figure 6.1 is a quantitative tool to identify the potential for improved heat recovery, and at the same time a qualitative picture of the situation indicating how costly the corresponding retrofit projects will be. What are needed next are some guidelines on how to actually modify the network.

The reason why an existing design, such as network (e) in figure 6.1, is using more than the minimum amount of energy (both heating and cooling), is the fact that ***heat*** is being ***transferred across*** the heat recovery ***Pinch***. Such heat transfer can take three different forms, as indicated in figure 6.2.

The heat recovery Pinch divides the process into a heat deficit part above Pinch and a heat surplus part below Pinch. Of course, it would not make sense to transfer heat from the deficit part to the surplus part. Nevertheless, when heat exchanger networks are designed without the knowledge about the heat recovery Pinch, such heat transfer is often inevitable. This is why ***large potentials*** for energy savings have been identified in existing plants, and the more complex these processes are, the more likely it is that considerable cross Pinch heat transfer takes place. Typical examples are petrochemical plants and oil refineries, however, significant potentials have also been identified in other industries as well.

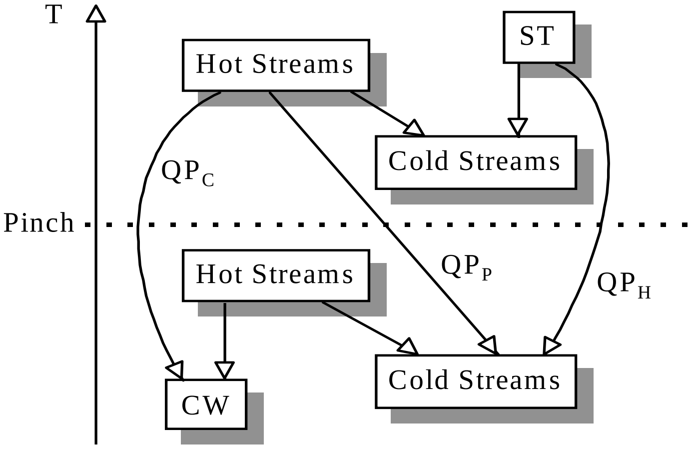

Fig. 6.2 The Penalty Heat Flow Diagram for Heat Exchanger Networks

There may also be ***practical*** reasons for such heat transfer across the Pinch. One of the major limitations of the Composite Curves and the corresponding Pinch Analysis, is that hot and cold streams are regarded to be heating and cooling resources that can be used without limitation. In practice, however, there will be match combinations among hot and cold streams that one would avoid. Examples include safety considerations, geographical distance, start-up considerations, ensuring product purity, etc.

In many of these cases, heat transfer across the Pinch is inevitable, however, there are some degrees of freedom in how this heat transfer takes place. The ***Penalty Heat Flow Diagram*** (Linnhoff and O'Young, 1987) in figure 6.2 shows that heat can be transferred across the heat recovery Pinch in the following ***three*** ways:

- Heat transfer from a hot stream above Pinch to a cold stream below Pinch: QP_P
- Heating a cold stream below Pinch with hot utility, such as steam: QP_H
- Cooling a hot stream above Pinch with cold utility, such as cooling water: QP_C

The total ***Energy Penalty*** for heat transfer across the Pinch is then the sum of these individual heat flow components:

$$QP = QP_P + QP_H + QP_C$$

This penalty is then the difference between the current energy consumption and the minimum energy consumption for a given value of ΔT_{min}:

$$Q_{H,exist} = Q_{H,min} + QP$$
$$Q_{C,exist} = Q_{C,min} + QP$$

The three components of penalty heat flow (QP_P, QP_H and QP_C) can be considered as ***variables*** that can be used to take advantage of the situation when practical constraints result in an energy penalty. When trying to minimize the cost penalty of such constraints, the three variables provide ***two degrees of freedom***. This is obvious from figure 6.2, since there are two heat load loops that can be manipulated. The following advantages can be taken from a constrained situation:

- QP_P means heat transfer at larger driving forces, thus heat transfer area is reduced.
- QP_C can be realized as steam production, if the Pinch temperature is high enough.
- QP_H means that a cheaper hot utility with lower temperature can be used.

Since the energy target depends on the chosen ***value of*** $\boldsymbol{\Delta T_{min}}$, the corresponding potential for reduced energy consumption is larger for a smaller value of ΔT_{min}. The corresponding retrofit project will, however, also be more complex and costly. While targeting methods exist for the retrofit case that can identify a proper value for ΔT_{min} (will be described later), it is common practice in industry to use a larger value for ΔT_{min} in a retrofit situation than the corresponding and optimal value of ΔT_{min} in a grassroots case.

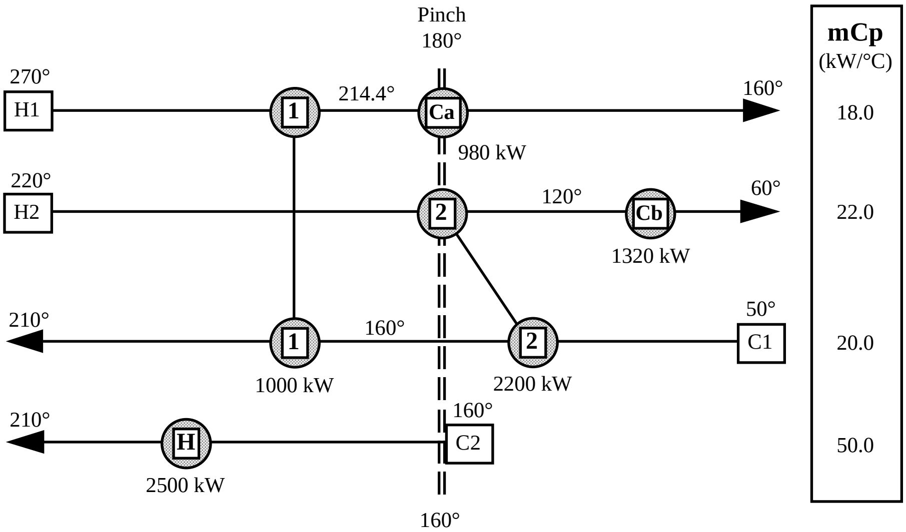

Fig. 6.3 Cross Pinch Heat Transfer in a Stream Grid

Having explained the features of an existing design that is responsible for a larger than minimum energy consumption, the next logical step is to look at the actual heat exchanger network to identify which process/process heat exchangers, external heaters and coolers that are actually transferring heat across pinch. The ***Stream Grid*** is an excellent tool for this purpose. In figure 6.3, an existing heat exchanger network is drawn in a stream grid in such a way that the relative position (in temperature) to the Pinch is indicated for all units.

6.2 A Preliminary Retrofit Discussion

It is now easy to identify which heat exchangers that transfer heat across the Pinch, and what amount of heat that is transferred across Pinch in each of these units. The sum of all these cross Pinch occurrences should add up to the total energy penalty. It should be noted, however, that there sometimes are cases where a heat exchanger operating with small temperature driving forces is transferring heat from below to above Pinch. These heat flows must then be subtracted when calculating the total energy penalty.

The heat exchanger network in figure 6.3 is using 2500 kW of hot utility and 2300 kW of cold utility. The corresponding minimum target values for $\Delta T_{min} = 20°C$ are $Q_{H,min} = 1000$ kW and $Q_{C,min} = 800$ kW (see the small example used for illustration in section 5.2). The total energy penalty for this existing design is thus:

$$QP = Q_{H,exist} - Q_{H,min} = Q_{C,exist} - Q_{C,min} = 1500 \text{ kW}$$

For the network in figure 6.3, cross Pinch heat transfer can be identified in heat exchanger (2) and cooler (Ca). The actual amount of heat transfer across the Pinch in these units can be calculated as follows:

Exchanger (2): $QP_P = 22 \cdot (220 - 180) = 880$ kW
Cooler (Ca): $QP_C = 18 \cdot (214.4 - 180) = 620$ kW

In this case, there is no external heating below Pinch, and the total energy penalty can be calculated from the occurrences of cross Pinch heat transfer:

$$QP = QP_P + QP_H + QP_C = 880 + 620 + 0 = 1500 \text{ kW}$$

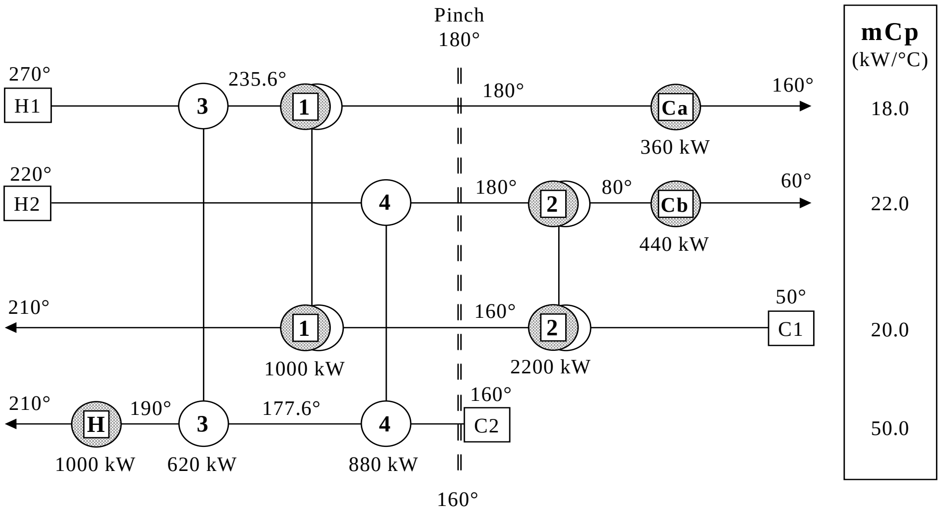

Fig. 6.4 A Retrofit Solution reaching Minimum Energy Consumption

Obvious retrofit projects should involve attempts to reduce heat transfer across the Pinch. Hot stream H2 is a heating resource above Pinch that could be used to heat up cold stream C2 and thus reduce the use of steam in the heater (H). Hot stream H1 is also a heating resource above Pinch, where some heat in the existing design is lost to cooling water.

Trying to realize the total potential for energy savings (1500 kW), would involve two new heat exchangers (3 and 4) and additional area in the existing ones (1 and 2), due to reduced driving forces. The corresponding heat exchanger network shown in figure 6.4 is actually identical to the initial MER design for the grassroots case shown in figure 5.11. Without actually performing cost calculations, it is obvious that the retrofitted network in figure 6.4 will be very expensive. It is almost an entirely new heat exchanger network.

An alternative solution would be to try to recover some of the heat that is lost from hot stream H1 into cooling water, by adding a new unit between hot stream H1 and cold stream C2. In this case, the existing heat exchangers are not modified (no additional area is needed), and the simple question is whether the saving of 620 kW of steam and cooling water will justify the investment in a new heat exchanger (3). The corresponding network is shown in figure 6.5.

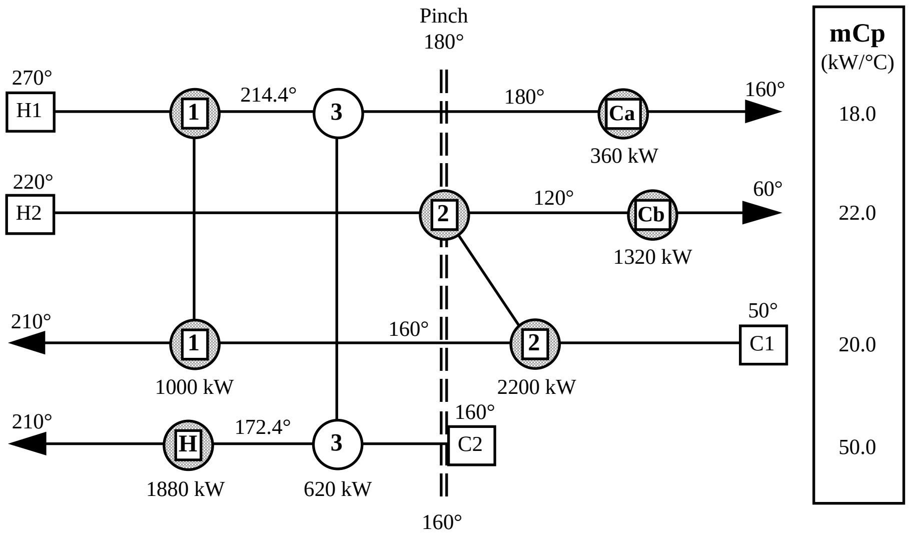

Fig. 6.5 A cheaper Retrofit Solution recovering part of the Potential Energy Savings

Having shown some of the useful representations and indicated a possible "thinking" in retrofit situations based on cross Pinch heat transfer, the remaining part of chapter 6 will be devoted to a presentation of the methods that can be used for heat exchanger network retrofit. Similar to the grassroots case, there are ***four*** distinct ***phases*** also for retrofit design:

1) Data Extraction 2) Targeting 3) Design 4) Optimization

There will, however, be significant differences in all of these phases when compared to the grassroots situation. These differences and the new objectives will be highlighted in the description of each of these phases.

6.3 Data Extraction (Phase 1)

While there are a number of similarities between data extraction in the retrofit situation and the grassroots case as described in section 5.1, there are also significant differences that will be highlighted here. In both cases, data extraction is a time consuming and critical activity for the outcome of a Process Integration project.

Typically, for a new design there will be material and energy balances available either manually derived or based on a simulation model. A rigorous simulation model has the distinct advantage that stream data can be extracted directly and even automatically with today's software. Unfortunately, such models may not always be available for an existing plant. In general, the following are possible sources for data that are needed in a retrofit heat recovery project, and often these sources have to be used in combination:

- Measurements (that are often not complete and not reliable)
- Design data (that are often outdated after plant modifications)
- Simulation models (that may not always reflect true plant behavior)

As a result, data reconciliation is important in retrofit projects. If measurements indicate that heat extracted from a hot stream in an existing heat exchanger does not match the heat absorbed by the cold stream in the same exchanger, it is necessary to analyze the situation. Stream data must be modified in such a way that heat balance is obtained; otherwise the heat recovery project will produce unrealistic results. It is important to notice that data accuracy is most important in the near Pinch region of the plant. Thus, it is common practice to try to establish a first draft of the Composite Curves, and then try to improve the accuracy only for process streams in the near Pinch region.

Another typical retrofit issue is related to which streams to include in the analysis. There may be a number of practical considerations suggesting that certain streams should not be included, since heat integration of these streams could cause operational problems. It is, however, good practice to start by including all streams that need heating or cooling, and then later exclude these streams one by one from the analysis. In this way, the engineer will know the loss in heat recovery potential from excluding certain streams.

In retrofit projects it is not necessary to iterate between data extraction and targeting, since the basic process (reactors, separators) is given and cannot easily be modified to improve heat recovery potential as the case is for grassroots projects. It would also be expensive to modify these process units, and would seldom "pay off" in pure energy based projects.

6.4 Retrofit Targets (Phase 2)

Targeting in the Retrofit situation is far more difficult than for Grassroots design. This is so because a number of different changes can be made to the heat exchanger network in order to reduce energy consumption. Typically, these modifications include:

- Addition of a new heat exchanger
- Additional area to an existing unit (for example a new shell)
- Change internals in heat exchangers
- Modify piping on one side of the exchanger
- Modify piping on both sides of the exchanger
- Moving a heat exchanger to a new location

Most of these retrofit actions will change the operating conditions for many of the heat exchangers, and a rigorous rating exercise is required to evaluate whether an existing unit will be able to operate in the new situation. The cost function for the retrofit project will exhibit a discontinuity whenever a heat exchanger switches from being large enough to become too small for the new operation.

In other words, the targeting of capital investment (new heat transfer area and new units) is much more difficult than in the grassroots case. Energy consumption, on the other hand, is much easier to predict, however, knowing the savings in energy cost is of limited value if it is not correctly linked with its corresponding investment cost. That is the true challenge in retrofit targeting.

6.4.1 Different ΔT Representations

The ultimate goal of the targeting exercise is to establish a good starting value for the level of heat recovery. In grassroots heat exchanger network design (Chapter 5), the parameter ΔT_{min} (minimum approach temperature) was used to represent this level of heat recovery. In most industrial processes, it does not make sense to require that all heat exchangers (and thus all process streams and utilities) obey the same minimum value for driving forces, since streams (and utilities) in general have very different heat transfer coefficients. Quite often, the difference in film heat transfer coefficients can be two orders of magnitude. Thus, some heat exchangers require large ΔT-values in order to avoid excessive heat transfer area, while other units manage well with much smaller ΔT-values.

Since this document is a Primer with focus on the key concepts in Process Integration, we did not discuss the details about heat transfer conditions and driving forces in Chapter 5. When considering the retrofit case, however, there are many reasons why we need to reconsider this question. Without going into too many details, we should at least acknowledge the need for two different approach temperatures:

HRAT = Heat Recovery Approach Temperature
EMAT = Exchanger Minimum Approach Temperature

While HRAT, as the name indicates, is a key parameter for the level of heat recovery (it is simply defined as the smallest vertical distance between the Composite Curves), EMAT is the minimum allowable temperature difference for the individual heat exchangers. In order to reach a certain level of heat recovery, (as specified by HRAT), the following inequality must be satisfied:

$$0 \leq \text{EMAT} \leq \text{HRAT}$$

As mentioned in section 5.2, it is also possible to assign individual contributions to the minimum driving forces for each stream and utility. Typically, these ΔT contributions should reflect heat transfer conditions, but they can also be used to represent the need for expensive material of construction, expensive heat exchanger types, etc. In this case, EMAT becomes stream dependent, and the following must be satisfied for a match between hot stream/utility (i) and cold stream/utility (j):

$$\Delta T_{i,j} \geq \text{EMAT (i,j)} = \Delta T_i + \Delta T_j$$

where ΔT_i and ΔT_j are the individual stream contributions. To illustrate how these different ΔT-values apply in retrofit situations, consider a typical oil refinery with a crude preheat train that warms up the crude from ambient temperature to the inlet of the furnace just before the crude fractionation tower. This is a complex heat exchanger network with many units, a large number of stream splits and considerable heat recovery from various hot streams in the refinery. In retrofit projects for such plants, it is common to design for a level of heat recovery that corresponds to HRAT = 30°C, however, the actual energy consumption in many such crude preheat trains corresponds to a value of HRAT well above 50°C. At the same time, there will be some heat exchangers typically where ΔT in one end of the units is in the range between 10 and 15°C. Thus, EMAT and the individual contributions ΔT_i and ΔT_j are considerably less than HRAT.

6.4.2 A Simple Energy Target

An obvious way to establish a target for energy savings in a retrofit project is to calculate the minimum external heating requirements for different values of HRAT (previously referred to as ΔT_{min}). One of these values of HRAT (typically a large one) corresponds to the current energy consumption, and the targeting exercise then becomes the identification of a new value of HRAT that is less than the "existing" value of HRAT:

$$\mathrm{HRAT}_{new} \leq \mathrm{HRAT}_{existing}$$

By plotting minimum energy consumption (or minimum energy cost in the case of multiple utilities) as a function of HRAT, it is possible to identify potential starting values of HRAT for the retrofit project.

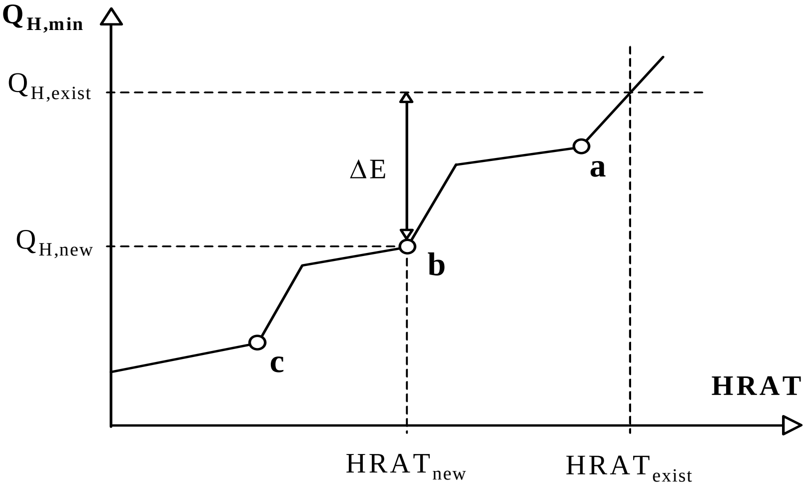

Fig. 6.6 A typical Energy Target Plot for the Retrofit Case

Consider the ***Energy Target Plot*** in figure 6.6, where the change in the slope illustrates the typical situation that minimum energy consumption does <u>not</u> always increase directly proportional with minimum driving forces. As a result, there are certain levels of heat recovery (represented by HRAT) that are more likely to be good retrofit candidates than others. Consider point (a) in figure 6.6. When trying to move towards larger energy savings, the change in $Q_{H,min}$ is relatively small, while the reduction in HRAT is considerable. Normally, this means large investments with moderate savings.

Figure 6.6 also indicates how the targeted savings in energy consumption (ΔE) can be read from the diagram for different values of HRAT. Also, by looking at figure 6.6, one may conclude that point (a) seems to save too little energy, while point (c) involves too large investments. Qualitatively, it may look as if point (b) provides a good trade-off between investments and savings in the retrofit case; thus HRAT_{new} is a good starting value for the retrofit project. Cross Pinch Analysis (section 6.1 and figure 6.3) will then be performed, where the existing heat exchanger network is drawn in a stream grid with a Pinch point according to $\Delta T_{min} = \mathrm{HRAT}_{new}$.

6.4.3 Targets for Area and Investment Cost

As stated in the beginning of section 6.4, targeting for heat transfer area and investment cost is far more complicated and uncertain in the retrofit situation than in the grassroots case. The identification of "promising" starting points in figure 6.6 may work in some cases, however, there is a need to quantify not only the energy saving part, but also the investment in new equipment and changes in piping.

Within Pinch Analysis, a Retrofit Targeting procedure has been proposed that is based on the concept of ***Area Efficiency*** (Tjoe and Linnhoff, 1986). This parameter can be easily obtained from the existing design and can be mathematically formulated as:

$$\alpha \;=\; [\,A_{min}\,] \,/\, [\,A_{exist}\,]$$

where α = Area Efficiency
A_{min} = Minimum area for the current level of heat recovery ($HRAT_{exist}$)
A_{exist} = Total heat transfer area in the existing network

A conservative assumption is that any new invested heat transfer area will at least have the same utilization level (area efficiency) as the installed area. This assumption (also referred to as the ***"constant α"*** approach) proved to work nicely for oil refineries and crude preheat trains, where area efficiency in existing plants was quite high (above 80%), while it did not work equally well in other industries. In processes with less heat integration, the constant α assumption can be too conservative. Attempts have been made to overcome this problem; one is the so-called ***"incremental α"*** approach (Silangwa, 1986), which means that area efficiency will change (improve) during the retrofit project.

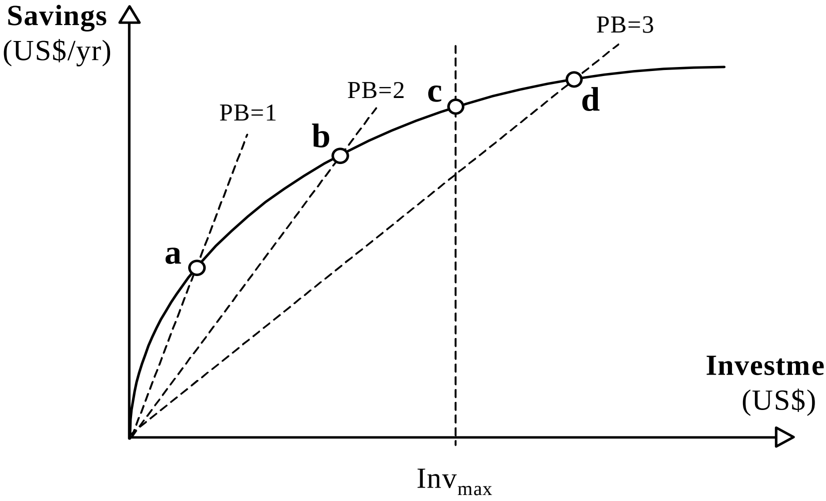

Fig. 6.7 A typical Retrofit Target Plot for Savings and Investment Cost

Irrespective of the actual approach chosen, using some kind of assumptions about area efficiency for new heat exchangers or additional shells, it becomes possible to estimate the need for new area (and thus investment cost) when targeting for different values of HRAT. By combining target values for area and energy for different values of HRAT (starting with the existing HRAT and then decreasing this value gradually), the ***Retrofit Target Curve*** in figure 6.7 can be obtained.

The curved line in figure 6.7 shows corresponding values for annual savings in energy cost and the total investment for new equipment (including installation). Each point on the curve represents a certain level of heat recovery (HRAT), starting in the origin of the diagram, where there are no investments made and no savings earned. Thus, the origin represents the situation before the retrofit project is started, and moving along the curve to the right means heading for smaller HRAT values and higher levels of heat recovery. As discussed in section 6.1, the most obvious errors in the existing network can be corrected first, often with small or moderate investments. Thus, the target line is initially steep, but then becomes more flat as we move towards higher levels of heat recovery.

Payback Time is simply defined as the Investment Cost divided with the Annual Savings in Operating Cost (energy). Considering the nature of the target curve in figure 6.7, it is obvious that Payback Time increases as we move along the curve towards larger energy savings. The dashed lines in the diagram illustrate typically Payback Times (PB) of one, two and three years. It is also quite common that management has set an upper limit on the investment that will be put into a certain energy saving project (indicated as Inv_{max} in figure 6.7). There will also be constraints on the Payback Time, and depending on whether maximum Payback Time for this particular example is set to two or three years, the retrofit targeting exercise will identify points (b) if minimum payback is two years or point (c) limited by maximum investment, if maximum payback is three years.

Points (b) and (c) in figure 6.7 correspond to different values of HRAT, which means that a target for the level of heat recovery has been identified. This target is an improvement compared with the more simplified discussion in section 6.4.2, since investment cost has been included and quantified, even though there are large uncertainties in these numbers. Again, once the new value for HRAT has been identified, the next stage is a cross Pinch analysis, as described in section 6.1.

6.5 Retrofit Design (Phase 3)

The Cross Pinch Analysis mentioned in the previous section is a good starting point for the design exercise. The first methods suggested to remove heat exchangers that transferred heat across the Pinch and to try to reuse these units in new locations. Since, however, heat exchangers in most cases are tailor made for a certain application (flowrates and types of streams) it is not easy and quite expensive to follow this approach.

6.5.1 Temperature “Shifting” of Heat Exchangers

Instead, Tjoe and Linnhoff, 1986, suggested to “shift” heat exchangers away from a cross Pinch situation. This shifting involves changes in operating conditions for the unit in such a way that hot stream temperatures are reduced and/or cold stream temperatures increased. The result is that cross Pinch heat transfer in that particular unit is reduced and possibly eliminated. Heating resources are released above Pinch and or cooling resources are released below Pinch. Consider the existing heat exchanger network in figure 6.3 that was used in the preliminary retrofit discussion of this chapter.

The cooler Ca and heat exchanger (2) are transferring a total of 1500 kW across Pinch, which is why external heating (2500 kW) and cooling (2300 kW) requirements are larger than the established minimum figures (1000 kW of heating and 800 kW of cooling). The shifting procedure means that the inlet temperature of stream H1 to the cooler Ca should be reduced from 214.4°C to at least 180°C (Pinch temperature for hot streams). This will release a heating resource from stream H1 above Pinch equal to 620 kW, and the duty of cooler Ca is reduced from 980 kW to 360 kW.

Similarly, the inlet temperature of stream H2 to heat exchanger (2) should be reduced from 220°C to 180°C. Assuming that the duty of this unit remains unchanged at 2200 kW (should always be questioned during network optimization), the duty of cooler Cb will be reduced by 880 kW to 440 kW. Figure 6.8 shows the incomplete network after these shifting operations. As indicated by the rectangles, there are two heating resources that have been released and not yet utilized above Pinch.

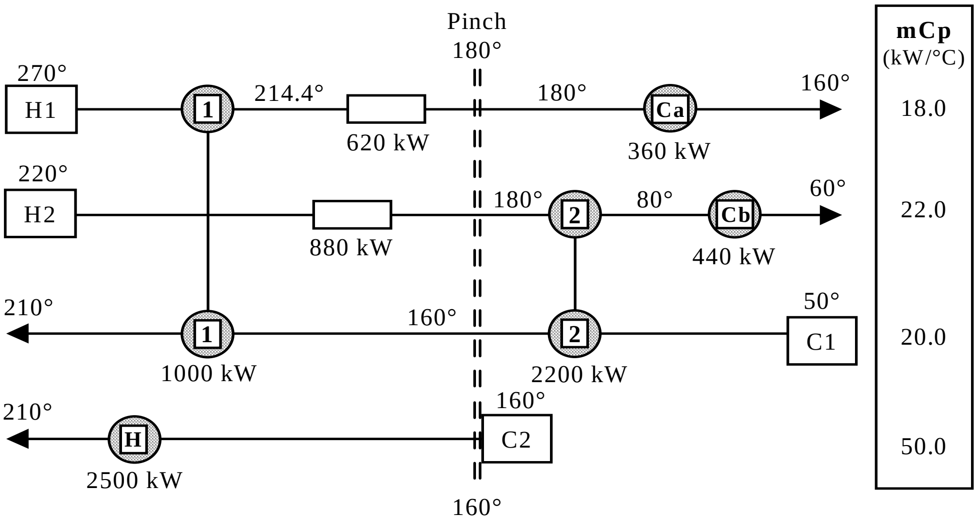

Fig. 6.8 Incomplete Heat Exchanger Network after "Shifting"

6.5.2 Introduction of New Heat Exchangers

The next obvious question is how to utilize these new heating resources above Pinch. Since cold stream C1 already is fully covered through heat recovery from hot stream H1, the obvious option is to try to use heat from hot streams H1 and H2 to partially heat cold stream C2 in order to reduce steam consumption in the heater.

Following the basic philosophy of the Pinch Design Method, cold stream C2 cannot fully utilize the two new heating resources (would involve taking both streams H1 and H2 down to Pinch temperature) unless stream C2 is split into two branches. Since mCp for stream C2 (50 kW/°C) is larger than the sum of mCp (18+22 kW/°C) for streams H1 and H2, this is a feasible option. Alternatively, the heating resource related to hot stream H1 could be shifted to the beginning (hottest part) of the stream. This option has already been shown in figure 6.4, however, as indicated in the same figure, heat exchanger (1) has considerably reduced driving forces and additional area is inevitable.

Figure 6.9 shows the initial retrofitted heat exchanger network when the stream split option is chosen. In this case, the operating conditions (duty and temperatures) for heat exchanger (1) are unchanged, and no additional area is needed. Heat exchanger (2) has, however, reduced driving forces with the same duty, and additional area is needed as indicated. A comparison with the alternative retrofit design in figure 6.4 will be made before going into the optimization stage.

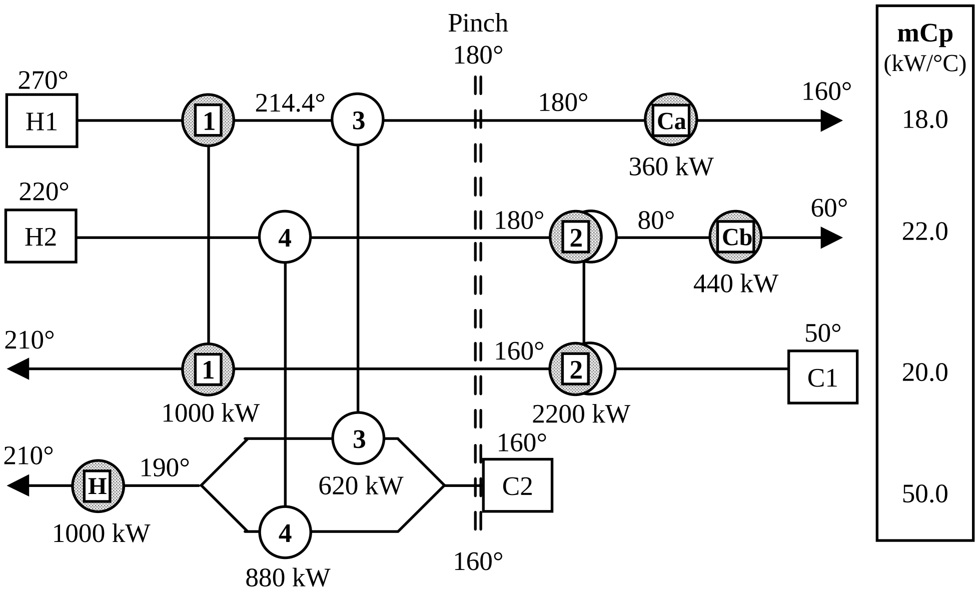

Fig. 6.9 Complete Retrofitted Heat Exchanger Network with Stream Split

In order to compare the two alternative initial retrofit heat exchanger networks in figure 6.4 and figure 6.9, details about heat transfer conditions and cost equations are needed. In this particular case, we do have information about heat transfer coefficients for streams and utilities (table 5.1), however, for the purpose of this Primer we do not want to go into detailed cost calculations. Instead, comparison between the two alternatives will be made on the basis of a simple ***UA analysis***.

It is easy from the heat transfer equation to calculate UA-values for the heat exchangers before and after retrofit modifications. If we assume that the units are pure counter current, UA-values can be obtained from:

$$UA = Q / \Delta T_{LM}$$

Table 6.1 shows UA-values for existing and new heat exchangers before and after retrofit modifications for the two alternative designs A (figure 6.4) and B (figure 6.9). Utility exchangers are not included, since the duties of these units are reduced in such a way that no additional area is needed (actually, these units will not be fully utilized after the retrofit modifications). Isothermal mixing is assumed for stream C2 after the split.

As indicated in table 6.1, the UA analysis does not give any strong preference for design A (figure 6.4) or design B (figure 6.9). The difference in total UA needed in the retrofitted networks is not significant, and a stronger argument for choosing design B is probably that the number of modifications is less, since there is no change needed for heat exchanger (1) in this case, however, there is a stream split introduced.

Table 6.1 UA-values (kW/°C) for two alternative Retrofit Designs

Heat Exchanger	Existing Design	Retrofit Networks Design A	Design B
1	17.49	44.12	17.49
2	33.91	89.20	89.20
3	0	9.07	27.99
4	0	29.52	35.68
Total	51.40	171.91	170.36

While both design A and design B fully recover the energy saving potential of 1500 kW, in most cases one can only justify economically to realize some fraction of this potential. The figures for UA listed in table 6.1 indicate that heat transfer area must be more than tripled in order to reduce energy consumption to its minimum for HRAT = 20°C. Thus, more recent retrofit methods use a "greedy" approach trying to identify the most economic retrofit projects with the fewest number of topological changes.

6.5.3 Matrix Methods for Retrofit Design

Some interesting matrix based methods have also been proposed for heat exchanger network retrofit situations. Shokoya, 1992, focused on heat transfer area in a method where targeting and design are closely linked. The so-called ***Area Matrix*** method is an adoption of the vertical heat transfer model (see the Area Targeting method in section 5.2.4). For various levels of heat recovery, the best vertical match area contribution is found using Linear Programming (LP). The result is a significantly improved retrofit area targeting method when compared with the constant α or incremental α methods mentioned in section 6.4.3. While the Area Matrix method primarily is a targeting procedure, the results from the LP optimization can also be used for retrofit design.

Another matrix based method for retrofit design is the ***Cost Matrix*** method developed by Carlsson et al., 1993. The method is based on the experience from a number of retrofit projects that other costs such as pumping and piping may have a larger influence on the optimal design than the number of units and heat transfer area. A Cost Matrix for possible matches is established, where the cost for each match is estimated taking into account parameters such as physical distance between process streams, material requirements, type of heat exchangers, auxiliary equipment (such as valves), heat transfer coefficients, space requirements, pumping cost, maintenance cost and fouling. The method uses the greedy approach due to its sequential nature, and there is no targeting involved.

6.5.4 More Recent Retrofit Methods

A number of more recent methods for retrofit heat exchanger networks using optimization (Mathematical Programming) to a large extent have been developed (e.g. Asante and Zhu, 1996, Briones and Kokossis, 1996). Due to the rather complex nature of these methods, however, they are only briefly mentioned in chapter 9 and omitted here. The complexity of these methods also means that software is an absolute requirement. Typically, these methods acknowledge the fact that only a few carefully selected modifications will be economically worthwhile, and the approach is to identify these retrofit actions.

6.6 Network Optimization (Phase 4)

As mentioned in the previous section, optimization is used in some of the more recent retrofit methods for network design, and the distinct classification into targeting, design and optimization has been reduced and almost eliminated. This section, however, will discuss how initial retrofit designs developed using the methods described in sections 6.5.1 and 6.5.2 can be improved economically and simplified with respect to network structure, using the same optimization philosophy as in the grassroots case.

Degrees of freedom in the form of ***heat load loops*** and ***paths*** as well as ***stream splits*** can be used to improve the initial retrofit design. One important new aspect in the retrofit case is to maximize the utilization of existing heat exchangers. After the shifting of cross Pinch heat exchangers and the introduction of new units, some of the existing heat exchangers may have a reduced duty and therefore no longer require all the area installed. In such cases it may be worthwhile to shift duty in heat load loops and/or paths until the existing units are better utilized.

Similar to grassroots situations, retrofit network optimization is a combination of discrete and continuous adjustments. The discrete part takes care of the removal of small new heat exchangers or small area additions to existing units, while the continuous part takes care of the trade-off between investment cost and obtained energy savings. The continuous part also includes, as mentioned above, the maximum utilization (if possible) of existing units.

Figure 6.5 shows an alternative retrofit heat exchanger network for this problem, where only one topological change is suggested. The introduction of the new heat exchanger (3) between H1 and C2 recovers heat that is lost to cooling water above Pinch in the existing design. In this retrofit alternative, the existing heat exchangers (1) and (2) are not changed, and the optimization simply becomes a one-dimensional search to identify the largest duty for heat exchanger (3) that satisfies constraints such as maximum Payback Time and maximum Investment Cost. Figure 6.10 illustrates that the optimization problem is reduced to the issue of finding the best duty for the new heat exchanger (variable y may take positive and negative values), and how this affects the heat load path from the heater through the new unit to the cooler Ca. Temperatures T_1 and T_2 depends on the value of y.

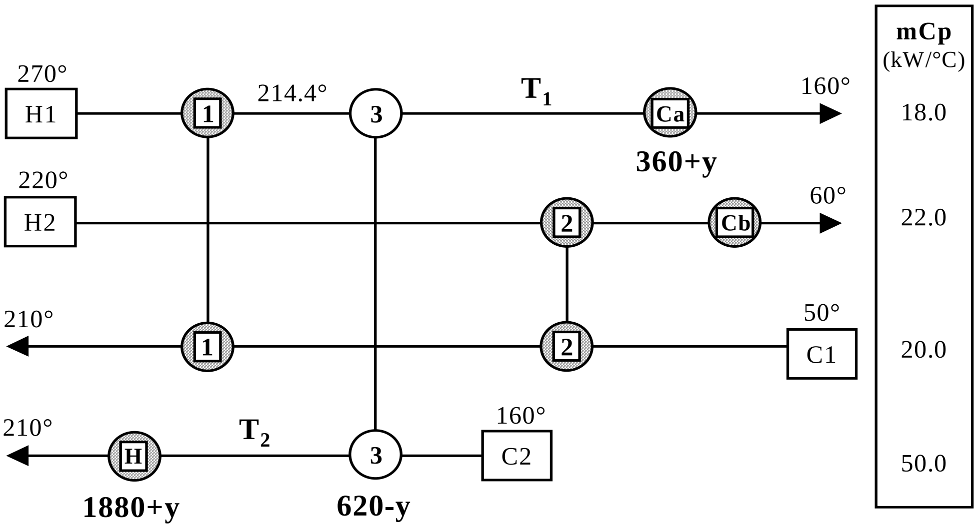

Fig. 6.10 A limited Retrofit Network Optimization Problem